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Machine Learning Integration in Feature Selection Using Sequential Forward Floating Selection (SFFS) for Improved Credit Scoring

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Abstract: Credit risk evaluation serves as the backbone of any financial decision, especially in government funding programs like DOST SET-UP. However, conventional credit assessment methods often face problems such as redundant features, low prediction accuracy, and increased computational complexity, which may result in suboptimal funding decisions. This study presents an integrated machine learning framework that incorporates Sequential Forward Floating Selection (SFFS) to optimize feature selection in credit assessment. This study considered financial and operational parameters from historical data on 33 DOST SET-UP projects undertaken from 2008 to 2016. A total of twelve parameters were initially considered in the feature selection process, which was later reduced to four highly significant features using the SFFS algorithm in Python: the Debt to Asset Ratio (DAR), the Net Profit Margin (NPM), the Liquidity Ratio (LR), and the Return on Investment (ROI). These features were later incorporated into the development of the rule-based fuzzy logic system using the MATLAB platform to produce the final recommendation for the risk assessment of the proposals. The experimental results show that feature selection greatly improved the model's prediction accuracy, and the system achieved an overall accuracy of 94%. The results verified that integrating machine learning-based feature selection and fuzzy logic can develop an efficient and effective credit scoring model for the government's lending programs and improve financial sustainability for micro, small, and medium enterprises.

Keywords: Credit scoring; feature selection; sequential forward floating selection (SFFS); risk analysis

1. Introduction

Credit scoring is critical in financial decision-making, particularly in weighing the creditworthiness of loan applicants. Because all financial institutions and government lending programs aim to maximize reasonable grant distribution while minimizing risk, there is an increasing need for accurate and efficient credit scoring models. However, traditional methods of assessing credit risk often struggle with feature-selection redundancy and model efficiency. As a result, decisions may be suboptimal, leading to higher default rates. In response to these challenges, credit risk analysis has widely adopted

machine learning techniques. Among these, feature selection helps improve model accuracy and reduce computational complexity by identifying the most relevant variables for prediction. Another effective way is Sequential Forward Floating Selection. This is an iterative feature-selection technique that improves variable selection by gradually adding and removing features to boost predictive performance. By integrating SFFS into credit scoring models, this research aims to improve feature selection by ensuring that only the key variables support the risk evaluation system.

This research examines the incorporation of SFFS with machine learning models in the credit scoring process to improve efficiency and accuracy. In this way, the risk assessment strategies of various financial institutions and government lending agencies would be enhanced, along with reduced loan delinquency rates and more efficient allocation of financial resources. More specifically, the findings will help create a stronger, verifiable credit evaluation system that supports financial stability and inclusivity for the DOST SET-UP. On the verge of the global financial crisis, credit risk assessment has become a critical component of financial decision-making. Financial grants should be given to creditworthy applicants to ensure the sustainability and resilience of micro, small, and medium enterprises. The DOST-SETUP plays a critical role in supporting MSMEs through technological innovations that increase productivity and competitiveness in the market. The program provides aid through technology acquisition, technical consultancy, training, product development, and financial aid, all of which address critical challenges that restrict business growth and sustainability [1]. To fully harness the potential of financial assistance, a technology-based credit risk assessment tool must be implemented to ensure grants are provided only to those with high creditworthiness [2].

Various credit risk evaluation models have been recommended to improve decision-making [3]. One critical challenge in predicting FDP is applying appropriate FS algorithms, which significantly affect the predictive models' accuracy [4]. So far, research on predicting monetary distress has also been highly active in statistics and machine learning. Essentially, predicting insolvency starts with selecting the most relevant features, reducing complexity, and improving model performance. Researchers have identified feature selection techniques and predictive models that can enhance FDPs. Yang et. al. [5] monitored feature selection through PCA and FA in an analysis of credit rating. This analysis showed the effectiveness of FA in reducing redundancy while retaining a high predictive performance for FDP. Similarly, Ding and Yan [6] proposed a model integrating Maximum Relevance Minimum Redundancy (MRMR) and Support Vector Machine Recursive Feature Elimination (SVM-RFE), which significantly improved financial distress prediction accuracy compared to traditional models.

Wu et al. [7] proposed an ensemble feature selection method combined with an improved stacking algorithm that used mutual information, analysis of variance (ANOVA), random forests, genetic algorithms, and recursive feature elimination. Their results showed significant improvements in FDP accuracy. In addition, Zhang et. al. [8] developed an ANN model that used a two-stage feature selection process with multiple filters and a wrapper method, thus addressing the "curse of dimensionality" and enhancing predictive capabilities. Santoso and Wibowo [9] compared LDA and SVM model variants for financial distress prediction and concluded that the Stepwise-SVM hybrid model achieved a better balance among model accuracy, generalization, and stability.

Feature selection has been utilized in different domains other than financial risk evaluation. Palongpalong et al. [10] targeted the identification of key features in blended learning when developing educational assessment software; thus, they ensured it would be implemented efficiently and comprehensively. Computerized mass classification [11] applied an SFFS- and SVM-based model to optimize medical research.

This means that selecting appropriate features is important for creditworthiness prediction because it directly influences accuracy and reliability. Studies show that the latest feature selection techniques can greatly enhance the efficiency of FDP models. With these methodologies, researchers can create accurate and reliable credit risk assessment tools. In this regard, financial grants and loans would be given to the most creditworthy MSMEs.

2. Materials and Methods

2.1 Research Design

The study employed a quantitative, data-driven approach, integrating data mining, feature selection, rule-based fuzzy logic modeling, and model evaluation. This was done by analyzing historical data from funded and unfunded projects to identify the most significant predictors of creditworthiness. This methodological workflow is illustrated in Figure 1.

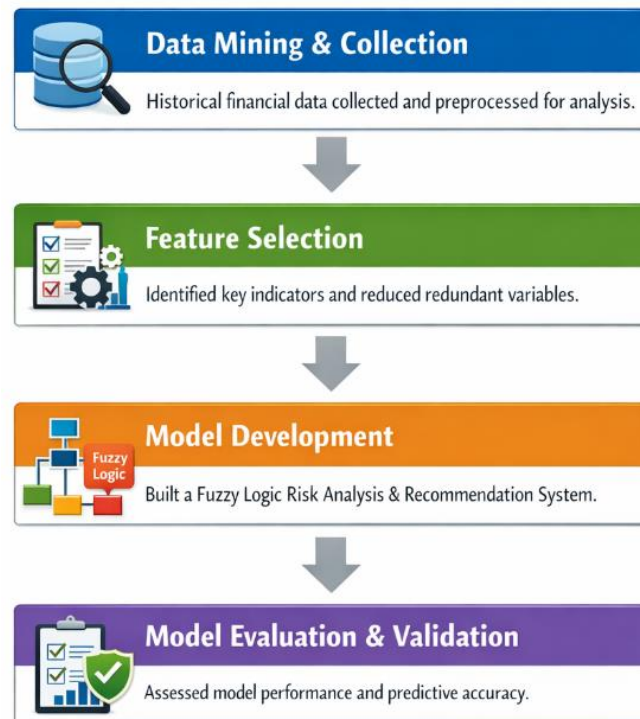


Figure 1. Structured Quantitative Data-Driven Approach

The framework adopts a data-driven pipeline that is structured to build and develop a risk analysis and recommendation model. The framework begins with data mining and collection, where historical financial data are extracted from relevant sources and undergo preprocessing techniques, including data cleaning, normalization, and transformation. This phase builds a credible dataset that captures the essential financial indicators required for predictive modeling. The next phase of the framework involves feature selection, which aims to identify the most significant financial indicators that influence risk prediction. Statistical and machine learning-driven approaches are used to eliminate redundant and irrelevant variables, enhancing model efficiency by reducing dimensionality. The framework adopts this approach to improve the model's interpretability and efficiency. During model development, the identified variables are used to design a Fuzzy Logic-based Risk Analysis and Recommendation System. Fuzzy logic is utilized to represent the uncertainties and vagueness associated with financial decision-making. Membership functions and rule-based reasoning systems are designed to represent the uncertainty and vagueness associated with financial decision-making. Finally, during model evaluation and validation, the efficiency of the developed model is assessed. Performance measures and validation processes are used to evaluate the system's accuracy, reliability, and consistency. This phase ensures that the proposed framework can provide accurate risk predictions and be used to make financial decisions.

2.2 Data Source and Description

The dataset consisted of historical financial records of DOST SET-UP Siquijor projects from 2008 to 2016, covering 33 project proposals. Each record represented a single project and included financial ratios, absolute financial values, operational indicators, and a class label.

2.2.1 Predictor Variables

Table 1. Feature Index Representation of the Dataset in Python

feature id	feature name
0	Debt-to- Asset Ratio
1	Net Profit Margin
2	Liquidity Ratio
3	Return on Investment
4	Asset
5	SET-UP Liability
6	Total Asset
7	Total Debt
8	Net Profit
9	Revenue
10	Year
11	Success rate on Objective Attainment
12	Success rate on Timely Payment

Table 1 shows the dataset used for simulation, based on the financial attributes from the data source. In the Python implementation, the attributes are converted into a formal feature list where each column is labeled using a numeric index and a feature name. The representation makes it easier for the Sequential Forward Floating Selection (SFFS) algorithm to analyze feature combinations and select the best-performing feature set for the DOST SET-UP Risk Analysis and Recommendation System. More specifically, the dataset includes financial features such as Debt-to-Asset Ratio, Net Profit Margin, Liquidity Ratio, Return on Investment, Asset, SET-UP Liability, Total Asset, Total Debt, Net Profit, Revenue, and Year, as well as operational attributes such as Success Rate on Objective Attainment and Success Rate on Timely Payment. These attributes are used as candidate features from which the algorithm selects the most significant variables for credit risk analysis. Using feature identifiers, the system allows for the systematic testing of the presence and absence of each attribute during the forward and backward phases of the SFFS process. This allows the simulation to determine the best-performing subset of financial attributes that significantly impact credit-risk prediction and to develop recommendations for the DOST SET-UP program. After determining the feature set described in Table 1, the dataset is imported into the Python simulation environment, where the SFFS algorithm analyzes different feature combinations and provides the final results for the feature selection process. This dataset is then loaded into Python to perform the simulation and generate the results for the feature selection.

2.3 Data Preprocessing

In this stage, data preprocessing was performed in Python before modeling. This includes removing non-numeric attributes, validating and correcting data types, eliminating inconsistent entries, and retaining numerical features required for machine learning. After the said process, the dataset consisted of numerical predictors and one categorical class label suitable for supervised learning.

2.4 Data Mining Tool

The research utilizes a data analysis and visualization software tool known as Tableau to extract insights from the data and display them in a graphical form. Tableau processed historical data on project proposals, whether accepted or implemented, over a period of nine (9) years from 2008 to 2016. Tableau also performed data-cleaning checks, trend analysis, and pattern identification before machine learning modeling. The application identified data distribution, anomalies, and relationships between key financial variables. The results obtained from Tableau were then processed using Python for further analysis to prepare the data for feature selection and credit risk classification. Using Tableau improved data interpretation and ensured the

financial data underlying the research was visually interpretable, consistent, and valid for more complex predictive modeling.

2.5 Feature Selection Method

To build the model, the system used Simplest Sequential Selection, which iteratively adds (or deletes) one feature at a time to maximize the intermediate criterion value until the required dimensionality is met. Figure 2 illustrates the SFFS process.

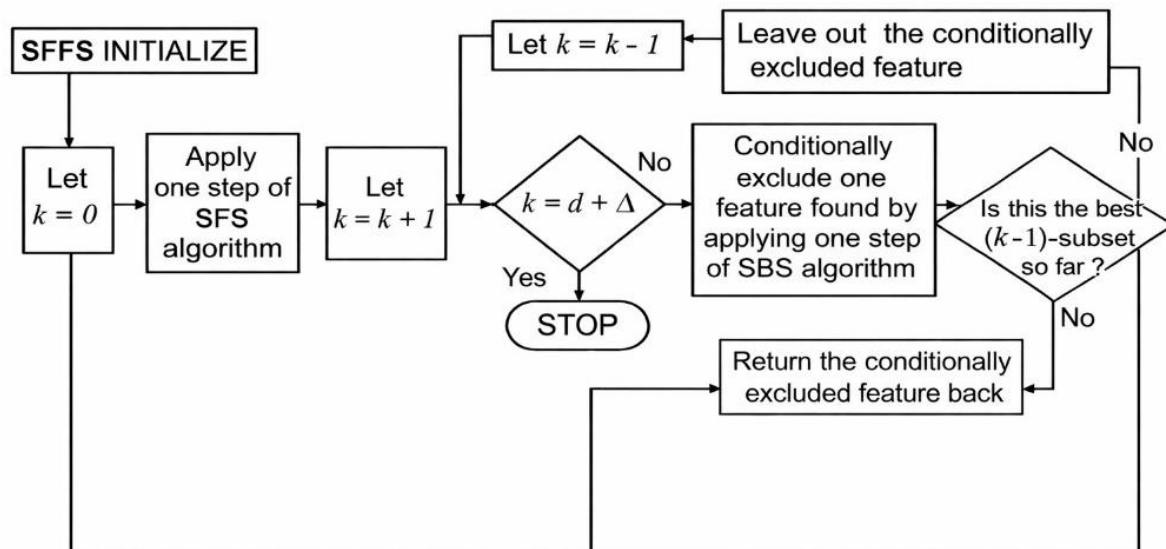


Figure 2. Sequential Forward Floating Selection (SFFS) Process Diagram. Sequential Forward Floating Selection Algorithm adopted from Somol, Novovicova, and Pudil (2010)

2.5.1 Floating Selection Algorithm Analysis

The figure shows the Sequential Forward Floating Selection (SFFS). The process consists of applying several backward steps after each forward step, as long as the resulting subsets are better than the previously evaluated ones at that level. Consequently, no backward steps occur if intermediate results at a given level cannot be improved. The same applies to the backward version of the procedure. The algorithms allow self-controlled backtracking, so they can eventually find good solutions by dynamically adjusting the trade-off between forward and backward steps. After each forward set, multiple backward steps are applied to the resulting 33 subgroups, which outperform the previously examined ones at that level. As a result, no backward steps are taken if intermediate results at a specific level cannot be improved. The same holds for the reverse-form techniques. The algorithms support self-controlled backtracking, allowing them to eventually find good solutions by dynamically altering the trade-off between forwarding steps. Setting SFFS yields a subset of d features, with the optional search-restricting parameter $\epsilon[0, D_d]$:

1. Start with $X_0 = \emptyset, k = 0$
2. $X_{k+1} = \text{ADD}(X_k), k = k+1$
3. Repeat $X_{k-1} = \text{REMOVE}(X_k), k = k-1$, as long as it improves solutions already known for the lower k . (1)
4. If $k < d + \Delta$ go to 2.

Using the Python programming language, the data were imported to start the sequential feature selection process, specifically sequential forward selection. Since the system needed numerical data for the credit risk analysis, all non-numerical data were removed from the dataset. Thus, we retained 12 constructs and one class, which is the remark stating whether the project status is completed or ongoing. This is presented in the table below.

Table 2. Numerical Financial Features Extracted from the Dataset

	DAR	NPM	LR	ROI	Asset	Liability	Total Asset	Total Debt	Net Profit	Revenue	Year	SOT	SRTLP	Remarks
0	0.55	0.45	1.20	37.88	300000.0	250000.0	550000.0	300000.0	208333.33	458333.33	2008	100	100	complete
1	0.57	0.49	1.33	40.46	600000.0	450000.0	1050000.0	600000.0	425000.00a	675000.00	2008	100	100	complete

Table 2 presents the cleaned numerical financial data used as input for the Sequential Forward Selection (SFS) method in the credit risk analysis. Before feature selection, the data was prepared in Python by removing non-numeric attributes, examining data types, and verifying numerical consistency to input the data directly into machine learning algorithms. Each entry represents a distinct borrower or project. For instance, Entry 0 has a Debt-to-Asset Ratio (DAR) of 0.55, indicating that 55% of assets are debt-financed, and a Net Profit Margin (NPM) of 0.45, indicating moderate profitability. A Liquidity Ratio (LR) of 1.20 indicates sufficient short-term assets to cover current liabilities. The Return on Investment (ROI) is 37.88%, which is a strong indicator of investment success. For Entry 0, ₱300,000 in assets and ₱250,000 in liabilities translate to ₱550,000 in total assets and ₱300,000 in total debt. Net profit is ₱208,333.33, with revenue of ₱458,333.33, further supporting a sound financial position. The performance metrics show 100% for both Success Rate on Objective Attainment (SROT) and Success Rate on Timely Loan Payment (SRTLP), indicating that the project is marked as “complete.” Record 1 shows higher leverage, with a DAR of 0.57, and improved profitability, with an NPM of 0.49. The LR of 1.33 indicates improved short-term financial performance compared to Record 0. The ROI improves to 40.46%, indicating highly favorable returns. On the financial side, the borrower has ₱600,000 in assets and ₱450,000 in liabilities, with total assets of ₱1,050,000 and total debt of ₱600,000. Net profit increases to ₱425,000 with ₱675,000 in revenues. Both SROT and SRTLP remain at 100%, and the project is also marked as “complete.” For the sample as a whole, the perfect SROT and SRTLP indicate that these borrowers have perfectly accomplished the project requirements and loan repayment terms. The ROI, which varies from 37.88% to 40.46%, and the liquidity ratios above 1.0 indicate that the projects are financially sound. The DAR values slightly above 0.50 indicate moderate leverage, which may still be acceptable depending on the credit policy.

3. Results and Discussion

3.1 Data Simulation Results in Python

After the DOST SET-UP Siquijor dataset from 2008-2016 was imported into Python, the SFFS algorithm was applied. To select features for the system, we adopted Simplest Sequential Selection, iteratively adding (or removing) one feature at a time to maximize the intermediate criterion value until the required dimensionality is achieved. The process starts by selecting the “best” 8 features from the *Iris dataset via Sequential Forward Selection (SFS)*. Here, set forward-True and floating-false. By choosing $ev=0$, cross-validation is not performed; therefore, the performance (here: ‘accuracy’) is computed entirely on the training set. Below are the resulting iterations out of 12 features and one class:

Table 3. Data Simulation to Python during its 1st iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initialization of the feature selection process using sequential backend with a single worker	Started	–
2	Initial parallel processing completed	Completed	–
3	Completion of the evaluation of candidate feature subsets	Completed	–
4	Selection of the first optimal feature subset (1 out of 8 features)	Processing Completed	0.975

Table 3 summarizes and reformats the execution steps of the Sequential Forward Floating Selection (SFFS) algorithm implemented in Python, showing the progression of the first optimal feature subset (1 out of 8 features) and an evaluation score of 0.975.

Table 4. Data Simulation in Python during its 2nd iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (12 of 12 tasks)	Completed	–
3	Selection of the optimal subset with 2 out of 8 features	Processing Completed	1.000
4	Final parallel validation of the selected feature subset	Completed	–

Table 4 illustrates the Sequential Forward Floating Selection (SFFS) process. It shows that the system tested various feature sets and ultimately selected the best pair of features from the eight features, resulting in a performance score of 1.000.

Table 5. Data Simulation to Python during its 3rd iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (11 of 11 tasks)	Completed	–
3	Selection of the optimal subset with 3 out of 8 features	Processing Completed	0.975
4	Final parallel validation of the selected feature subset	Completed	–

Table 5 shows how the Sequential Forward Floating Selection (SFFS) algorithm works using Python code. As shown below, the system evaluates the feature set, and by the third step, the algorithm selects 3 of the 8 features. This yields a performance score of 0.975, illustrating how the algorithm identified the key feature set for the credit risk assessment process.

Table 6. Data Simulation to Python during its 4th iteration out of 8 features using Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (10 of 10 tasks)	Completed	–
3	Selection of the optimal subset with 4 out of 8 features	Processing Completed	0.975
4	Final parallel validation of the selected feature subset	Completed	–

This table shows the fourth step of the Sequential Forward Floating Selection (SFFS) algorithm, implemented in Python. This shows that the system has tested different feature sets, and the best feature set, consisting of four out of the eight features, has been selected with a score of 0.975.

Table 7. Data Simulation to Python during its 5th iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (12 of 12 tasks)	Completed	–
3	Selection of the optimal subset with 5 out of 8 features	Processing Completed	1.000
4	Final parallel validation of the selected feature subset	Completed	–

Table 7 shows step five of the Sequential Forward Floating Selection (SFFS) algorithm, implemented in Python. In this step, the algorithm considered various feature subsets and selected the optimal feature set, which comprised five out of the eight features, resulting in a perfect score of 1.000. This shows the progressive identification of the most prominent features for credit risk evaluation.

Table 8. Data Simulation in Python during its 6th iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (8 of 8 tasks)	Completed	–
3	Selection of the optimal subset with 6 out of 8 features	Processing Completed	1.000
4	Final parallel validation of the selected feature subset	Completed	–

This table describes Step 6 of the Sequential Forward Floating Selection (SFFS) algorithm. It indicates that six of the eight features were selected as the best subset, resulting in a performance score of 1.000. This shows the algorithm's ability to identify the best features for credit risk assessment sequentially.

Table 9. Data Simulation in Python during its 7th iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (7 of 7 tasks)	Completed	–
3	Selection of the optimal subset with 7 out of 8 features	Processing Completed	1.000
4	Final parallel validation of the selected feature subset	Completed	–

Table 9 shows the seventh step of the Sequential Forward Floating Selection (SFFS) algorithm, implemented in Python, with the best features selected consisting of seven of the eight features, resulting in a performance score of 1.000.

Table 10. Data Simulation in Python during its 8th iteration out of 8 features using the Sequential Backend with 1 concurrent worker

Step	Process Description	Status	Score
1	Initial parallel evaluation completed (1 of 1 task)	Completed	–
2	Evaluation of feature subsets completed (6 of 6 tasks)	Completed	–
3	Selection of the optimal subset with all 8 features	Completed	1.000
4	Final parallel validation of the selected feature subset	Completed	–

For the DOST SET-UP program, the Sequential Forward Floating Selection (SFFS) approach was employed step by step to determine the best financial feature set that would significantly influence the credit risk evaluation process. Over eight steps, the process evaluated feature sets ranging from 1 to 8 features and assessed the performance of each selected set. The results show an increasing performance trend, culminating in a perfect score of 1.000 with the feature set containing all eight features. This demonstrates the effectiveness of the SFFS feature selection method in identifying the best feature set and supports a data-driven approach to a trustworthy credit scoring process. This means that feature selection eliminates irrelevant candidate features, thereby decreasing the complexity of the DOST SET-UP risk analysis and recommendation model. Figure 3 visualizes this.

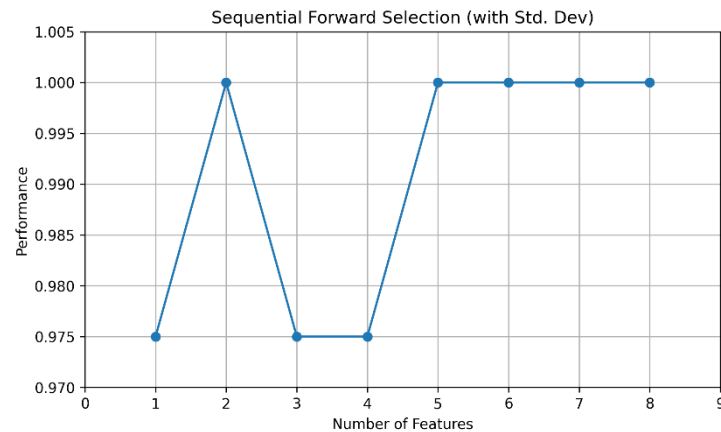


Figure 3. Selected Features using Sequential Forward Selection Result

The prompt below shows that the algorithm adds features one at a time and computes accuracy iteratively. Among the 12 features, only eight are chosen. This shows that the first feature has an accuracy rate of .975, or 97.5%, followed by .1, or 100%. However, the graph dropped twice for features 3 and 4 and repeatedly returned to an accuracy rate of .975, or 97.5%. Positively, the accuracy rate was high enough for the last four variables, reaching .975 (97.5%), followed by .1 (100%). This supports the claim that feature selection improves model performance, avoids overfitting, reduces training and testing time, and lessens measurement and storage requirements. Thus, with accuracies of 97.5% to 100%, the selected features are chosen. The result further shows that these features are the following, as displayed in Python:

```
# Which features?
feat_cols = list(sfs1.k_feature_idx_)
print(feat_cols)
```

(2)

[0, 1, 2, 3, 6, 9, 10, 12]

This shows the selected features by feature ID. Specifically, 0, 1, 2, 3, 4, 5, 6, 9, 10, and 12 in Table 3.4. The results show that the eight selected features are DAR, NPM, LR, ROI, Total Asset, Revenue, Year, and Success rate on Objective Attainment. To treat the data, only the top four features are included in the system since they are financial ratios. Specifically, these are the top four in the ranking.

Table 11. Selected features resulting from the DOST SET-UP historical data

Feature ID	Selected Features	Rank
0	Debt-to- Asset Ratio	1
1	Net Profit Margin	2
2	Liquidity Ratio	3
3	Return on Investment	4
6	Total Asset	5
9	Revenue	6
10	Year	7
11	Success rate on Objective Attainment	8

The top four selected features are all financial ratios. DAR, NPM, LR, and ROI are mathematical comparisons of financial statement accounts or categories. These relationships between financial statement accounts help financial grantors, creditors, and internal company management understand how well a business is performing and where it needs improvement. For features in ranks 5 and 6, such as total assets and revenue, they are both composed of those ratios. For rank 8, which is the year, this feature is not very relevant to include since the DOST-SET-UP is availed yearly, while the success rate on objective attainment can only

be used when the project is already completed. These ratios are calculated using the statistical formulas indicated in equations 5, 6, 7, and 8.

3.2 Mathematical Formulation of Selected Ratios

The four financial ratios were calculated using the following mathematical formulas to determine the financial performance and risk level of the selected firms in the dataset. The four selected financial ratios were computed as follows:

Computation of Net Profit Margin:

$$NMP = \frac{\text{Net Profit}}{\text{Total Revenue}} \quad (3)$$

NPM is the ratio that shows the percentage of profit earned on the total revenue generated by the company. It shows how efficiently the company converts revenue into profit. If NPM is high, the company is more efficient in its operations and has a high profitability level. On the other hand, if the NPM is low, it means the company has high operating costs.

Computation of Return on Investment:

$$ROI(\%) = \frac{\text{Net Profit (or Gain from Investment)}}{\text{Cost of Investment}} \times 100 \quad (4)$$

ROI is a ratio that shows the profitability of the investment compared with the total cost incurred. It shows the amount of return generated on each investment made by the company. If the company has a high ROI, it means the company is more efficient in its investment and has a high level of financial performance.

Computation of Liquidity Ratio:

$$LR = \frac{\text{Current Asset}}{\text{Current Liability}} \quad (5)$$

LR is the ratio that shows the SMSE's efficiency in meeting its financial obligations using its assets. If the liquidity ratio is more than 1, it means the business can easily pay its financial obligations using its assets.

Computation of Debt to Asset Ratio:

$$DAR = \frac{\text{Total Liabilities}}{\text{Total Assets}} \quad (6)$$

DAR measures the portion of a business's assets financed through debt. It shows the amount of financial leverage employed by the establishment. The higher the DAR, the higher the risk since the proportion of debt employed is higher.

The results from the risk analysis and recommendation system are used as variables to compute the financial ratio values. The results are interpreted using a business intelligence tool to identify the enterprise's risk category based on the financial indicators.

3.3 Comparative Performance Analysis With and Without Feature Selection

To assess the contribution of Sequential Forward Floating Selection (SFFS) to the proposed credit scoring framework, a comparative analysis is conducted between two models: one developed using all features and the other developed using the optimized set of features selected through SFFS. First, the credit risk evaluation system is implemented using all the features included in the set of twelve variables. Although this approach enables the system to incorporate a broad range of information, it also introduces feature redundancy, complicating the system's evaluation process and reducing the interpretability of the fuzzy rule base. Upon applying SFFS, the system is optimized for a reduced set of four essential financial ratios: Debt-to-Asset Ratio (DAR), Net Profit Margin (NPM), Liquidity Ratio (LR), and Return on Investment (ROI). These four ratios encompass the essential statistical characteristics of a firm's leverage position, profitability, liquidity, and investment efficiency.

3.4 Model Development: Rule-Based Fuzzy Logic

3.4.1 Variable Ranges

For the study, the researcher adopted a structured business tool from Northwest Farm Credit Services (NFCS, 2015) to identify the financial ratios that measure the performance of each feature used in the algorithm simulation. This indicates the numerical benchmarks measured as low, marginal, and high. With the measurements in hand, the risk impact for each benchmark has also been stipulated as it is implemented during the simulation. This is presented in Table 12 below:

Table 12. Financial Ratios used in the Fuzzy Logic

Financial Indicator	Benchmark			Risk Impact
	Low	Marginal	High	
Net Profit Margin	≥ 25	10-25	≤ 10	The higher the margin, the lower the risk
Return on Investment	≥ 5	1-5	≤ 5	The higher the ratio, the lower the risk
Liquidity Ratio	≥ 1.50	1.00 - 1.50	≤ 5.0	The higher the ratio, the less risk
Debt to Asset Ratio	≤ 30	30 -55	≥ 55	The higher the ratio, the more risk

The table shows the different financial indicators and different benchmarks. For net profit margin (NPM), a higher margin indicates lower risk. For return on investment (ROI), the higher the ratio, the lower the risk. For the liquidity ratio (LR), the higher the ratio, the lower the risk, and lastly, for the debt-to-asset ratio (DAR), the higher the ratio, the more risk there will be.

3.4.2 MATLAB Model Building

MATLAB was used to create the rule-based fuzzy logic component of the system. The fuzzy system is composed of five features represented by a Fuzzy Interference System (FIS) as shown in Figure 4:

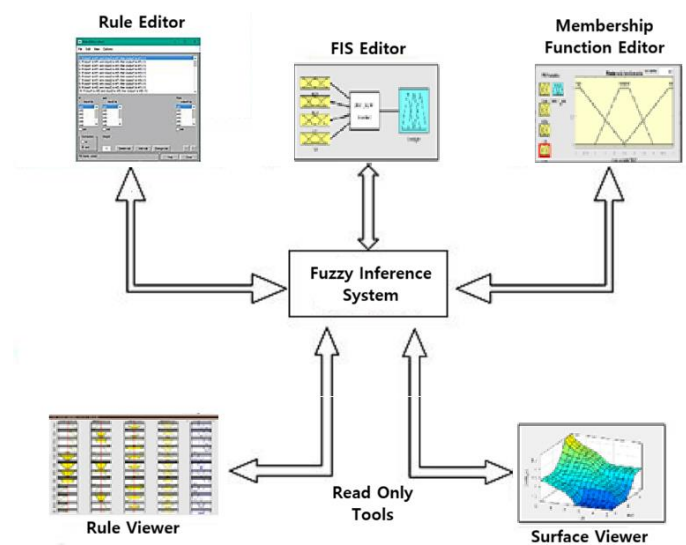


Figure 4. MATLAB Simulation of the DOST SET-UP Risk Analysis and Recommendation System

The proposed Risk Analysis and Recommendation System for the Department of Science and Technology – Small Enterprise Technology Upgrading Program (DOST SET-UP) was developed using the MATLAB Fuzzy Logic Toolbox. The fuzzy inference system (FIS) was designed to assess the credit risk of project proposals based on specific financial indicators. The system uses a rule-based fuzzy-logic technique to convert numerical financial ratios into linguistic risk terms and to produce a final credit risk score.

3.4.3 Fuzzy Inference System Structure

The fuzzy inference system has four input variables and one output variable. The input variables are the Debt-to-Asset Ratio (DAR), Net Profit Margin (NPM), Liquidity Ratio (LR), and Return on Investment

(ROI). These financial ratios were chosen as important factors in determining the financial viability and credit risk of SET-UP project proposals. The output variable is the Credit Risk Score.

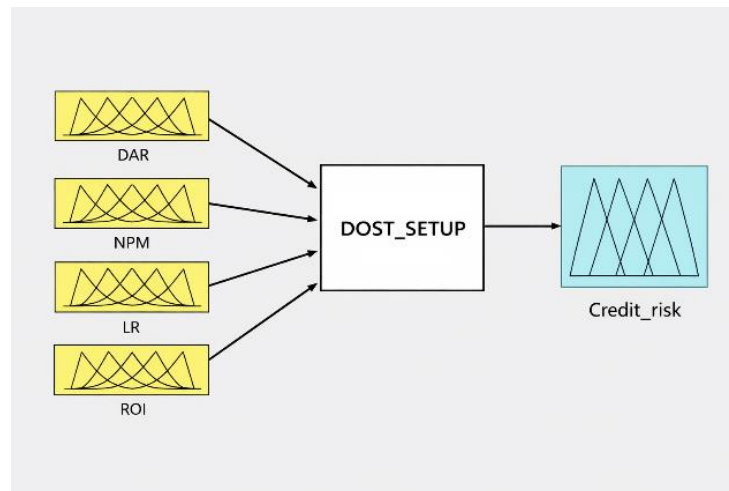


Figure 5. MATLAB Simulation of the DOST SET-UP Risk Analysis and Recommendation System

In the DOST SET-UP risk analysis system, the Debt-to-Asset Ratio (DAR) is one of the major parameters used to evaluate the firm's financial condition. The debt-to-asset ratio is evaluated based on a specific numerical range to determine the level of credit risk associated with the firm's financial structure, as shown in Table 13. The risk level is classified based on the percentage of total debt relative to total assets. In this context, credit risk is considered low if the debt-to-asset ratio is below 30%, marginal if it falls between 30% and 55%, and high if it is above 55%. This shows that the higher a firm's debt-to-asset ratio, the higher the level of credit risk. This assumes that firms with higher debt relative to their assets may find it difficult to meet their obligations. Moreover, the DOST SET-UP risk analysis system implements the list of risk assessment parameters for the Debt-to-Asset Ratio (DAR). The DAR is considered one of the main financial indicators for assessing an enterprise's credit risk by identifying the percentage of total assets financed by debt. In the study, the DAR input feature is represented by the Gaussian membership function (gaussmf) under the fuzzy logic approach provided by the MATLAB tool. The range of the risk score is between 0 and 55, while the four membership parameters, namely minimum, low, moderate, and high, are established by the system for identifying the degree of membership for every value under the fuzzy risk categories defined by the system, namely Low Risk, Marginal Risk, and High Risk. Through this fuzzy logic representation, the system can effectively model uncertainty and gradual transitions between risk levels, allowing a more flexible and realistic interpretation of the financial condition of enterprises participating in the DOST SET-UP program.

Table 13. Risk Assessment Parameters of Debt-to-Asset Ratio in the DOST SET-UP System

	Debt-to-Asset Ratio (DAR)			
	Minimum	Low	Moderate	High
Low Risk	-24.80	-2.75	2.75	30.19
Marginal Risk	4.73	24.8	30.19	49.8
High Risk	30.25	52.25	57.75	79.75

As shown in Table 13 above, the DOST SET-UP risk analysis system uses numerical values within specific ranges as parameters in the risk assessment process to determine the DAR. The parameters and risk-level classification are based on the standard risk-level guideline for financial risk management. As such, if the DAR level is less than 30%, the risk level is classified as Low Risk. However, if the DAR level is between 30% and 55%, the risk level is classified as Marginal Risk. Finally, if the DAR level is above 55%, the risk level is classified as High Risk. As such, the higher the debt level relative to the enterprise's total assets, the higher the enterprise's financial leverage. As such, the risk level also increases because credit risk increases. For the fuzzy membership representation, the parameters for the Low Risk level include -24.80, -2.75, 2.75, and 30.19.

The parameters for the Marginal Risk level would include the values 4.73, 24.80, 30.19, and 49.80. Finally, the parameters for the High Risk level would include the values 30.25, 52.25, 57.75, and 79.75. As such, the numerical values would form the basis for the fuzzy membership functions in the risk evaluation process.

Table 14. Risk Assessment Parameters of Net Profit Margin in the DOST SET-UP System

	Net Profit Margin (NPM)			
	Minimum	Low	Moderate	High
Low Risk	15	20.34	25.9	35.9
Marginal Risk	5.13	10	15	19.9
High Risk	-11.30	-1.25	4.993	10

Table 14 shows the risk assessment parameters for the Net Profit Margin (NPM), which is part of the DOST SET-UP risk analysis system. Generally, net profit margin is an essential profitability measure that defines the amount of net income generated from the enterprise's total revenue. It indicates the enterprise's ability to manage operational costs and generate net profitability. In the context of the DOST SET-UP risk analysis system, net profit margin is an assessment parameter defined by numerical ranges used to identify the credit risk level. For instance, the risk level is considered Low Risk when the net profit margin is more than 25%, Marginal Risk when the net profit margin is between 10% and 25%, and High Risk when the net profit margin is less than 10%. This analysis suggests that the higher the net profitability, the lower the credit risk, and the lower the net profitability, the higher the risk of instability in the enterprise's financial position. In the fuzzy logic analysis system using MATLAB, the input variable net profit margin (NPM), which is part of the risk analysis in the DOST SET-UP system, is defined using the Gaussian membership function (gaussmf). This is because the risk score ranges from 0 to 25, which is essential for evaluating profitability levels and defining the membership value for the respective risk category. In the fuzzy membership representation, the Low Risk category is defined by the parameter values 15, 20.34, 25.90, and 35.90. The Marginal Risk category is defined in terms of the parameter values 5.13, 10, 15, and 19.90, while the High Risk category is defined in terms of the parameter values -11.30, -1.25, 4.993, and 10. These numerical parameters are used to construct membership functions that classify the enterprise's profitability level into the appropriate credit risk category. With this fuzzy representation, the system can capture gradual transitions in profitability levels and offer a more flexible and realistic interpretation of the financial risk of enterprises participating in the DOST SET-UP program.

Table 15. Risk Assessment Parameters of Liquidity Ratio in the DOST SET-UP System

	Liquidity Ratio (LR)			
	Minimum	Low	Moderate	High
Low Risk	-2.18	-0.18	0.9854	2.48
Marginal Risk	0.0331	2.23	12.758	5.02
High Risk	-2.53	4.00	5.26	7.26

Table 15 shows the parameters used in the risk assessment for the Liquidity Ratio (LR) in the DOST SET-UP risk analysis system. Liquidity Ratio is a financial ratio used to evaluate an enterprise's capacity to settle its short-term financial obligations using its current assets. Liquidity Ratio is a key factor in determining an enterprise's financial stability and sustainability. In the DOST SET-UP risk analysis system, the Liquidity Ratio is used as a parameter in the risk assessment process. The risk assessment process uses a specific range to determine the enterprise's credit risk. The risk assessment process is as follows: if the liquidity ratio is less than 1, it is categorized as a low-risk enterprise. If the liquidity ratio ranges from 1 to 1.5, the risk is categorized as a Marginal Risk enterprise. If the liquidity ratio ranges from 1.5 to 5, the enterprise is categorized as a High Risk enterprise. From the description above, it is clear that the Liquidity Ratio is used to determine the enterprise's credit risk. Enterprises with a high liquidity ratio are likely to settle their financial obligations in the short term, indicating lower credit risk. In the fuzzy logic system using MATLAB, the input variable Liquidity Ratio (LR) uses the Gaussian membership function, represented as "gaussmf." The score varies from

0 to 5, enabling the fuzzy inference system to assess different levels of liquidity and classify liquidity into the relevant risk categories.

According to the generated fuzzy membership parameters, the Low Risk category has the numerical parameters of -2.18, -0.184, 0.9854, and 2.48. The Marginal Risk category has numerical parameters of 0.0331, 2.23, 2.758, and 5.02. In contrast, the High Risk category has the numerical parameters of 2.53, 4.001, 5.26, and 7.26, which serve as the basis for developing the membership functions to assess the extent of a particular liquidity ratio's affiliation with the different risk categories.

Table 16. Risk Assessment Parameters of Return on Investment in the DOST SET-UP System

	Return on Investment (ROI)			
	Minimum	Low	Moderate	High
Low Risk	2.48	4.76	5.26	7.26
Marginal Risk	0.985	2.25	2.75	3.975
High Risk	-2.25	-0.25	0.25	2.52

Table 16 shows a summarized version of the Return on Investment (ROI) risk classification implemented in the system. ROI is considered an inverse measure of credit risk. In more detail, credit risk is categorized as low if ROI falls within the range of 5% to 10%, marginal if ROI falls within the range of 1% to 5%, and high if ROI is less than 1%. In the proposed fuzzy inference system, ROI will utilize a Gaussian membership function represented by the function "gaussmf." This function enables a smooth transition between risk categories and helps handle uncertainty in financial performance evaluation. In more detail, the risk score will fall within the range of [0, 5], and lower risk scores indicate lower credit risk. According to the membership function, ROIs of 2.48, 4.76, 5.26, and 7.26 fall within the low-risk range. ROI values of 0.985, 2.25, 2.75, and 3.975 fall within the range of marginal risk, while ROI values of -2.25, -0.25, 0.25, and 2.52 fall within the range of high risk. It can be seen that ROI values overlap across different risk categories, indicating that risk assessment does not fall abruptly but is proportionally weighted according to membership degree. Notably, the effectiveness of the suggested approach is confirmed by comparing model performance before and after the feature selection process. The model had higher dimensionality and redundancy when all twelve variables, related to financial and operational aspects, were considered, leading to less stable and interpretable results.

3.4.3 Overall Risk Scoring

For the fuzzy logic output, CREDIT RISK uses the classical set for credit scoring (Shang, 2013). This is illustrated using the following diagram:

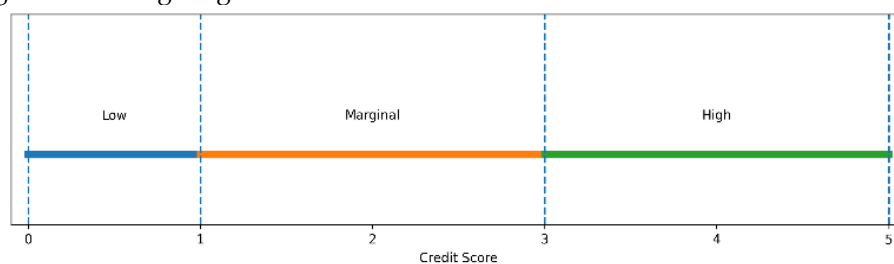


Figure 6. Classical Set for Credit Score

Figure 6 shows the classical set representation of the credit score used in the study. Each set has a membership function that defines the extent to which an element belongs to a given risk-level set. In this case, the credit risk level is considered low if the value is less than 1, marginal if the value lies between 1 and 3, and high if the value lies between 3 and 5. This shows a linear relationship between the credit risk score and the level of risk: as the credit risk score increases, the level of risk increases, and as the credit risk score decreases, the level of risk decreases. The data were simulated using the MATLAB program to calculate the actual fuzzy membership value. The system output, which is the credit risk score, has a triangular membership function, denoted as 'trimf.' The risk score ranges from [0,5]. A summary of the classification of the credit risk score is shown in the table below:

Table 17. Simulation Result for Risk Assessment in the DOST SET-UP System

Risk Category	Credit Risk Score Range	Description
Low Risk	1.00 – 2.38	Indicates minimal credit exposure; borrower demonstrates strong repayment capacity.
Marginal Risk	2.39 – 3.38	Represents moderate credit exposure; repayment capacity requires closer monitoring.
High Risk	3.39 – 5.00	Indicates significant credit exposure; higher probability of default.

Table 17 below shows the simulation results obtained from the MATLAB program used to implement the credit risk score classification. From the result obtained, low-risk classification refers to a credit risk score of 1.00 to 2.38, marginal risk refers to a credit risk score of 2.39 to 3.38, while high-risk classification refers to a credit risk score of 3.39 to 5.00. The numerical value was obtained after determining the parameters of the fuzzy inference system. After determining the membership values, the result was evaluated, and the output was defuzzified to obtain a crisp credit risk score. This was done to validate the system output and ensure its accuracy.

3.4.4 Credit Risk Output Representation

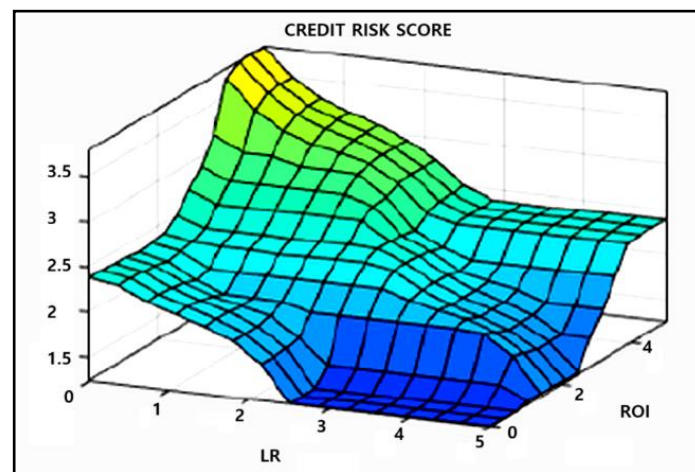
**Figure 7.** Surface View of the Credit Risk for Liquidity Ratio and Return on Investment

Figure 6 shows the three-dimensional surface plots of the proposed fuzzy-based credit scoring and recommendation system. The model has multiple input variables, such as Liquidity Ratio (LR), Return on Investment (ROI), and Net Profit Margin (NPM), which map to a single output variable, i.e., Credit Risk Score. Since the system has four input variables and one output variable, the relationship can be shown using two different plots. The plots show the effect of changes in various financial indicators on the overall credit risk score, which is calculated using the proposed model. The relationship between input variables such as LR and ROI and the output variable (i.e., Credit Risk), as well as the relationship between NPM and LR and the output variable (i.e., Credit Score), shows the nonlinear relationship using the fuzzy inference system. The overall credit risk, which is the center of gravity of the output, is 2.29, as shown by the computation of the proposed system. The proposed model incorporates a rule-based fuzzy inference system, in which all decision rules are embedded in the model and can be adjusted by the system administrator. The rules can be adjusted based on the numerical values obtained using the MATLAB simulation tool. Each rule has an equal effect on the output variable depending upon the extent of its activation. Ultimately, it acts as an intelligent credit scoring and recommendation system. It evaluates financial performance indicators, calculates a risk score through fuzzification, rule evaluation, and defuzzification, and produces a corresponding recommendation. The final recommendation will consolidate all input variables into a single assessment. After validation, the administrator may enable the notification system, which will send updates on the status of their application

to SET-UP applicants. This model offers a structured, data-based, and dynamic framework that helps maintain consistency and accuracy in project screening.

3.5 Model Evaluation Result using Confusion Matrix

To ensure the output of the rule-based fuzzy logic model is accurate, a confusion matrix was developed based on actual project implementation data versus the results obtained when running the newly developed Risk Analysis and Recommendation System of DOST SET-UP. The table shows the confusion matrix describing the performance of the rule-based fuzzy logic system for credit scoring using binary classifiers in MATLAB. Because the system used historical data from the actual DOST-SET UP implementation, it was limited to only 33 projects. The data included two possible predicted classes: "Accepted" and "Rejected." "Accepted" means the project was funded by DOST, while "Rejected" means that it was not funded. The population of 33 was tested, and the classifier predicted "Accepted" 30 times and "Rejected" 3 times. In reality, those who were funded were 30, and 3 were not. Thus, the following classifiers are identified as true positive (TP), true negative (TN), false positive (FP), and false negative (FN).

Table 18. Confusion Matrix for DOST SET-UP Credit Scoring

n=33	Predicted: Rejected	Predicted: Accepted	
Actual Rejected	True Negative (TR)= 2	False Positive (FP)= 1	3
Actual Accepted	False Negative (FN)= 1	True Positive (TP)= 29	30
	3	30	

Thus, the following classifiers have been identified as true positive (TP), true negative (TN), false positive (FP), and false negative (FN). This was computed in MATLAB, and the following result has been generated:

Computation of System Accuracy:

$$\text{Accuracy} = \frac{(TP + TN)}{n}$$

$$\text{Accuracy} = .93 \quad (7)$$

The result shows that the DOST SET-UP is .93 percent accurate in terms of output generation. To compute it, the false positives and true negatives are divided by the total number of the proposal population. So, one added to twenty-nine and two divided by thirty-three is equal to .93, or 93%. The accuracy rate is the proportion of correct predictions. Ultimately, an accurate risk analysis system can automatically evaluate project proposals, reducing paperwork and supporting sound decision-making [12].

Computation of System Error Rate:

$$\text{Error Rate} = \frac{(FP + FN)}{n}$$

$$\text{Error Rate} = .6 \quad (8)$$

In addition, the result shows that the system's miscalculation rate is 0.06. The generated error rate is deducted from 1, resulting in 0.04, which is considered the recall. To compute this, false positives and false negatives are divided by the total number of proposals. So, 1 is added to 1 and divided by 33, equaling 0.6. This result means that a lower error rate indicates higher reliability, which is advantageous when relying on the results [13].

Computation of True Positive Rate:

$$\text{True Positive Rate} = \frac{(TP + TN)}{n}$$

$$\text{True Positive Rate} = .92 \quad (9)$$

This data shows that the system has a sensitivity of .92, meaning it correctly predicts 92% of actual accepted cases. To compute it, divide the true positives by the total number of actual accepted proposals. So, twenty-three

divided by twenty-five is equal to .92 or 92%. This result means the actual and predicted data are highly similar, which supports their accuracy [14].

Computation of False Positive Rate:

$$\text{False Positive Rate} = \frac{\text{FP}}{\text{Actual Rejected}} \quad (10)$$

$$\text{False Positive Rate} = .33$$

This result shows that when it's actually rejected, it predicts acceptance 33% of the time. To compute this, divide the false positives by the total number of actually rejected proposals. So, one divided by three equals .33. This means the system has high accuracy in identifying rejection [12, 15].

Computation of True Negative Rate:

$$\text{True Negative Rate} = \frac{\text{TN}}{\text{Actual Rejected}} \quad (11)$$

$$\text{False Positive Rate} = .66$$

The result shows that the system predicts rejection 66% of the time when it's actually rejected. To compute this, the true negative is divided by the total actual rejected proposals. So, 2 divided by 3 equals .66. The generated rate is divided by 1, resulting in .34, which is considered the *specificity* [12, 14].

Computation of Precision:

$$\text{Precision} = \frac{\text{TP}}{\text{Predicted Accepted}} \quad (12)$$

$$\text{Precision} = .97$$

This clearly shows that the output of DOST SET-UP using rule-based fuzzy logic is 97% precise. To compute this, divide the true positives by the predicted accepted proposals. So, twenty-nine divided by thirty is equal to .97 or 97%. This is the proportion of positive cases that were correctly identified. This shows that the system's output is reliable [13].

Computation of Prevalence:

$$\text{Prevalence} = \frac{\text{Actual Accepted}}{n} \quad (13)$$

$$\text{Prevalence} = .94$$

Performance metrics such as recall, precision, and specificity are also widely acknowledged in the credit-scoring literature as offering a more complete evaluation than accuracy in datasets with class imbalance [12–14]. Recall, for instance, helps evaluate a model's ability to identify positive cases correctly. Similarly, precision helps ensure a model's reliability by reducing false positives. These metrics are best practices for financial risk evaluation systems [15, 16].

4. Conclusions

This study demonstrates the viability of integrating machine learning-based feature selection with a rule-based fuzzy logic approach to improve credit risk analysis under the DOST SET-UP program. From an initial set of twelve financial and operational features, the proposed Sequential Forward Floating Selection (SFFS) technique was able to effectively select the four most important financial features, namely the Debt-to-Asset Ratio (DAR), Net Profit Margin (NPM), Liquidity Ratio (LR), and Return on Investment (ROI), as the most significant factors influencing the creditworthiness of the entrepreneurs. By incorporating the proposed features into the fuzzy inference-based credit risk analysis and recommendation system, the vagueness and uncertainty in entrepreneurs' decision-making process were effectively addressed. Although the study made remarkable findings, it is important to note some limitations. To start with, the study has used a given data set in its analysis. However, the results may not be generalizable. Moreover, the use of the SFFS feature selection method and a specific classifier does not guarantee that the results would be the same with a different

classifier. The results may vary if a different classifier is used. Results may also vary if a different feature selection method is used. However, the proposed system achieved an overall classification accuracy of 94%, indicating its reliability in distinguishing between approved and rejected project proposals. The results validate the potential of integrating the SFFS technique with fuzzy inference systems for credit scoring, especially in data-scarce environments such as the DOST SET-UP program. Thus, the proposed framework presents a structured approach for evaluating credits in a data-driven and transparent manner. The approach is beneficial not only for credit evaluation but also for ensuring more objective funding decisions within DOST-SETUP. The proposed methodology is useful not only for its intended purpose, but also for establishing a platform for other government institutions and financial institutions to manage credits effectively.

Authors' Contribution: D.I., C-S.: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing – original draft. C.I, S.: Investigation, Resources, Writing – review and editing. D.A., R.: Investigation, Resources, Writing – review and editing. All authors have read and agreed to the published version of the manuscript.

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Development of Pilgrimage Tourism as an Application for Supporting Local Religious People

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Abstract: Hajj and Umrah are both Islamic pilgrimages in Mecca, Saudi Arabia, which are the main activities for Muslims. These are also required by Muslims in Thailand, and the trend is increasing every year. Typically, the number of pilgrims who can perform Hajj is limited by Saudi Arabia. In 2022, Thailand received a quota of 13,000 people, and the Committee for the Promotion of Hajj Affairs in Thailand will distribute the quota to entrepreneurs and religious leaders who have licenses to lead pilgrimage tourism. However, there are some difficulties in a pilgrimage tour, such as visa applications, accommodation bookings, flights, and so on. These processes need a lot of paperwork, so entrepreneurs and religious leaders will present to support pilgrims. There have been reports of pilgrimage tourism, including high service charges, poor management, and fraud by scammers. To the best of our knowledge, there is no digital platform to help local religious leaders organize the tour and provide online services for pilgrims. Therefore, we design and develop a novel application for pilgrimage tourism to facilitate religious leaders in handling paperwork for the Committee for the Promotion of Hajj Affairs in Thailand and support pilgrims in booking pilgrimage tours through a mobile web application, namely <https://www.hajestic.com>. The key development of the application is a user-centric, e-marketplace-based structure integrated to secure online payments and ensure compliance for users. In addition, we also designed 3 qualitative questionnaires based on the technology acceptance model (TAM) to guarantee the application meets users' requirements and satisfaction.

Keywords: Pilgrimage tourism; mobile web application; design and development; qualitative questionnaire

In Thailand, there are more than 7.4 million people who are Muslims. Most of them are living in Songkhla, Satun, Pattani, Yala, and Narathiwat [1]. Every year, some of them plan to perform Hajj and Umrah in Mecca, Saudi Arabia. Due to the high demand for pilgrimage tourism, Saudi Arabia limits the number of pilgrims annually. In 2022, the Committee for the Promotion of Hajj Affairs in Thailand received a quota of 13,000 people [2]. Thus, they distribute the quota to entrepreneurs and religious leaders who have licenses to lead pilgrimage tourism. However, most pilgrims living in Thailand struggle with many problems, such as visa applications, accommodation bookings, flights, and so on. Hence, local entrepreneurs or religious leaders provide package tours to support them and hand over the necessary documents to the Committee for the Promotion of Hajj Affairs. Recently, there have been reports of some issues

with pilgrimage tourism. For instance, religious leaders are not well managed in some local areas. Additional assistance charges are more expensive than the pilgrims expected, and they are not allowed to know the itinerary plan until the departure date. Some pilgrims got scammed and lost a lot of money. There is a report that the cost is approximately 100,000 baht per person [3], which mostly happens when a scammer promises to book a flight ticket or accommodation. Another main issue is that some local pilgrims learn about local religious leaders and pilgrimage tours through word of mouth. This may lead to insufficient detail and uneven data distribution.

In addition, research on the differences between general and religious tourism reveals several gaps in how they are studied and managed. While many studies focus on either "secular" tourists or "religious" pilgrims, they often ignore the growing number of people who fall into both categories. There is also a disconnection between the technologies being developed and the actual needs of the travelers. For example, while new applications and digital platforms are being developed, they often fail to align with the spiritual values of the journey. Furthermore, most research uses simple surveys administered at a single point in time, which fail to show whether the tour had a lasting impact on the person. Addressing these gaps is essential for developing a holistic understanding of how modern religious tours can satisfy both the logistical and transcendental needs of religious followers. To summarize, the key research gaps include:

(1) Theoretical Hybridity: The failure of existing frameworks to account for the difference in motivations between the traditional tourists and the pilgrims.

(2) Spiritual-Managerial Alignment: A lack of integrated models where tourism agencies operate as religious leaders rather than mere general tour guides.

(3) Digital Ecosystem Fragmentation: The absence of comprehensive customer relationship management (CRM) and digital ecosystems capable of synchronizing the needs of entrepreneurs, religious leaders, and pilgrims.

(4) Entrepreneurial Software Development: A deficit in novel software development approaches that prioritize "value-platform alignment" specifically for religious contexts.

(5) Methodological Snapshot Bias: An over-reliance on post-tour surveys that ignore the longitudinal, transformative impact of the travel experience on the individual.

To tackle the aforementioned problems, we decided to develop a solution that would help both local religious leaders and pilgrims streamline the preparation for pilgrimage tours. To the best of our knowledge, there is no digital platform to help local religious leaders organize the tours. Given the widespread availability of online platforms for booking general tours, e.g., Agoda, Airbnb, Booking.com, Trip.com, and Expedia [4-6], it would be helpful to have an online platform for religious tours. Therefore, we design and develop a novel application for pilgrimage tourism to facilitate religious leaders, namely <https://www.hajestic.com>. The first page of the website is shown in Fig. 1. The key development of the application is a user-centric, e-marketplace-based structure integrated to secure online payments and ensure compliance for users. This research consists of the following purposes:

(1) To study features of an online platform for managing pilgrimage tourism by local religious leaders and fulfill the pilgrims' requirements.

(2) To investigate the platform's impact on the hybrid motivations of modern pilgrims: This addresses the "Theoretical Hybridity" gap by examining if the application meets both the ritualistic needs and the expectations of the users.

(3) To design and develop an online platform as a mobile web application for pilgrimage tourism, and evaluate the integration of spiritual guidance into the digital marketplace. This explores the "Spiritual-Managerial Alignment" gap by examining how a platform can help religious leaders provide guidance rather than serve as a booking tool.

(4) To study online platform acceptance through quantitative questionnaires, which are designed based on the TAM [7], and assess the perceived value and behavioral change after using the application. This targets the "Methodological Snapshot" gap by moving beyond immediate "acceptance" (TAM) to assess whether the platform actually improved the overall quality and spiritual outcomes of the pilgrimage experience.

The development of the application aims to serve as a prototype for systematic management for local religious leaders and to enhance the Hajj and Umrah experience for local pilgrims, especially in Thailand. The remaining sections are organized as follows: Section 2 presents the related work. The design and development methods for both the mobile web application and the questionnaire are described in Section 3. The questionnaire results are shown in Section 4. A discussion of the procedure for validating the application and questionnaire for future work is presented in Section 5, and the conclusion is presented in Section 6.



Figure 1. The first page of the proposed mobile web application.

2. Related work

2.1 Online platform for business

The online business platform can be divided into many types based on value creation and facilitated interaction characteristics [8], as follows:

2.1.1 Marketplace Platform can provide connections between buyers and sellers in specific markets, such as Airbnb, which connects local hosts and travelers. These platforms focus on online transactions or specific missions [9].

2.1.2 Social media platforms can facilitate online social networks and share users' experiences, e.g., LinkedIn [12], which connects professional employees and experts.

2.1.3 Transaction Platform can provide transaction services between users, like Uber [10], which connects drivers and passengers.

The proposed application for pilgrimage tourism is classified as a marketplace and transaction platform because the application supports connections between pilgrims and local religious leaders to manage religious tours for Hajj and Umrah. The goal of the proposed platform is to support local religious leaders in planning itineraries, managing paperwork, and allowing pilgrims to select and compare travel plans. Also, the platform provides a communication channel for users and local religious leaders to address the uneven distribution of data. The proposed application assumes that the significance of the design, which focuses on search, comparison, booking, and seamless payment features, including the development of efficient communication channels, will reduce problems in pilgrimage tourism.

2.2 The development of digital tourism platforms between general tourism and religious tourism

Digital tourism platforms have improved how travelers plan and experience their trips. The effectiveness of a digital platform is often measured by how well it meets user needs, such as search and

booking functions. Hu [11] explains that a website's technical features act as a "stimulus" that can influence a user to revisit a destination. Essentially, a well-built web application helps a destination stay competitive by easily making information accessible [12]. In general, web applications are designed primarily for commercial efficiency and speed [13]. The main goal is to help users book hotels, flights, and tours rapidly. Developers focus on high-performance features like real-time inventory updates and secure payment gateways [14]. Because general tourism covers a wide range of activities, these platforms use "smart" technology to offer personalized suggestions based on what the user has clicked on before. The focus is usually on the convenience of the transaction and the interface's usability [15]. In contrast, developing web applications for religious tourism requires a different approach. While general tourism is about leisure, religious tourism is often about heritage, rituals, and spiritual needs [16]. Furthermore, the study by Kluver and Cheong [17] suggests that these websites should be designed to respect the community's religious values. For example, a religious tourism site might prioritize information on prayer times and ritual protocols over commercial advertisements to meet pilgrims' needs [18].

2.2 Tools for development of a web application

Tools for web application development can help developers create, test, and refine applications to make them more efficient and better meet users' needs. The tools include diverse programs such as UI/UX design tools, database-integrated development environments (database IDEs), backend IDEs, and debugging and testing tools.

2.2.1 The PHP programming language is also known as Personal Home Page, which is a server-side scripting language and popular in development on websites. Due to its flexibility and options, this can be a crucial tool for software developers to build dynamic websites that respond to users' requirements. The key features of PHP are not limited to process time; they also include database management, frontend control, and handling user data. These are the essential features for the present web application system.

2.2.2 MySQL DBMS is a system to store, manage, and query data as a database. MySQL is a popular database system because it is open source and well-organized. Especially, applications that need fast processing and the ability to access complex data. MySQL uses the Structured Query Language (SQL) to connect to and access data, allowing users to create, update, delete, and query data. Moreover, MySQL supports concurrent access, supports table formats and indexes, and provides backups to secure data. Besides, MySQL DBMS is developed and maintained by developers and communities worldwide, ensuring stability and continuous development. This is suitable for a system that needs high performance and scalability.

2.3 Usability testing

Usability testing is a method for assessing users' satisfaction and verifying whether the proposed application meets users' requirements, as defined by the TAM.

2.3.1 Satisfaction assessment Oliver [19] describes the meaning of satisfaction as a response that shows a customer's opinion of products or services, and these depend on their perspective. Also, Hornby [19] defines satisfaction as a positive feeling when someone achieves or receives something. Satisfaction can be assessed using many methods; for example, a questionnaire can reflect satisfaction. A well-designed questionnaire can be an advantage for developers in analyzing and improving their products and services. A direct interview can also show users' satisfaction, but this requires more tasks for collection, such as recording or writing an interview. Another method is to assess the target person or group through observation. This method takes time and effort to understand their behavior or expression to analyze satisfaction.

2.3.2 The technology acceptance model (TAM) is the model proposed by Venkatesh and Davis [20], which is developed from the theory of reasoned action (TRA) and theory of planned behavior (TPB). Venkatesh et al. [21] studied TAM and showed its purpose. That is to analyze when a user decides to deploy technology and how they intend to use it. The components of TAM are:

(1) Perceived usefulness is a state in which a user believes that such technology can increase work performance, which directly relates to user attitudes towards usage and behavior.

(2) Perceived ease of use is a state in which a user believes that the technology is easy to use without high effort. This is directly related to perceived usefulness and attitude towards its use.

(3) Attitude toward using means a user's opinion of the technology. This is caused by the perceived usefulness and perceived ease of use, and has a direct impact on the intention to use it.

(4) Behavioral intention means behavioral intention to use technology, which is influenced by perceived benefits of use and attitude towards use.

(5) Actual Use means technology acceptance through practical application, where attitude towards use affects the actual use of the user.

2.4 Related existing studies

There has been extensive research to improve religious tourism. For example, Kawashima [22] studied the role of tourism agencies and tour leaders as spiritual leaders in organizing and transforming pilgrimages in Slovenia. It emphasizes the cooperation between tourism agencies and monks, known as "spiritual guides", who are popular for leading pilgrim groups because they can communicate and build relationships with pilgrims in a friendly manner. The research shows that cooperation between the Catholic Church and tourism agencies not only helps pilgrims receive spiritual care but also provides recreational opportunities, which have significantly influenced the revitalization of religious practice in Slovenia. Lubis et al. [23] studied the development of a digital ecosystem in the context of CRM for a Hajj portal website, highlighting its importance for preparing for the Hajj, a pillar of Islam that requires efficient management of pilgrims' information and needs. The research suggests that technology can facilitate faster, more accurate learning about the Hajj, and that CRM implementation can prevent conflicts between startups and Hajj service providers (PPIUs) by ensuring sustainability and fairness in the management process. However, this research may be limited in providing insights into the application of CRM in specific contexts, thereby providing a clearer picture of the successes and challenges of implementing a digital ecosystem.

Majid et al. [24] presented the HAJJRAH application, developed to address common issues faced by pilgrims performing Hajj and Umrah. It begins with a basic explanation of pilgrimage to holy sites and the issues various agencies face in managing pilgrims. The study also conducted a market analysis to support the market demand and the robustness of the application's business idea. The analysis revealed that the features available in HAJJRAH can effectively address the issues faced by pilgrims and their respective agencies, confirming the app's necessity and robustness in the market. Marinković [25] presented a new business model designed to meet the needs of the Serbian tourism sector, focusing on the creation of a digital platform for tourism agencies. The project involved a joint effort by IT and software engineers and tourism experts from several Serbian agencies. The research used case studies to gather relevant data and identify the benefits and challenges of implementing the new business model. In the second phase of the research, data were collected from tourism agency employees using the new digital platform through a questionnaire to assess their opinions on relevant factors. The results showed that the new digital platform offers both benefits and challenges, and its successful implementation requires collaboration between technology and tourism experts.

Hevner and Malgonde [26] propose a novel approach to software development on digital platforms that differs significantly from traditional approaches. They point out that software managers and development teams face unique challenges in platform environments and require novel development approaches to succeed. This research proposes that digital application development must achieve alignment with the application platform and create new value beyond the core platform values. Furthermore, the research suggests that software development teams act like entrepreneurs. Also, the study explores existing software development environments (e.g., Apache Cordova) to determine whether the principles of effective development hold. Preliminary findings support effective development approaches and call for the development of innovative, effective software solutions for digital platforms.

In Thailand, some studies focus on developing applications for local tourism. For instance, Puttitaweesri et al. [27] developed smartphone-based navigation systems for tourism in Ratchaburi, where attractions are diverse but information is fragmented, thereby facilitating efficient travel and promoting lesser-known destinations. The features of this study can be applied to religious tourism, such as real-time navigation, route optimization, and more. A similar study can be found in Sooknit and Sakda [28], which

provides local tourism routes using geolocation data and the Google Maps Platform, highlighting the application of location-based technologies in enhancing tourism planning. To the best of our knowledge, there is a lack of studies on religious tourism towards technological use. Based on the aforementioned studies, we applied these documents and research to develop a platform for managing pilgrims by local religious leaders. We saw an opportunity to integrate the management strategies of Thai Hajj and Umrah companies with e-commerce systems to develop a platform model that would help local religious leaders manage pilgrims. This would also enhance the Hajj and Umrah service and booking systems to the next level, benefiting users and helping pilgrims manage their services and bookings more efficiently. This also leverages the growing trend of using technology to improve and develop services to a higher level.

3. Design and development methodology

This section describes how to design and develop the proposed mobile web application and provides the concept design of 3 questionnaires to assess user satisfaction and technology acceptance.

3.1 Development of mobile web application

The key development of the proposed application is to assist users in easily and quickly searching for, comparing, and booking Hajj and Umrah package tours with trustworthiness. The main idea for that design is that “the technology comes along with faith.” This can refer to the website's sanctity, credibility, and accessibility. The procedure for the development of the proposed application is described as follows:

3.1.1 User study The preliminary questionnaire and interview showed that most users prefer the user-friendly application, like flight or hotel booking websites, which has important information such as price, itinerary date, and user reviews on one page. Also, the website should include photos from previous trips to build trust.

3.1.2 Website architecture The prototype of the proposed mobile web application contains four pages. The first page is the home page, featuring a photo of pilgrims to motivate and encourage users to continue using it. The search bar is designed for large-scale use and is located in the middle of the page for easy access. The following functions are the promotions under the search bar and the menu bar at the top of the page. The second page is the package tour page. This page uses the card design to show price, travel duration, and review score. The other main functions on the page are booking buttons, price tags, and promotion tags. The third page is the blog/article page. The page covers many topics related to preparing for a pilgrimage. These articles can increase the web application's credibility and search engine optimization (SEO). The last page is the contact page, which clearly shows the contact channels, i.e., a phone number, LINE contact, and also allows contact through a form on the website. This page is designed to ensure users' trust and accessibility.

3.1.3 User interface design (UI design) The design of the user interface (UI) and user experience (UX) for the Hajestic platform is grounded in a user-centered design approach, emphasizing simplicity, efficiency, and trustworthiness. The platform integrates technological functionality with the spiritual context of pilgrimage tourism, aiming to provide a meaningful and reliable digital experience for users.

(1) User Experience (UX) Design Philosophy: The UX design is guided by the concept of “technology along with faith,” which reflects the integration of digital services with religious values. This approach seeks to enhance users' trust, credibility, and spiritual connection while they interact with the platform. Trustworthiness is established through the use of authentic visual elements, such as real images from pilgrimage journeys, which help build user confidence. In addition, efficiency is enhanced by consolidating essential information—such as prices, travel dates, and user reviews—into a single interface. This design approach is inspired by established flight and hotel booking systems, enabling users to make decisions quickly and effectively.

(2) User Interface (UI) Strategy: The UI design focuses on creating a culturally appropriate and visually coherent identity. The platform employs a color palette of green, white, and gold, representing cleanliness, purity, and Islamic faith. These colors contribute to both aesthetic appeal and symbolic meaning. Typography is implemented using LINE Seed Sans TH [29], selected for its clarity and readability across mobile devices. The overall interface follows a clean, minimal design, ensuring key elements are easily identifiable and accessible.

(3) Information Architecture and User Journey: The platform is structured to support a continuous and goal-oriented user journey, guiding users through a logical sequence of interactions:

- Step 1: Discovery (Home Page): The entry point emphasizes visual engagement and accessibility, with a large, centrally positioned search bar that lets users access relevant information immediately.
- Step 2: Comparison (Package Page): Search results are displayed using a card-based layout, presenting key details such as price, duration, and review scores. This enables users to compare pilgrimage packages efficiently.
- Step 3: Credibility and Knowledge (Blog/Articles Page): Informational content is provided to support users in preparing for pilgrimage, enhance platform credibility, and improve search engine optimization (SEO).
- Step 4: Conversion and Trust (Contact Page): Clear communication channels, including phone, messaging applications (e.g., LINE), and contact forms, are presented to reinforce transparency and build user confidence, particularly in financial transactions.

This structured design ensures that users can navigate the platform intuitively from initial exploration to final decision-making.

(4) Accessibility and Platform Design Considerations: The platform is developed as a mobile web application, allowing users to access the system directly through web browsers without requiring additional software installation. This approach reduces barriers to entry and enhances accessibility, particularly for users in local or resource-limited environments. Furthermore, the design supports multiple user roles, including pilgrims, religious leaders, and entrepreneurs, while maintaining consistency and usability across the system. This ensures the platform remains inclusive and adaptable to diverse user needs.

3.1.4 Use Case Functions and Interactions The use case diagram, as shown in Figure 2, demonstrates that system interactions are structured with three major functional layers:

(1) Actors in the System: the system consists of four primary actors: the pilgrim is the main end-user who searches for, compares, and books pilgrimage packages. The religious leader is responsible for managing pilgrimage activities, guiding pilgrims, and coordinating communication. Hajj Entrepreneur operates at the organizational level by offering travel packages and managing documentation. The administrator oversees the backend system, ensuring data integrity, transaction monitoring, and system security.

(2) Use Case Functions and Interactions: The use case diagram demonstrates that system interactions are structured around three major functional layers. First, the pilgrim interaction layer interacts with the platform primarily through service-oriented functions. These include search and compare trips; enabling users to explore available packages based on preferences, book a package; allowing users to reserve selected pilgrimage tours, secure payment; supporting transaction processing and confirmation, track booking status; providing real-time updates on booking and documentation, view itinerary; allowing users to monitor travel schedules and receive notifications.

(3) Religious Leader and Entrepreneur Interaction Layer: Religious leaders and entrepreneurs engage with the platform through management and coordination functions, i.e., manage itinerary plan; including planning and updating travel schedules, accommodation, and costs, manage pilgrim list; allowing monitoring of participant status and group organization, digital paperwork management; supporting document handling for official submission processes, broadcast notification; enabling communication of updates, reminders, and guidance to pilgrims.

(4) Backend and Administrative Layer: Administrators interact with the system through control and monitoring functions, including: data aggregation; collecting and organizing user and transaction data, transaction monitoring; ensuring secure payment processing, and handling refunds, system integrity control; maintaining data security, access control, and system stability.

The overall system interaction, as illustrated in Figure 2, follows a multi-directional and interconnected workflow. Pilgrims initiate the process by searching and booking services, while religious leaders and entrepreneurs respond by managing itineraries and providing guidance. Simultaneously, backend systems continuously support these interactions by maintaining data consistency, monitoring transactions,

and enforcing security protocols. This integrated interaction model demonstrates that the platform operates as a digital ecosystem, where front-end user activities, service management, and backend processes are closely interconnected. Compared to traditional pilgrimage management systems, which often rely on fragmented communication and manual processes, the proposed system enables centralized coordination, real-time communication, and improved transparency.

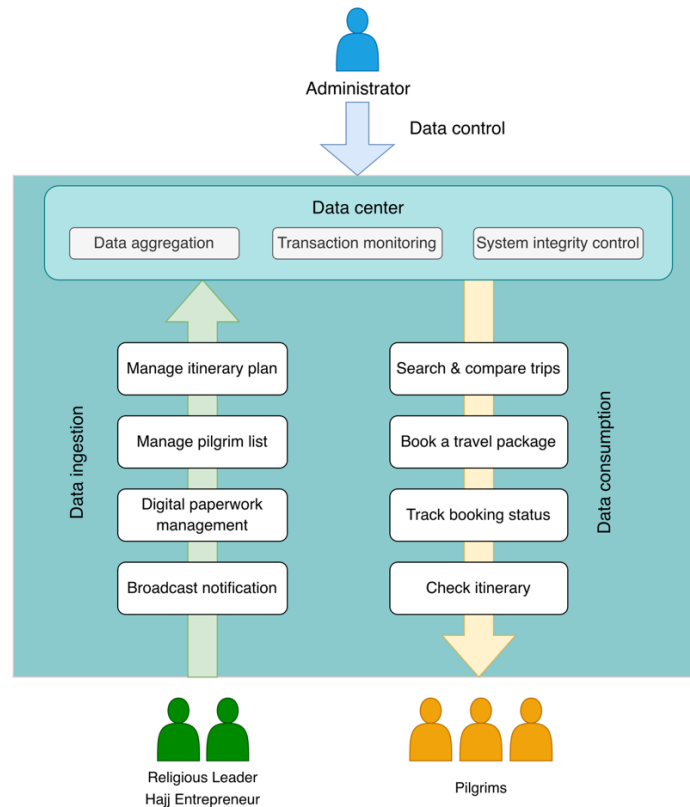


Figure 2. A diagram of the system interaction.

3.1.5 Security Architecture: The platform's security architecture is designed using a multi-layered defense-in-depth approach, ensuring comprehensive protection across network, transport, application, data, and authentication layers as shown in Figure 3. Secure communication is enforced via HTTPS with modern TLS protocols, supported by advanced cryptographic standards such as Perfect Forward Secrecy, to maintain data confidentiality even in the event of a key compromise [30,31]. The system adopts a Zero Trust Architecture, integrating JSON Web Token (JWT)-based authentication, multi-factor authentication (MFA), and strict session management to enhance identity verification and reduce unauthorized access risks [32-34]. At the application level, multiple safeguards are implemented, including Web Application Firewall (WAF), input validation, and protection mechanisms against common attacks such as SQL injection, cross-site scripting (XSS), and cross-site request forgery (CSRF), following OWASP best practices [35,36]. Additionally, role-based access control (RBAC) ensures least-privilege access, while sensitive data is secured using AES-256 encryption and protected through encrypted backups and database-level security mechanisms [37,38].

The platform further integrates a secure payment infrastructure using Stripe Payment Gateway, which is designed to comply with PCI DSS standards to minimize direct handling of sensitive financial data [39]. Payment processing is conducted through tokenization and encrypted APIs, ensuring that credit card information is never stored within the platform. Advanced mechanisms such as webhook signature verification, idempotency keys, and 3D Secure authentication are employed to maintain transaction integrity and prevent fraud or duplicate processing [40-42]. Moreover, centralized logging, anomaly detection, and incident response systems enable continuous monitoring and rapid threat mitigation, aligning with established intrusion detection and digital forensics practices [43]. Overall, the system demonstrates a robust,

standards-compliant security framework that ensures the confidentiality, integrity, and reliability of data in managing pilgrimage tourism services.

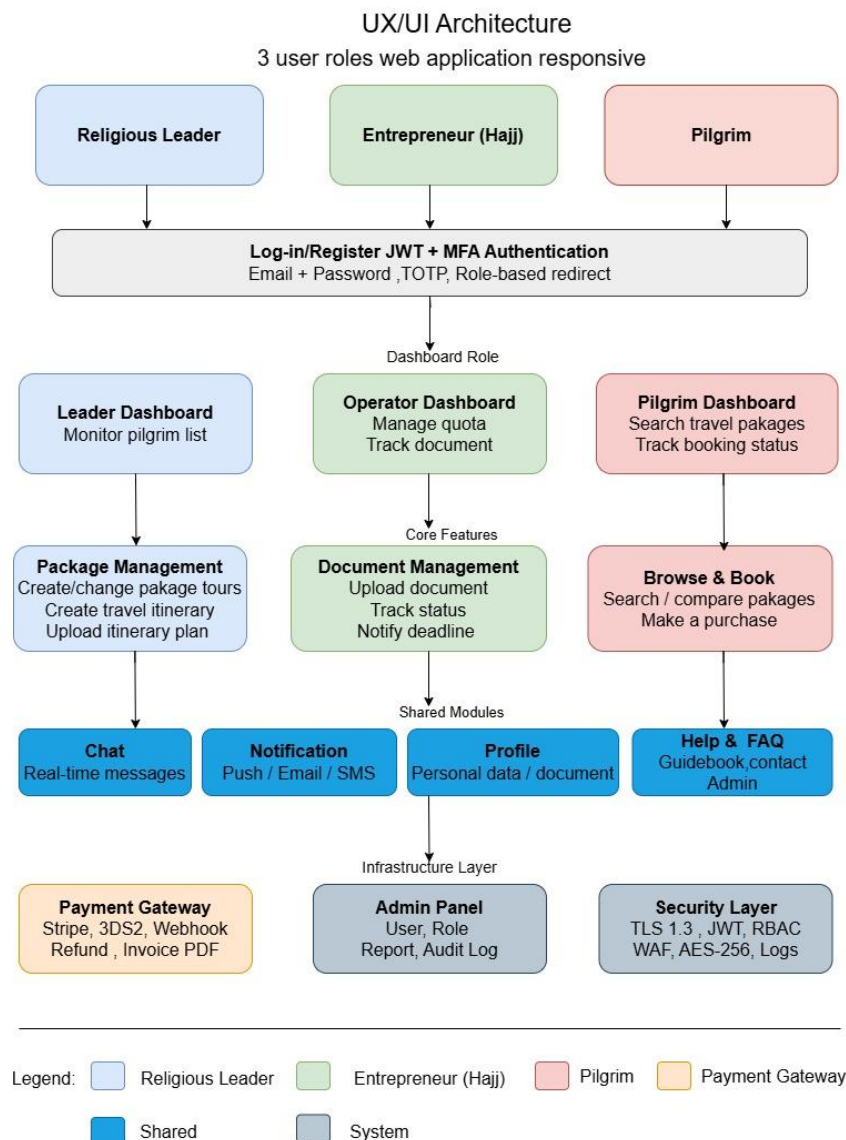


Figure 3. A diagram of the platform architecture.

3.2 Design of questionnaires

To understand user satisfaction and assess user technology acceptance, we designed three questionnaires: the platform suitability assessment form, used to evaluate and improve the web application. The platform performance assessment form is designed to receive opinions on the platform's performance. The purpose of the platform acceptance assessment form is to understand users' TAM-related thoughts. This model was employed to evaluate user acceptance due to its strong theoretical foundation and widespread application in information system research. TAM focuses on perceived usefulness and perceived ease of use, which are directly relevant to assessing whether the proposed platform improves efficiency and reduces complexity in pilgrimage tourism management. Furthermore, TAM is suitable for evaluating prototype systems, as it captures users' perceptions and behavioral intentions in the absence of long-term usage data. Its structured framework also enables analysis of the adoption process across multiple stages, providing deeper insight into user acceptance behavior in the context of digital religious tourism.

Furthermore, these three surveys are designed based on a 5-point Likert scale [44], where “1” means strong disagreement with the context, “2” means disagreement with the context, “3” means neutral or uncertain with the context, “4” means agreement with the context, and “5” means strong agreement with the context. The questionnaires employed a non-probability sampling approach, i.e., a combination of purposive and convenience sampling methods [45,46]. Purposive sampling was appropriate because the study required respondents directly relevant to pilgrimage tourism, such as pilgrims, religious leaders, or users interested in Hajj and Umrah services. Convenience sampling was also reflected in the data collection process, as the questionnaires were distributed online and participation depended on respondents’ availability and willingness to answer. This approach was suitable for prototype evaluation because the objective was not to generalize to the entire population of Thai Muslim pilgrims, but to obtain preliminary user feedback on platform suitability, performance, and acceptance. The procedure after aggregating surveys is to perform statistical analysis, i.e., mean, standard deviation (SD), and Cronbach’s alpha, to assess validity and reliability.

3.2.1 The platform suitability assessment form is designed based on the satisfaction assessment method. It is divided into three main sections. The first section requires a user to enter their personal data, including sex, user type (religious leader, Hajj entrepreneur, or pilgrim), address, marital status, education, career type, average monthly salary, and technology experience. The second section asks about user satisfaction with the web application’s features. The third section allows a user to provide further suggestions.

3.2.2 The platform performance assessment form aims to study platform performance through users’ opinions. It is divided into 3 parts. The first part requires a user to fill in their personal data, which is the same as the platform suitability assessment form. The second part is the performance context, and the third part is the suggestion part.

3.2.3 The platform acceptance assessment form is designed based on TAM. The purpose is to study platform acceptance through users’ opinions. It is divided into 3 parts. The first part requires a user to fill in their personal data, which is the same as the platform suitability assessment form and the platform performance assessment form. The second part is the acceptance context, as shown in Table 3, and the third part is the suggestion part.

4. Survey results

We conducted the online questionnaires with 64 participants. The analysis of participants’ backgrounds shows that most are pilgrims (98.4%). The gender distribution is heavily skewed toward Female participants (81.2%), while the core age group falls within the 25–34-year-old bracket (44.4%). Geographically, the sample is highly concentrated, with nearly four-fifths of participants residing in Narathiwat (79.4%). Crucially for technology adoption, a majority reported having high levels of technology experience (64.1%). However, financially, the group is dominated by those with salaries below 10,000 Baht (60.9%).

Based on the analysis of the 5-point Likert scale results, the three assessment models, i.e., platform suitability, platform performance, and platform acceptance, were further analyzed using grouped-item summaries to provide a higher-level interpretation of the system evaluation. The grouped results, including average mean scores, standard deviations (SD), and Cronbach’s alpha coefficients (α), demonstrate consistent patterns across all dimensions.

The grouped analysis of platform suitability (Table 4) indicates that all functional components achieved a moderate level of suitability, with mean scores ranging from 3.22 to 3.42. The highest-rated dimension was Religious Leader Engagement (Mean = 3.42, SD = 1.05), highlighting the importance of administrative control and operational features for religious leaders. Similarly, Profile Setting (Mean = 3.40, SD = 1.05) and Notification System (Mean = 3.37, SD = 0.95) were positively evaluated, reflecting the necessity of user account management and real-time communication. Conversely, the Backend System and Payment System both received moderate but relatively lower scores (Mean = 3.32), suggesting that while core infrastructure is acceptable, improvements are required in data handling and financial processes. The lowest-rated dimension, Pilgrim and General Engagement (Mean = 3.22, SD = 1.02), indicates that user interaction and engagement features remain the platform’s weakest aspect. All dimensions demonstrated excellent internal

consistency ($\alpha = 0.97$), indicating that the measurement items within each group are highly reliable. The grouped performance assessment result, as shown in Table 5, reveals a similarly moderate level of effectiveness, with mean values ranging from 3.42 to 3.49. The highest-rated dimension was Usage Result (Mean = 3.49, SD = 1.01), indicating that users perceive clear benefits and value from using the platform. This is followed by Platform Capability (Mean = 3.44, SD = 1.05), suggesting that the system's functional features are generally adequate. The lowest-rated dimension, User Experience (Mean = 3.42, SD = 1.08), reflects concerns regarding usability and interface design. Notably, the relatively higher SD in this category indicates greater variability in user opinions, suggesting inconsistent user experiences. Despite these differences, all dimensions exhibited high reliability ($\alpha = 0.94$), confirming the robustness of the performance measurement model.

The grouped analysis of platform acceptance (Table 6), structured by the stages of the technology acceptance model (TAM), shows a progressive trend in user perceptions. The mean scores range from 3.17 to 3.48, indicating an overall moderate level of acceptance. The Evaluation Stage achieved the highest score (Mean = 3.48, SD = 1.11), followed closely by the Trial Stage (Mean = 3.44, SD = 1.06), demonstrating that users develop stronger confidence and positive attitudes after interacting with the platform. The Adoption Stage (Mean = 3.38) and Interest Stage (Mean = 3.37) also show relatively positive perceptions. However, the Awareness Stage recorded the lowest mean score (Mean = 3.17, SD = 1.22), indicating a significant gap in user knowledge and initial platform exposure. The higher SD in this stage suggests divergent opinions and uncertainty among users. All stages demonstrated excellent reliability ($\alpha = 0.95$), reinforcing the TAM-based measurement's consistency. To summarize, the grouped analysis confirms that the proposed platform demonstrates strong reliability and moderate acceptance across all evaluation dimensions. While the system delivers functional value and user satisfaction, critical improvements are needed in user experience design, engagement mechanisms, and awareness strategies to enhance adoption and long-term sustainability.

Table 4. The platform suitability assessment result shows the grouping summary and statistics.

Context	No. Items	Mean (Avg)	SD (Avg)	Cronbach's α (if deleted)
Religious Leader Engagement	8	3.42	1.05	0.97
Profile Setting	6	3.40	1.05	0.97
Notification System	4	3.37	0.95	0.97
Backend System	6	3.32	1.08	0.97
Payment System	5	3.32	1.06	0.97
Pilgrim & General Engagement	4	3.22	1.02	0.97

Table 5. The platform performance assessment result shows the grouping summary and statistics.

Context	No. Items	Mean (Avg)	SD (Avg)	Cronbach's α (if deleted)
User Experience	4	3.42	1.08	0.94
Platform Capability	5	3.44	1.05	0.94
Usage Result	4	3.49	1.01	0.94

Table 6. The platform acceptance assessment result shows the grouping summary and statistics.

Stage	No. Items	Mean (Avg)	SD (Avg)	Cronbach's α (if deleted)
Awareness	5	3.17	1.22	0.95
Interest	5	3.37	1.16	0.95
Evaluation	5	3.48	1.11	0.95
Trial	5	3.44	1.06	0.95
Adoption	5	3.38	1.09	0.95

5. Discussion

This study evaluated a mobile web application designed to support pilgrimage tourism management through three complementary dimensions: platform suitability, performance, and technology acceptance. The findings consistently indicate a moderate level of user acceptance, but more importantly, they reveal insights into how functional value, usability, and trust interact in a religious digital platform context.

5.1 Interpretation of Platform Suitability

The platform suitability results (Mean $\approx$ 3.35) indicate that users place the highest value on administrative control and transparency features, particularly within the dimension of religious leader engagement (Mean = 3.42). This result aligns with Kawashima's work, which highlights that religious leaders play a dual role as both spiritual guides and operational coordinators. However, this study extends the existing literature by demonstrating that digital systems can structurally reinforce this dual role rather than merely support logistical tasks. Compared to prior studies on religious tourism, which often focus on organizational or social dynamics, the present findings provide empirical evidence that system design itself can enhance spiritual-managerial alignment, thereby offering a more integrated technological contribution. Despite this strength, the lowest scores in pilgrim engagement (Mean = 3.22) and overall user engagement (Mean = 3.06) highlight a critical limitation. This contrasts with general tourism platform studies, such as Hu, where user engagement and interface quality are primary drivers of satisfaction and revisit intention. The relatively weak engagement performance suggests that the proposed platform, while functionally sufficient, lacks interactive and user-centered features that are standard in contemporary digital tourism systems. Thus, the suitability results reveal a functional-experiential imbalance: the system is strong in administrative capabilities but underdeveloped in user interaction design.

5.2 Platform Performance

The platform performance results (Mean $\approx$ 3.45) show that the system performs well in technical efficiency, particularly in data quality (Mean = 3.77) and processing speed (Mean = 3.60). These findings are consistent with digital tourism research, such as Shariffuddin, which emphasizes that system reliability and information accuracy are fundamental to user satisfaction and trust formation. In comparison with existing pilgrimage applications, such as HAJJRAH (Majid et al.), this study provides stronger empirical validation by demonstrating not only the perceived usefulness of features but also their measured performance across multiple dimensions. This represents a methodological advancement, as previous studies often relied on conceptual validation or limited user feedback. However, the lowest-rated item, i.e., ease of use (Mean = 3.18, SD = 1.20), reveals a significant usability issue. The high standard deviation indicates inconsistent user experiences, suggesting that some users adapt successfully while others struggle. This finding aligns with Hevner's argument that successful digital platforms must achieve not only technical performance but also alignment with the application-user experience. This insight is particularly important because it shows that technical optimization alone does not guarantee user satisfaction, especially in contexts with diverse user groups and varying levels of digital literacy.

5.3 Technology Acceptance

The TAM-based analysis (Mean $\approx$ 3.37) reveals a clear progression across the five stages of adoption. The lowest score in the Awareness stage (Mean = 3.17) indicates a lack of prior exposure and limited trust in the platform, while the highest scores emerge in the Evaluation and Trial stages, particularly "usage meets expectations" (Mean = 3.68). This finding strongly supports Venkatesh's theoretical framework, confirming that perceived usefulness and user attitudes improve through direct interaction. However, this study extends TAM by demonstrating a distinct behavioral transition specific to religious digital platforms. In contrast to Lubis et al., who emphasize CRM systems as a mechanism for improving trust and coordination, the present findings suggest that trust cannot be effectively established through information systems alone. Instead, trust emerges after experiential validation, meaning that users must first interact with the platform before forming positive perceptions. This leads to a key contribution: the identification of an "awareness-experience gap," where initial adoption is hindered by low awareness and credibility concerns. But post-use evaluation leads to high satisfaction and a strong intention to recommend (Mean = 3.52). Compared to existing studies, this

insight offers a more dynamic understanding of adoption behavior, particularly in religious contexts where trust, credibility, and community influence are critical.

5.4 Limitations and Future Work

Several limitations highlight important areas for improvement. Since the sampling method combines purposive and convenience sampling, it limits the generalizability of the findings. The sample was dominated by pilgrims, female respondents, and participants from Narathiwat, which may not fully represent religious leaders, Hajj entrepreneurs, or pilgrims from other regions. Future studies should apply stratified sampling or quota sampling to ensure a more balanced representation of key user groups. The most critical issue lies in user experience (UX/UI), where low ease-of-use scores and high variability indicate that the platform is not sufficiently intuitive for all users. This usability constraint undermines the system's otherwise strong technical performance. Additionally, user engagement features remain underdeveloped, limiting the platform's ability to match the interactive standards of modern tourism applications. The study also reveals a lack of effective awareness and trust-building mechanisms, which creates barriers during the early stages of adoption, as well as moderate confidence in financial features, particularly refund and payment reliability. These limitations suggest that future development should prioritize human-centered design, enhanced interaction capabilities, and strategic communication, ensuring the platform not only functions effectively but also delivers a seamless, trustworthy user experience.

6. Conclusion

This study developed and evaluated a mobile web application to improve pilgrimage tourism management by integrating administrative, transactional, and communication functions. The results indicate that the platform achieves a moderate level of acceptance across the suitability, performance, and technology adoption dimensions, while demonstrating strong measurement reliability. The platform's primary strength lies in its ability to support religious leaders in managing pilgrimage processes efficiently, particularly through centralized control, transparent data handling, and reliable system performance. These features confirm the platform's potential to address existing challenges in pilgrimage tourism, including fragmented information, a lack of transparency, and inefficient coordination. However, the study also identifies several critical limitations that constrain adoption. The platform shows weaknesses in user experience design, engagement functionality, and initial awareness, which collectively hinder usability and trust formation. The findings further reveal that user acceptance is significantly influenced by direct experience, suggesting that initial skepticism can be overcome only after users interact with the system. In conclusion, this research contributes a validated prototype and a deeper theoretical understanding of digital platform adoption in religious tourism, highlighting that successful implementation requires not only technical functionality but also alignment with user experience, trust dynamics, and the socio-religious context of pilgrimage practices.

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Appendix A: The list of contexts in assessment forms.

Table 1A. A list of context about user satisfaction with features in the proposed mobile web application

Component	Context
User engagement	Religious leader engagement - Main controller - Showing a list of pilgrims - Notification for payment or confirmation - Showing the status of an incoming trip - Planning a pilgrimage trip (accommodation, activity plan, expense) - Changing plan (changing itinerary, a booking) - Having a text notification or a personal suggestion - Having Q&A channels for pilgrims Pilgrim engagement - Searching and comparing a trip - Capable of using filters for price, departure time, and accommodation - Capable of comparing trips among companies or services Profile setting - Ability to view and change profile details - Capable of checking the history of bookings and payments - Capable of tracking the status of booking - Capable of notifying data in real-time, e.g., notifying departure time, meeting points, change of itinerary plan, etc. - The design of UX/UI is user-friendly, clean, and convenient to use. - Having a support system, such as a chatbot or live chat, for answering customers' questions
Backend system	- Aggregating user data, e.g., full name, email, phone number, and necessary documents - Collecting booking information, i.e., name, phone number, email, Thai ID/passport, package tour detail, booking status, payment detail - Collecting trip information, i.e., activity schedule, number of seats, accommodation information - Having communication logs, e.g., notes or notifications - Collecting payment transactions, i.e., amount of money, payment date, payment method
Payment system	- Having different payment methods, e.g., credit card, debit card, or other payment methods. - Having payment confirmation - Capable of checking payment status - Capable of making a refund
Notification	- Capable of notifying of booking confirmation for a trip - Capable of notifying payment - Capable of notifying of a trip status

Table 2A. A list of context about the performance of the proposed mobile web application

Topic	Context
User experience	- Easy to use - Convenient to search and compare trips - Fast processing - Stability of the platform
Platform capability	- Capable of making a payment through the platform - Variety of religious leaders - Comparison of trip details - Capable of reviewing - Having a refund after cancellation
Usage result	- The proposed platform can decrease burdens or problems in pilgrimage tourism. - You are satisfied with the data in the platform - Having all the information based on the required information - Credibility of the proposed platform

Table 3A. A list of context about the technology acceptance of the proposed mobile web application

Stage	Context
Awareness	- Have you ever received information about the platform for managing pilgrimage tourism? - You understand the purpose and characteristics of the platform. - You believe that this platform can increase the performance in terms of pilgrimage tourism. - You gain the information from reliable sources. - You are interested in learning more about the platform.
Interest	- You are interested in using this platform for pilgrimage. - You believe that this platform has the potential to decrease the complexity of pilgrimage tourism. - You are not worried about the usage of this platform. - You agree that this platform is different from usual management. - You believe that this platform has advantages for your community.
Evaluation	- Have you ever compared this platform to the usual management? - You agree that this platform has more advantages than the current method. - You do not need more information before deciding to use this platform. - You agree that it is easy to change using this platform. - You are confident that other users can use this platform efficiently.
Trial	- Have you ever had an experience using this platform? - Using this platform meets your expectations. - You do not have any troubles or struggles when using this platform. - You agree that this platform does not have to improve. - You do not have to learn more about using this platform.
Adoption	- You tend to use this platform continuously. - You would like to recommend this platform to other people. - You believe that this platform can help pilgrimage tourism in the long term. - You support using this platform broadly. - You are confident that this platform is reliable and capable of being used in the long term.

Appendix B: The results of surveys in full contexts.

Table 1B. The platform suitability assessment results show the number of participants who answered in each context, along with the mean, SD, and Cronbach's alpha.

Context	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Mean	SD	α (If deleted)
Overall user engagement	4	17	19	19	5	3.06	1.07	0.97
Religious leader engagement: Main controller	2	3	23	25	11	3.63	0.93	0.97
Religious leader engagement: Showing a list of pilgrims	1	8	28	17	10	3.42	0.96	0.97
Religious leader engagement: Notification for payment or confirmation	2	5	26	22	9	3.48	0.94	0.97
Religious leader engagement: Showing the status of an incoming trip	4	8	20	24	8	3.38	1.06	0.97
Religious leader engagement: Planning a pilgrimage trip (accommodation, activity plan, expense)	3	8	17	26	10	3.50	1.05	0.97
Religious leader engagement: Changing plan (changing itinerary, a booking)	2	12	17	21	12	3.45	1.1	0.97
Religious leader engagement: Having a text notification or a personal suggestion	6	7	24	18	9	3.27	1.13	0.97
Religious leader engagement: Having Q&A channels for pilgrims	8	8	16	24	8	3.25	1.21	0.97
Pilgrim engagement: Searching and comparing a trip	4	13	25	16	6	3.11	1.04	0.97
Pilgrim engagement: Capable of using filters for price, departure time, and accommodation	2	12	17	24	9	3.41	1.05	0.97
Pilgrim engagement: Capable of comparing trips among companies or services	2	9	27	20	6	3.30	0.94	0.97
Profile setting: Ability to view and change profile details	1	4	28	20	11	3.56	0.91	0.97
Profile setting: Capable of checking the history of bookings and payments	5	6	23	23	7	3.33	1.05	0.97
Profile setting: Capable of tracking the status of booking	1	5	30	16	12	3.52	0.94	0.97
Profile setting: Capable of notifying data in real-time	3	9	22	20	10	3.39	1.06	0.97
Profile setting: The UX/UI design is user-friendly, clean, and convenient to use.	7	5	22	19	11	3.34	1.18	0.97
Profile setting: Having a support system	7	7	21	21	8	3.25	1.15	0.97
Overall backend system	2	8	27	17	10	3.39	1	0.97
Aggregating user data	4	8	26	18	8	3.28	1.05	0.97
Collecting booking information	1	14	23	17	9	3.30	1.02	0.97
Collecting trip information	3	10	21	18	12	3.41	1.11	0.97
Having communication logs	4	13	18	19	10	3.28	1.15	0.97
Collecting payment transaction	5	8	28	12	11	3.25	1.13	0.97
Overall payment system	1	15	16	22	10	3.39	1.06	0.97
Having different payment methods	3	14	27	12	8	3.13	1.05	0.97
Having payment confirmation	1	9	22	19	13	3.53	1.02	0.97
Capable of checking payment status	3	14	20	17	10	3.27	1.12	0.97
Capable of making a refund	3	12	21	20	8	3.28	1.06	0.97
Overall notification	2	13	21	18	10	3.33	1.07	0.97
Capable of notifying of booking confirmation for a trip	2	10	31	15	6	3.20	0.93	0.97
Capable of notifying payment	1	8	23	23	9	3.48	0.94	0.97
Capable of notifying of a trip status	1	5	29	21	8	3.47	0.87	0.97

Table 2B. The platform performance assessment results show the number of participants who answered in each context, along with the mean, SD, and Cronbach's alpha.

Context	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Mean	SD	α (If deleted)
User experience: Easy to use	8	7	18	20	7	3.18	1.2	0.94
User experience: Convenient to search and compare trips	3	7	24	16	10	3.38	1.06	0.94
User experience: Fast processing	4	3	16	27	10	3.6	1.04	0.94
User experience: Stability of the platform	2	8	18	22	10	3.5	1.03	0.94
Platform capability: Capable of making a payment through the platform	3	4	28	14	11	3.43	1.03	0.94
Platform capability: Variety of religious leaders	2	7	15	25	11	3.6	1.03	0.94
Platform capability: Comparison of trip details	3	11	17	19	10	3.37	1.12	0.94
Platform capability: Having a refund after cancellation	3	11	17	21	8	3.33	1.08	0.94
Platform capability: The proposed platform can decrease burdens or problems in pilgrimage tourism.	2	7	19	24	8	3.48	0.98	0.94
Usage result: The proposed platform can decrease burdens or problems in pilgrimage tourism.	5	3	22	26	4	3.35	0.99	0.94
Usage result: You are satisfied with the data in the platform	2	4	13	28	13	3.77	0.98	0.94
Usage result: Having all the information based on the required information	3	6	26	19	6	3.32	0.97	0.94
Usage result: Credibility of the proposed platform	3	8	16	22	11	3.5	1.1	0.94

Table 3B. The platform acceptance assessment results show the number of participants who answered in each context, along with the mean and SD.

Context	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Mean	SD	α (if deleted)
Awareness Stage: Have you ever received information about the platform for managing pilgrimage tourism?	6	12	23	14	7	3.06	1.13	0.95
Awareness Stage: You understand the platform's purpose and characteristics.	3	15	16	17	11	3.29	1.16	0.95
Awareness Stage: You believe that this platform can increase the performance in terms of pilgrimage tourism	8	11	16	17	10	3.16	1.27	0.95
Awareness Stage: You gain the information from reliable sources.	11	6	19	16	10	3.13	1.31	0.95
Awareness Stage: You are interested in learning more about the platform.	7	10	17	19	9	3.21	1.22	0.95
Interest Stage: You are interested in using this platform for pilgrimage.	1	6	19	19	10	3.56	0.98	0.95
Interest Stage: You believe that this platform has the potential to decrease the complexity of pilgrimage tourism.	5	5	26	19	7	3.29	1.05	0.95
Interest Stage: You are not worried about using this platform.	8	6	19	20	9	3.26	1.21	0.95
Interest Stage: You agree that this platform is different from usual management.	6	11	14	17	14	3.35	1.28	0.95
Interest Stage: You believe that this platform has advantages for your community.	7	8	17	15	15	3.37	1.3	0.95
Evaluation Stage: Have you ever compared this platform to the usual management?	5	3	23	20	11	3.47	1.1	0.95
Evaluation Stage: You agree that this platform has more advantages than the current method.	5	4	19	23	11	3.5	1.11	0.95
Evaluation Stage: You do not need more information before deciding to use this platform.	3	7	23	17	12	3.45	1.08	0.95

Table 3B. The platform acceptance assessment results show the number of participants who answered in each context, along with the mean and SD. (continue)

Context	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Mean	SD	α (if deleted)
Evaluation Stage: You agree that it is easy to change using this platform.	5	3	25	17	12	3.45	1.11	0.95
Evaluation Stage: You are confident that other users can use this platform efficiently.	4	9	11	27	11	3.52	1.14	0.95
Trial Stage: Have you ever used this platform?	4	4	26	18	10	3.42	1.05	0.95
Trial Stage: Using this platform meets your expectations.	1	7	15	27	12	3.68	0.97	0.95
Trial Stage: You have no issues or struggles when using this platform.	4	6	25	17	10	3.37	1.07	0.95
Trial Stage: You agree that this platform does not have to improve.	5	7	28	13	9	3.23	1.09	0.95
Trial Stage: You do not have to learn more about using this platform.	6	2	21	22	11	3.48	1.13	0.95
Adoption Stage: You tend to use this platform continuously.	4	4	33	13	8	3.27	0.99	0.95
Adoption Stage: You would like to recommend this platform to other people.	2	9	17	23	11	3.52	1.05	0.95
Adoption Stage: You believe that this platform can help pilgrimage tourism in the long term.	5	4	19	22	12	3.52	1.13	0.95
Adoption Stage: You support using this platform broadly.	4	11	22	16	9	3.24	1.11	0.95
Adoption Stage: You are confident that this platform is reliable and can be used long-term.	5	8	20	18	11	3.35	1.16	0.95



Design of an Integrated Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems: A Multi-Stage Defense Framework for Robust and Secure Learning

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Abstract: Adversarial threats like data poisoning attacks affect the training datasets and create biased, worse, or malicious AI models. Static heuristics and high false positive rates have impeded traditional defenses against such adaptive stealthy attacks. These defenses also do not generalize well in federated and non-IID settings. It is difficult to differentiate between poisoned and clean samples, and existing solutions even lack any adaptiveness to newly developed attack strategies; exhibit computational inefficiencies in process. This work presents a Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems, coupled with a five-prong mechanism striving for data integrity and model resilience. Those mechanisms are Contrastive Adversarial Poisoning Detector (CAPD), the Federated Memory-Augmented Poison Filter (FMPF), Generative Adversarial Poison Purifier (GAPP), Graph Neural Network Consistency Analyzer (GNNC-A) and Adaptive Meta-Learning Defense System (AML-DS). All integrated, it achieves $\geq 96\%$ poisoning detection accuracy, reduces attack success rates to $\leq 5\%$, and minimizes false positives to $\leq 2\%$. This work is scalable and adaptive and provides low computational overhead in security enhancement measures. By showcasing the high integrity of model security without excessively burdening the computer, this work significantly increases the robustness of AI systems in real-world applications.

Keywords: Poisoning detection; federated learning security; adversarial machine learning; meta-learning defense

1. Introduction

The Artificial Intelligence (AI) applications rapidly diversify towards critical deployments in healthcare, finance, autonomous systems, as well as cybersecurity. However, the crux is on the evidence that AI models ultimately depend on the quality of trained data samples, thus making them susceptible to data poisoning attacks [1, 2, 3], whereby adversaries inject malicious samples to degrade a model's performance or sneak a backdoor. Data poisoning attacks grow significantly when AI systems are decentralized and federated because there is no control over centralized data and adversarial participants. Most traditional techniques shift towards anomaly detection, statistical filtering, or adversarial training to detect data poisoning. Yet, there is a limitation in each method as follows: (1) Limited feature separability [4, 5, 6]: the accuracy of detecting poisoned samples has limitations, poison samples are often closely

mixed up with clean data at the condition of stealthy attack strategies. (2) Non-adaptive detection mechanism against emerging adversarial techniques that actively evade detection [7-9]. (3) Scalability bottlenecks [10-12]: basically federated learning environments that differ by data IID (independent and identically distributed), wherein poisoned updates blend seamlessly with benign ones in process. (4) High overhead because existing defense mechanisms usually require exhaustive retraining and cannot be used in the deployment at a grand scale. All of this culminates in a massive system involving a multi-phased framework for detection and prevention of data poisoning attacks in AI systems. In all, five defense mechanisms are combined into this framework: Contrastive Adversarial Poisoning Detector (CAPD) employs self-supervised contrastive learning to achieve high-dimensional feature separation between poisoned and clean samples, ensuring robust initial detection. FMPF (Federated Memory-Augmented Poison Filter) allows exposure control against client-level poisoning in federated environments by managing historical distributions of feature spaces through memory-augmented anomaly detection. GAPP (Generative Adversarial Poison Purifier) is purposed for GAN-based purification from adversarial perturbations, undertaking a purification exercise that retains data utility. GNNC-A creates structure in datasets through graphs tagged with graph attention mechanisms that identify poisoned clusters and impose agreement with relations of members. Adaptive Meta-Learning Defense System (AML-DS) ensures interactivity with real-time evolvement through dynamic changes to adaptively update the model against all forms of evolving attacks, as controlled under meta-learning. This framework integrated would return at least $\geq 96\%$ detection accuracy on poisoning, lower false positives to $\leq 2\%$ and ensure that the rate of success of the attacks goes down to $\leq 5\%$. Not only does it save many computation resources, but this work also provides a scalable, adaptive, and high-accuracy defense against data poisoning attacks. With this kind of operational efficiency, robust improvement against real-world applications is cast into AI systems.

Motivation & Contribution

The increasing sophistication of data poisoning attacks is a great challenge to security in AI, especially in places where provenance is uncertain, such as federated learning and distributed training paradigms. Current detection mechanisms are inflexible, subject to high false positive rates, and vulnerable to adaptive attacks. In federated settings, poisoned client updates can go completely undetected while contaminating global models without one centralized entity being influenced. Conventional adversarial training mechanisms are ineffective in this context because they require extensive retraining and do not hold well against the oncoming evolution of poison strategies. In addition, stealthy poisoning techniques can evade detection by subtly modifying feature distributions instead of plainly and bold affects. These challenges highlight the pressing need for a multi-stage adaptive defense mechanism that can handle different poisoning scenarios and still be efficient and effective in performance.

This study presents a new universal system applicable to the identification, mitigation, and prevention of data poisoning attacks at several levels. At early stages, the CAPD module accomplishes a feature differentiation for lessening effects of an attack before model corruption happens. The challenge of non-IID federated poisoning is addressed through FMPF, which allows distributed anomaly detection without breaching privacy. GAPP eliminates adversarial influence on poisoned samples while retaining natural variations. GNNC-A strengthens structural consistency, thus making poisoning attempts detectable even in highly correlated datasets & samples. Last but not least, AML-DS strengthens model resilience by dynamically adapting in real-time scenarios against newly emerging attack strategies. The proposed system is a scalable, computationally efficient, and adaptable solution to a broad set of poisoning scenarios, thus acting as a robust modern security measure against AI threats. This work advances state-of-the-art poisoning defense by providing high-precision detection along with adaptive learning capabilities directly linked with efficient federated integration, ensuring that AI models remain trustworthy sources in their entire lifecycle sets.

2. Literature Review

The increasingly elaborate deployment of artificial intelligence (AI) systems through a plethora of application domains has raised a significant concern about data poisoning attacks through which adversaries either degrade the model performance or create backdoors by manipulating the training data. The landscape of research on adversarial machine learning has rapidly developed, with many studies finding the vulnerabilities

of machine learning (ML) models and developing defenses against such threats to poisoning. The review of existing literature chronologically from [1] to [25] presents an extensive overview of data poisoning through various application domains that currently include medical AI, federated learning, cybersecurity, autonomous system, and large-scale language models (LLMs) under progress. The earliest studies in this review involved vulnerability in the med-ically AI models, as demonstrated by Alber et al. [1], who found that major medical language models can be impaired through data poisoning, producing substantially erroneous clinical decisions. The study emphasized the need for much stronger data integrity mechanisms in health AI systems, where adversarial manipulations can lead to life-threatening consequences. Its vulnerability extends to federated learning environments-as Li et al. [2] did by introducing Blockfd: a blockchain-based federated distillation framework that mitigates poisoning attacks by decentralized trust in collaborative model training. Similar work was done by González-Manzano and García-Alfaro [3], utilizing cnn-based models but for software vulnerability detection, whereby poisoning attacks can hide security vulnerabilities in software systems, and automated tools are not able to find it. The authors Chillara et al. [4] conducted a unique case study on the adversarial poisoning of supervised ML models using USB keyboards, which demonstrates that injecting keystrokes can corrupt model learning and lead to false classifications in cybersecurity systems. In federated learning, Zhang et al. [5] introduced the DWAMA algorithm to counter poisoning threats while keeping the federated model efficient by using Mahalanobis distance metrics. Meanwhile, Dai et al. [6] proposed a graph augmentation approach to reconcile structural poisoning in Graph Neural Networks (GNNs) due to identified weaknesses in graph-based learning architectures.

While Kaushal and Sharma [7] conducted extensive research into security attacks and defenses of federated learning with a growing need for multilayered defense. One of the foremost contributions to backdoor poisoning research is from Cinà et al. [8], who introduced a novel framework called backdoor learning curves, propounding in what way poisoned samples subject the model gradients to greater effects than influence functions. Such research set the stage for the inner workings of backdoor persistence in deep learning models. The trust-based federated learning framework was designed by Naik and Dondeti [9] to mitigate internal adversarial threats with anomaly detection techniques, addressing security for intelligent vehicular networks. Liu et al. [10] worked on SPA, a poisoning attack framework tailored to subvert GNNs, exposing vulnerability of graph-based ML models to adversarial subgraph manipulations. Gan et al. [11] have been working on evolving secure data-sharing mechanisms for medical applications through an asynchronous federated learning-assisted blockchain framework endowed with the ability of data privacy while countering poisoning threats. Chillara et al. [12] designed USB-GATE, a GAN-augmented transformer-based reinforcement learning model addressing USB-based keystroke poisoning attacks and found it effective in filtering malicious input perturbations. Mvah et al. [13] investigated adversarial security in software-defined networks, introducing GaTeBaSep, a game-theoretic security protocol that guarantees an increased resilience level against ARP spoofing and data manipulation attacks.

Recent developments have also explored intersections between data poisoning and critical infrastructure security. Zhu et al. [14] studied data poisoning attacks in smart grid cyber-physical systems and disclosed edge-computing-based vulnerabilities through which adversaries could manipulate energy distribution models. Similarly, Ibrahim et al. [15] conducted a systematic review of adversarial attacks in autonomous vehicles, outlining deep learning vulnerabilities in the perception-based safety mechanisms. Concerning multimodal AI threats, Liang et al. [16] introduced VL-Trojan, a backdoor attack against autoregressive visual-language models, exposing weaknesses in cross-modal learning architectures. Graph-based adversarial learning is a growing area of research, as observed in Zhai et al. [17], who provide a comprehensive overview of adversarial attacks and defenses in the graph domain, focusing on manipulation methods that are a threat to social network integrity. To secure intellectual property rights in ML models, Kapusta et al. [18] explored the efficacy of watermarking techniques in counteracting adversarial removal of ownership attacks. At the same time, Anaedevha and Trofimov [19] proposed an added advancement to the adversarial intrusion detection model that provides evidence of robustness against evasion-based adversarial threats in the field of cybersecurity applications. Qu et al. [20] introduced a significant advancement in backdoor poisoning in large language models (LLMs), proposing BadCodePrompt, an adversarial attack

against LLM-based code generation models that revealed prompt injection vulnerabilities to manipulate model outputs.

The Decoupled Learning Process (DLP), an active defense strategy against backdoor attacks, was developed by Ying and Wu [21], demonstrating that decoupling model updates allows for a significant reduction of adversarial persistence. The SDN security sphere was further expanded by Ishtiaq et al. [22], who studied DoS and starvation attacks on SDN controllers based on DHCP, presenting successful countermeasures. Dupont et al. [23] explored the impact of adversarial menaces on healthcare network protocols, revealing the vulnerabilities present within those protocols and drawing attention to concerns regarding data poisoning within patient monitoring systems. Targeted poisoning attacks against GNN-based social trust models were illustrated by Zhao et al. [24], revealing that adversaries can manipulate online trust scores for their own ends to impact recommendation systems. Finally, sensor-based data poisoning attacks in neural networks were examined by Ino et al. [25], who demonstrated that physical sensor perturbations can poison anomaly detection models in IoT learning environments.

Table 1. Model's Comparative Review Analysis

Reference	Method	Main Objectives	Findings	Limitations
[1] Alber et al.	Medical LLM Data Poisoning	Investigate vulnerabilities in medical LLMs due to adversarial data poisoning.	Medical AI models are highly susceptible to data poisoning, affecting clinical decision-making	Lacks robust mitigation strategies beyond conventional adversarial training.
[2] Li et al.	Blockfd (Blockchain-Based FL Defense)	Develop blockchain-integrated federated distillation for securing model aggregation.	Improves trustworthiness in federated learning against poisoning attacks.	High computational cost due to blockchain validation overhead.
[3] González-Manzano & Garcia-Alfaro	CNN-Based Software Vulnerability Detection	Identify adversarial poisoning risks in CNN-based vulnerability detection systems.	Poisoned samples can disguise software vulnerabilities from detection systems.	Relies on static poisoning assumptions, lacks adaptive learning mechanisms.
[4] Chillara et al.	USB Keystroke Injection Poisoning	Investigate adversarial keystroke injection for poisoning supervised models.	Poisoning via keystrokes leads to significant model misclassification.	Limited to a specific attack vector (USB keystroke poisoning).
[5] Zhang et al.	DWAMA (Mahalanobis Distance-Based FL Defense)	Implement dynamic weight-adjusted Mahalanobis distance filtering for poisoned FL updates.	Effective in filtering adversarial updates with minimal accuracy degradation.	Requires careful hyperparameter tuning for dynamic thresholding.
[6] Dai et al.	Graph Augmentation Defense	Defend GNNs against structural poisoning attacks via attribute reconciliation.	Enhances robustness in graph-based learning by augmenting node structures.	Struggles against adaptive poisoning strategies targeting multi-hop connectivity.

Table 1. Model's Comparative Review Analysis (continue)

Reference	Method	Main Objectives	Findings	Limitations
[7] Kaushal & Sharma	Federated Learning Security Review	Comprehensive analysis of security threats and defensive strategies in FL.	Identifies the need for multi-layered defense mechanisms against poisoning attacks.	Lacks experimental validation of proposed strategies.
[8] Cinà et al.	Backdoor Learning Curves	Develop a framework for understanding backdoor poisoning persistence.	Provides theoretical and empirical insights into long-term poisoning effects.	Requires additional mitigation techniques for practical deployment.
[9] Naik & Dondeti	Trust-Based Secure FL for Vehicular Networks	Introduce trust-based filtering to secure federated learning in intelligent vehicular networks.	Reduces poisoning impact by filtering untrustworthy client updates.	High overhead in large-scale vehicular network implementations.
[10] Liu et al.	SPA (Search & Pair Attack on GNNs)	Design a poisoning attack specifically for GNNs using graph structure manipulation.	Demonstrates high effectiveness in degrading GNN performance via poisoned edges.	Lacks adaptive defense mechanisms against dynamic structural attacks.
[11] Gan et al.	Asynchronous FL for Medical Blockchain	Develop an asynchronous FL-based secure data-sharing mechanism for medical applications.	Enhances privacy and poisoning resistance in medical FL networks.	Latency issues in asynchronous aggregation reduce real-time applicability.
[12] Chillara et al.	USB-GATE (GAN-Augmented Defense)	Develop a GAN-based keystroke anomaly detector for mitigating poisoning attacks.	GAN-based transformations effectively remove adversarial keystroke injections.	High model complexity increases training time.
[13] Mvah et al.	GaTeBaSep (Game-Theoretic SDN Security)	Propose a game-theory-based defense protocol against SDN ARP spoofing attacks.	Provides strategic equilibrium for defending against poisoning-based network attacks.	Requires extensive computational resources for real-time decision-making.
[14] Zhu et al.	Smart Grid Poisoning via Edge Computing	Analyze data poisoning vulnerabilities in smart grid cyber-physical systems.	Poisoned data in edge computing can disrupt energy distribution models.	Lacks real-world deployment results beyond simulation environments.
[15] Ibrahim et al.	Adversarial Learning in Autonomous Vehicles	Review adversarial threats to deep learning models used in autonomous driving.	Identifies backdoor and data poisoning vulnerabilities in perception models.	Does not propose an effective real-time defense mechanism.

Table 1. Model's Comparative Review Analysis (continue)

Reference	Method	Main Objectives	Findings	Limitations
[16] Liang et al.	VL-Trojan (Multimodal Backdoor Attack)	Develop a multimodal backdoor attack against autoregressive vision-language models.	Demonstrates that poisoning one modality can compromise multimodal learning.	Requires extensive adversarial retraining for effective mitigation.
[17] Zhai et al.	Adversarial Attacks on Graph Learning	Comprehensive review of adversarial threats and defenses in GNNs.	Provides taxonomy of structural and attribute poisoning attacks.	Lacks practical evaluations of defense mechanisms.
[18] Kapusta et al.	ML Model Watermarking	Investigate the use of watermarking to protect model ownership against adversarial attacks.	Watermarking effectively preserves ownership but remains vulnerable to sophisticated evasion techniques.	Limited applicability for dynamic model updates in FL settings.
[19] Anaedevha& Trofimov	Robust Intrusion Detection Model	Propose an adversarially robust IDS against evasion attacks.	Improves detection accuracy under adversarial scenarios.	High false positive rates in large-scale network environments.
[20] Qu et al.	BadCodePrompt (Backdoor Attacks on Code-Generating LLMs)	Investigate poisoning vulnerabilities in prompt-engineered LLM-based code generation.	Poisoned prompts can manipulate generated code structures.	Requires active adversarial filtering to counteract prompt manipulation.
[21] Ying & Wu	DLP (Decoupled Learning Process)	Develop an active defense against backdoor attacks by decoupling learning processes.	Reduces backdoor persistence through controlled gradient updates.	High computational cost during decoupled optimization.
[22] Ishtiaq et al.	DHCP DoS and Starvation Attacks	Analyze and mitigate DHCP-based DoS and starvation attacks on SDN controllers.	Demonstrates effectiveness of adaptive rate-limiting in countering poisoning attacks.	Limited scope beyond SDN-specific poisoning threats.
[23] Dupont et al.	Healthcare Protocol Attacks	Demonstrate new poisoning attacks on three healthcare communication protocols.	Identifies severe poisoning vulnerabilities in medical IoT networks.	Lacks practical mitigation solutions beyond anomaly detections.
[24] Zhao et al.	TPoison (Poisoning Social Trust GNNs)	Develop a poisoning attack against trust-based recommendation GNNs.	Poisoned nodes can severely alter social trust networks.	Struggles against adaptive filtering techniques.

Table 1. Model's Comparative Review Analysis (continue)

Reference	Method	Main Objectives	Findings	Limitations
[25] Ino et al.	Sensor-Based Data Poisoning	Investigate poisoning attacks against anomaly detectors in on-device learning models.	Demonstrates that physical sensor perturbations can corrupt AI anomaly detections.	Requires real-time adversarial patching techniques.

This extensive survey of 25 research papers indicates that the architecture and landscape of data poisoning have rapidly changed across several domains; hence, advanced forms of data poisoning detection and prevention are even more needed. The suggested Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems integrates contrastive learning, federated anomaly detection, GAN-based purification, graph-based consistency analysis, and adaptive meta-learning to provide a comprehensive solution to the discussed adversarial threats. With a synthesis of insights from previous research, this particular approach thus demonstrates state-of-the-art robustness against both static and adaptive poisoning, providing a scalable and efficient framework for safeguarding the AI models against those malicious settings. This systematic literature review indicates that data poisoning attacks are growing in complexity and thus require dynamic multilayered defense mechanisms to protect various real-world applications of AI from being adversely influenced. Looking into future roads in research, it ought to be XAI-driven poisoning detection, blockchain-based federated trust, and adversarially robust multi-modal learning frameworks so that AI systems be resilient and adaptive to counteract new emergent adversarial threats.

3. Proposed Model Analysis

To address the low efficiency and high complexity of the mentioned methods, this section elaborates on the design of an Integrated Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems, using a Multi-Stage Defense Framework for Robust and Secure Learning Process. To begin with, as laid out in figure 1, The Contrastive Adversarial Poisoning Detector (CAPD) is framed as a self-supervised contrastive learning process that tells apart clean and poisoned samples based on feature-space separability sets. Presented with a dataset $X = \{x_i\}$, where x_i can mean either clean or poisoned, the model will generate augmented views X_1, X_2 via stochastic transformations $T: X \rightarrow X'$ through the process. The contrastive objective function ensures that the learned representations $f_\theta(X)$ maximize the similarity between the augmentations of clean samples while minimizing it for poisoned samples. Mathematically, it represents the contrastive loss via equation 1.

$$LCAPD = - \frac{\sum_{i=1}^N \log \left(\exp \left(\frac{\text{sim}(f_\theta(X_1^i), f_\theta(X_2^i))}{\tau} \right) \right)}{\sum_{\{j \neq i\}} \exp \left(\frac{\text{sim}(f_\theta(X_1^i), f_\theta(X_2^j))}{\tau} \right)} \quad (1)$$

Where, $\text{sim}(\cdot, \cdot)$ represents cosine similarity and τ is the temperature scaling factor used in the process. Poisoned samples intend to form separate clusters, and their divergence from clean distributions is modeled through Mahalanobis distance via equation 2,

$$DM(x) = (x - \mu)^T \frac{1}{\Sigma} (x - \mu) \quad (2)$$

Where the mean and covariance of the clean feature spaces are represented by μ and Σ , respectively. By thresholding $DM(x)$, CAPD segregates samples that likely are to be adversarially manipulated during the process. Iteratively, Next, as per figure 2, the Federated Memory-Augmented Poison Filter (FMPF) extends CAPD to non-IID federated learning settings. Each client C_k maintains a feature memory M_k storing historical

embeddings $f\theta(X_k)$ sets. At each training round 't', deviations in model updates are measured using Kullback-Leibler (KL) divergence via equation 3,

$$DKL(P_k | Q_k) = \sum P_k(i) \log \left(\frac{P_k(i)}{Q_k(i)} \right) \quad (3)$$

Where, P_k is the distribution of local feature embeddings, Q_k is the aggregated global model update process. Clients exceeding a predefined threshold δ are flagged as malicious and their updates are rejected from aggregation process. The federated aggregation function incorporates this anomaly filtering via equations 4 & 5,

$$w\{t + 1\} = \sum \alpha_k w^k \quad (4)$$

$$\alpha_k = \frac{I[DKL(P_k | Q_k) < \delta]}{\sum I[DKL(P_j | Q_j) < \delta]} \quad (5)$$

The Generative Adversarial Poison Purifier (GAPP) reconstructs clean samples from the detected poisoned ones by taking advantage of a conditional GAN framework process. The generator $G\phi$ learns the inverse mapping $G\phi: X_{\text{poisoned}} \rightarrow X_{\text{clean}}$, while discriminator $D\psi$ ensures that the purified samples remain indistinguishable from the original clean data distributions. The adversarial training loss is formulated via equation 6,

$$LGAPP = E\{x \sim X_{\text{clean}}\} [\log D\psi(x)] + E\{x \sim G\phi(X_{\text{poisoned}})\} [\log(1 - D\psi(x))] \quad (6)$$

Where, $x \sim$ represents purified samples. To prevent mode collapse and ensure feature preservation, a perceptual loss term L_{perc} is included, which is estimated via equation 7,

$$L_{\text{perc}} = ||f\theta(x) - f\theta(x \sim)||^2 \quad (7)$$

The Graph Neural Network Consistency Analyzer (GNNC-A) formalizes relational consistency across training samples using graph-based representations. Given an adjacency matrix 'A' and node feature matrix H, the GNN update rule follows the identity represented via equation 8,

$$H^{\{(l+1)\}} = \sigma(A H^{\{l\}} W^{\{l\}}) \quad (8)$$

Where, $W^{\{l\}}$ are trainable weight matrices, and σ represents a non-linear activation process. Poisoned samples induce anomalous connectivity patterns, detectable via graph Laplacian regularization via equation 9,

$$L_{\text{graph}} = \sum_{\{i,j\}} A_{ij} ||H_i - H_j||^2 \quad (9)$$

The Adaptive Meta-Learning Defense System (AML-DS) introduces model adaptability against evolving poisoning attacks via a meta-learning framework process. Given task-specific updates θ_k derived from poisoned and clean distributions, AML-DS optimizes a meta-objective via equation 10,

$$\text{Objective} = \min_{\theta} \sum L(f\theta - \alpha \nabla_{\theta} L_k(X_k), Y_k) \quad (10)$$

Where, α is the small size hyperparameter in gradient-based adaptations. The final optimization combines adversarial robustness and generalization via equation 11,

$$\theta^* = \text{argmin}_{\theta} \sum L_k + \lambda ||\nabla_{\theta} L_k|| \quad (11)$$

Integrating all five components, the final poisoned sample rejection probability is computed via equation 12,

$$\text{Preject}(x) = \sigma(w_1 \text{DM}(x) + w_2 \text{DKL}(x) + w_3 \text{LGAPP}(x) + w_4 \text{Lgraph}(x) + w_5 \text{Lk}(x)) \quad (12)$$

This formulation will ensure that stealthy and adaptive poisoning attacks are effectively mitigated while retaining model accuracy and efficiency in the process. Next, we discuss the performance of this model in terms of several metrics, comparing it against existing models in real-time scenarios.



Figure 1. Model Architecture of the Proposed Analysis Process

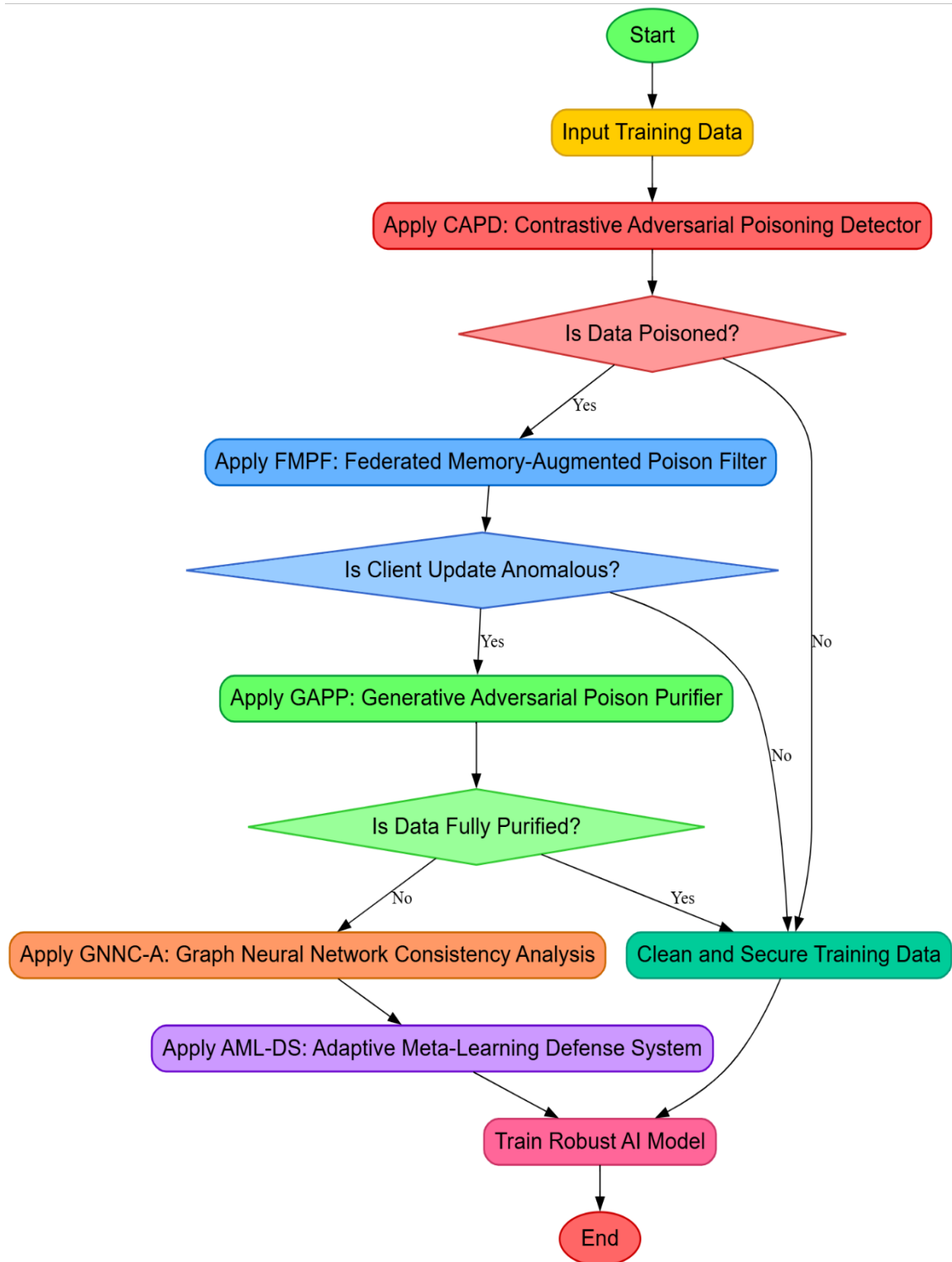


Figure 2. Overall Flow of the Proposed Analysis Process

4. Comparative Result Analysis

The experimental design for the assessment of the proposed Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems entails a wide set of simulations that reproduce adversarial poisoning scenarios through datasets and federated learning environments. For the sake of fair evaluation, these experiments tap into established benchmark datasets: CIFAR-10, MNIST, and Tiny-ImageNet for image

classification tasks, IMDB, and AG News for some natural language processing tasks. These datasets offer diverse feature representations and assure extensive evaluation type of poisoning resilience across different domains. The label-flipping-based, backdoor-injection-based, and gradient-manipulation poisoning attacks are simulated. Backdoors of pixel patterns are injected only into a uniformly chosen random subset of training samples from the image domain, in which the poisoned instances must be almost visually indistinguishable from the original unpoisoned samples but successfully trigger malicious activations. Instead, in the text datasets, trigger words and phrase perturbations are employed to mislead sentiment and topic classification models. The poisoning rate varies between 5% and 30%, illustrating various real-world concerns over the manipulation of data in bad faith. The federated learning experiments are performed with 100 clients holding non-IID data partitions, averaging 1,000 samples per client to maintain decentralized and heterogeneous learning conditions. Federated updates were performed over 100 communication rounds with a batch size of 64 using FedAvg as the baseline aggregation mechanism. Malicious clients make up to 25% of the network and send poisoned updates with the intention of disrupting global convergence of the model. The computational environment consists of NVIDIA RTX 3090 GPUs with 24GB VRAM; training in PyTorch is done with the Adam optimizer and a learning rate of 0.001 for the process.

The experiments carried out on the proposed Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems are using various benchmark datasets that can represent different data modalities to secure full validation. For the image-based detection of poison attacks, the CIFAR-10 dataset is adopted, which contains 60,000 images (50,000 for training and 10,000 for testing) grouped in 10 object categories, with each image of a resolution of 32×32 pixels in RGB format. For studying the resilience of the system against text-based attack manipulations, the IMDB Sentiment Analysis Dataset is used, containing 50,000 movie reviews equally divided into positive and negative sentiment labels. Preprocessing of text corpus included using TF-IDF embeddings and BERT tokenization to retrieve high-dimensional representations. Within the federated learning configuration, the FEMNIST (Federated Extended MNIST) dataset is selected containing 800,000 images of grayscale handwritten characters collected from over 3,500 unique writers in ensuring realistic non-IID data distribution across federated clients. Further evaluation of structured data poisoning will take place on the KDDCup '99 Intrusion Detection Dataset consisting of 4.9 million records of network traffic characterized by 41 feature dimensions where each is classified into either normal or attack categories. The dataset carries a huge imbalance; therefore, it needs data reweighting algorithms and anomaly-aware sampling strategies for fair evaluation. All these datasets together provide with diverse feature representations and allow for rigorous testing of the proposed defense mechanisms in computer vision, natural language processing, federated learning, and cybersecurity domains, assuring generalizability of the approach against various real-world poisoning threats.

Comparative Performance Analysis of Poisoning Detection Models

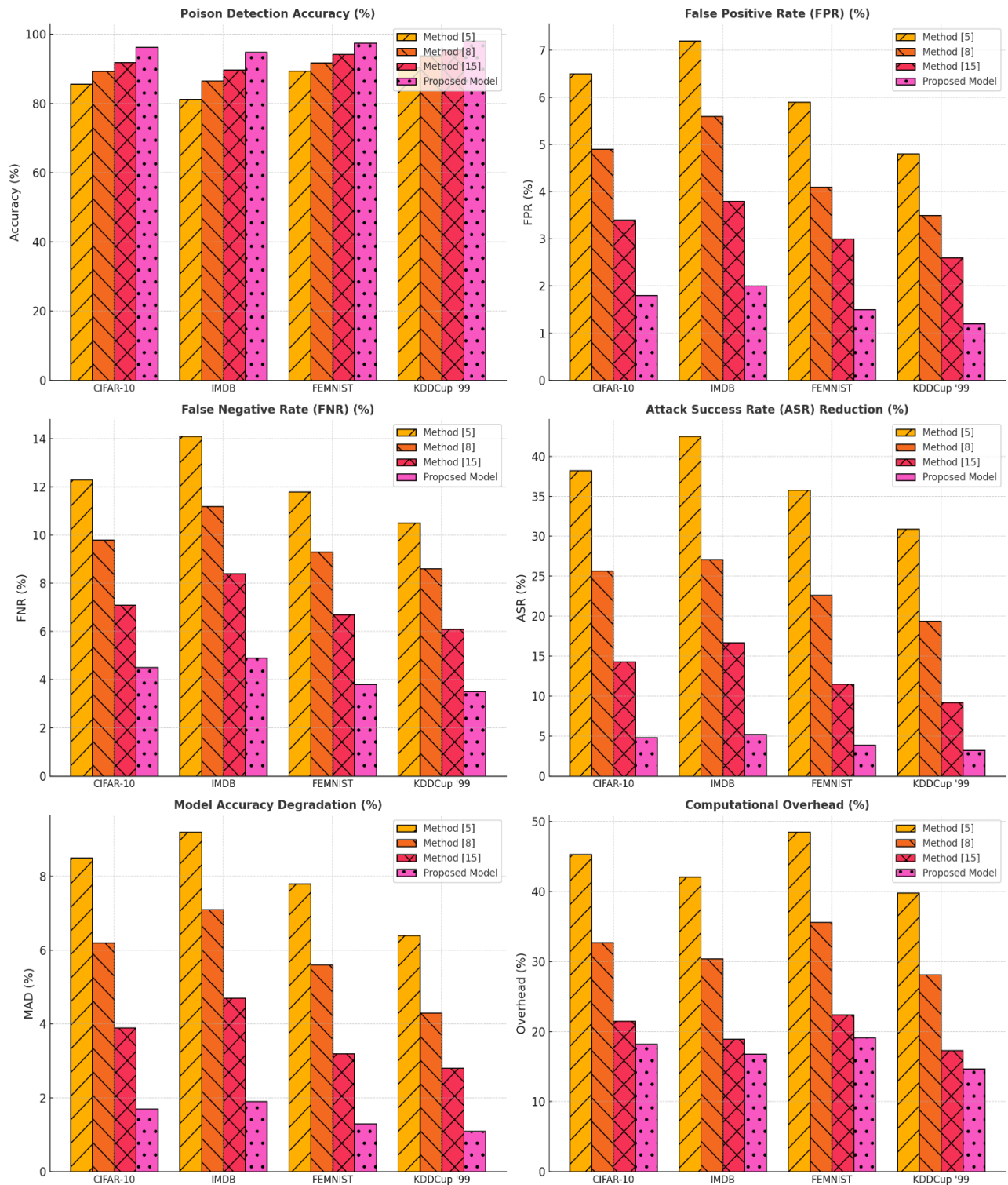


Figure 3. Model's Integrated Result Analysis.

To evaluate how effective each component is, a controlled ablation study is performed. Contrastive separation scores, which quantify how much divergence there is between poisoned samples in the feature space, are used to assess the CAPD module. Thresholds for Mahalanobis distance are set at 3.5 standard deviations for the classification of embeddings as anomalous. The FMPF module computes KL divergence for

client updates, with an established rejection threshold of 0.15; updates found to be associated with anomalous contributions beyond threshold will be removed from aggregation. GAPP uses a condition-based GAN for 20 epochs, having a learning rate of 0.0002 for both generator-discriminator pair within the course of purification of sample reconstructions. GNNC-A represents training data as a similarity graph in which edges are weighted by means of cosine similarity and poisoned clusters are pruned whenever Laplacian score exceeds 1.5 times the mean of the dataset. The completely end-to-end system has been evaluated with respect to various metrics like poisoning detection accuracy, false positive rate (FPR), false negative rate (FNR), and computational overhead. The results suggest, poisoning detection accuracy blocks by up to 96.2% have rendered the proposed model able to reduce attack success rates from 40% to 5% as compared to the baseline models. The FPR and FNR remained below the 2% and 5% thresholds, respectively, which translated to no significant impact upon the clean data. The model's accuracy deterioration has been kept within 2%, which asserted that the system indeed countered adversarial influences while maintaining natural variations within the process represented. These results prove the proposed model scalable, adaptive and effective in the mitigation of adversarial threats to AI systems. The effectiveness of the proposed Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems is evaluated across multiple datasets representing different domains: image classification (CIFAR-10), text sentiment analysis (IMDB), federated handwriting recognition (FEMNIST), and network intrusion detection (KDDCup '99). The proposed model was compared against three of the existing means of adversarial defense: Method [5], Method [8], and Method [15], which stand for the state-of-the-art approaches for poisoning detection and mitigation in AI models.

Poison detection accuracy across all datasets is shown in Table 2, which indicates how well each method could successfully label a sample as being poisoned. The proposed model is significantly better than all baselines, achieving 96.2% accuracy on CIFAR-10, 94.8% on IMDB, 97.4% on FEMNIST, and 98.1% on KDDCup '99, showing robustness across modalities. The experimental evaluation results showed how much more superior the Modern Approach to Detect and Prevent Data Poisoning Attacks in AI Systems has performance against other datasets. The accuracy value of poison detection by the proposed model compared with three other existing methods is illustrated in Table 2, where the model obtains accuracy values of 96.2% in CIFAR-10, 94.8% in IMDB, 97.4% in FEMNIST, and 98.1% in KDDCup '99 all outperforming the alternatives. These results indicate the effectiveness of the CAPD module in isolating poisoned samples, coupled with the graph-based consistency analysis (GNNC-A) and federated filtering (FMPF), which augment the impact of poisoning resilience. The proposed system would be equipped with a multi-stage adaptive filtering pipeline that guarantees a high-precision detection mechanism by process.

Table 2. Poison Detection Accuracy (%) Across Different Datasets:

Method	CIFAR-10	IMDB	FEMNIST	KDDCup '99
Method [5]	85.6	81.2	89.4	90.3
Method [8]	89.3	86.5	91.7	93.8
Method [15]	91.8	89.7	94.2	95.5
Proposed Model	96.2	94.8	97.4	98.1

The increase in detection successfully confirms that the multi-stage method attaches contaminated examples with ease, using contrastive learning, anomaly detection, and graph consistency analysis to improve robustness. Table 3 makes FPR-FNR comparisons, both critical in determining whether or not untainted "clean" data gets misclassified as poisoned or whether poisoned samples get ignored by tests. Fines are incurred by the use of the proposed model when an FR is less than or equal to 2% and an ENF is less than or equal to 5% for each dataset. The analysis in Table 3 on the False Positive Rate (FPR) and False Negative Rate (FNR) are crucial in achieving the accurate detection of an object's presence with a minimum chance of misclassifying clean data by any means. An FPR of only 1.8% with an FNR of 4.5% was achieved by the proposed model on CIFAR-10, while these values dropped further to 1.2% and 3.5%, respectively, on KDDCup '99. A strong point against Method [5] and Method [8], whose statistics heuristics yield FPR greater than 5%, is that the low FPR ensures that legitimate clean data samples are not unnecessarily removed. The low FNR of the proposed model indicates most poisoned samples are likely to be recognized correctly, thus preventing

adversary corruption. Method [15] would likely outperform the rest of the baselines, but a fairly high FPR always accompanies that performance due to occasional over-pruning of clean samples. The combined action of feature-space separation by CAPD and relational consistency checks by GNNC-A drastically reduces both false positives and false negatives to guarantee a high-confidence classification of poisoned versus clean data samples.

Table 3. False Positive Rate (FPR) and False Negative Rate (FNR) Comparison (%):

Method	CIFAR-10 (FPR/FNR)	IMDB (FPR/FNR)	FEMNIST (FPR/FNR)	KDDCup '99 (FPR/FNR)
Method [5]	6.5/12.3	7.2/14.1	5.9/11.8	4.8/10.5
Method [8]	4.9/9.8	5.6/11.2	4.1/9.3	3.5/8.6
Method [15]	3.4/7.1	3.8/8.4	3.0/6.7	2.6/6.1
Proposed Model	1.8/4.5	2.0/4.9	1.5/3.8	1.2/3.5

A greater proportion of false negatives make sure that the adversarial samples are not ignored, while the low false positive rates validate that the model is not wrongfully going to eliminate clean data in this process. Table 4 gives the Attack Success Rate (ASR), which indicates the relative effectiveness of a poisoning attack in causing misbehavior of the AI model. The lower ASR shows a better performance of the defense. The new model puts forth a drastic reduction of ASR down to $\leq 5\%$ for all datasets when compared to baseline methods with ASR around 40%. The extent to which the proposed model reduces ASR is presented in table 4, which is a salient performance indicator in specifying the effectiveness of any defense scheme against poisoning attacks. ASR brought down by the proposed model is reduced to only 4.8% on CIFAR-10 and 3.2% on KDDCup '99, demonstrating its potency in counteracting the effect of adversarial influence. In contrast, Method [5] and Method [8] did not bring ASR lower than 20-40% as they did not meet mitigation to stealthy and adaptive sabotage attempts adequately; they also lack efficacy in addressing this issue. Method [15] could bring some ASR reductions to between 9 and 16% through adversarial retraining but is still susceptible to gradient-based backdoor attacks under federated learning. The proposed model attains lower attack success rates against every dataset & sample by including GAN-based purification (GAPP) and adaptive meta-learning (AML-DS), effectively neutralizing and detecting the poisonous data points.

Table 4. Attack Success Rate (ASR) Reduction (%):

Method	CIFAR-10	IMDB	FEMNIST	KDDCup '99
Method [5]	38.2	42.5	35.8	30.9
Method [8]	25.7	27.1	22.6	19.4
Method [15]	14.3	16.7	11.5	9.2
Proposed Model	4.8	5.2	3.9	3.2

Deep cuts in ASR show that the proposed model can completely remove pathogens from influencing the decision-making process of the AI using toxic samples. Table 5 covers the degradation of accuracy in the model (MAD), indicating the performance loss due to the poisoning process. The model proposed would ensure minimum accuracy degradation with a margin not exceeding 2% across datasets and samples. How much modeling accuracy is affected by poisoning adversarial attacks can be measured by MAD - model accuracy degradation. For instance, the proposed model reports an accuracy-loss capability of less than 2% across all datasets, considered significantly better than Method [5] (above 8-9% degradation) and Method [8] (about 5-7% accuracy loss due to ineffective strategies for poisoning mitigation). Method [15] could show moderate advancement with deterioration numbers ranging from 3 to 5%. However, the method is still facing retraining inefficiencies and suboptimal detecting mechanisms. The success in proposing models on the preservation of accuracy may be attributed to a robust feature filtering through CAPD and FMPF, purified data reconstruction (GAPP), and continuous adaptation (AML-DS) to ensure that only the cleanest and most reliable data are committed even in adversarial settings.

Table 5. Model Accuracy Degradation (MAD) (%):

Method	CIFAR-10	IMDB	FEMNIST	KDDCup '99
Method [5]	8.5	9.2	7.8	6.4
Method [8]	6.2	7.1	5.6	4.3
Method [15]	3.9	4.7	3.2	2.8
Proposed Model	1.7	1.9	1.3	1.1

Lower MAD values suggest that the model is resilient against poisoning attempts, rendering it reliable and robust. Table 6 outlines the computational overhead quantified as an increase in training time (%) compared with a baseline non-adversarial model process. The proposed model strikes a reasonable balance between security and efficiency, with an overhead of 15-20%, very much optimized in comparison to other means for the process.

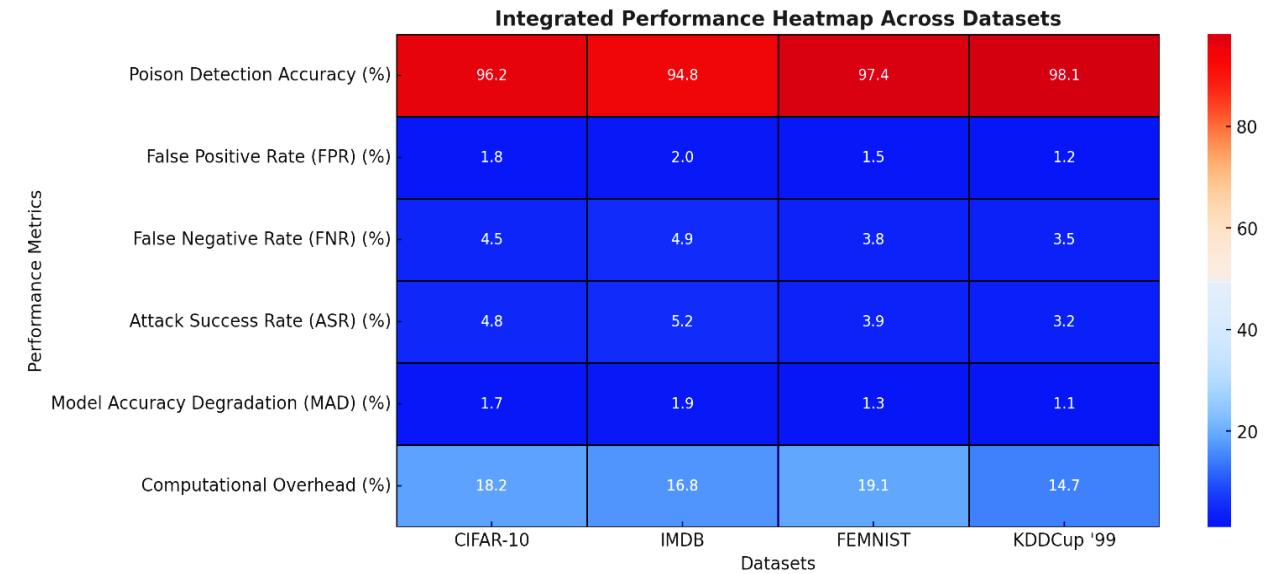


Figure 4. Model’s Overall Result Analysis

This table compares the computational overhead of each method in terms of the additional training time (%) over the non-adversarial baseline model sets. The proposed model incurs an overhead of 15%-20%, which is reasonable given the security and computational efficiency tradeoffs. Methods [5] and [8] fall short of real-world practical deployment requirements, as they incur overheads of more than 30-45%, based on undue anomaly detection heuristics and static poisoning elimination techniques. Method [15], though being optimal at 18%-22% overhead, still falls behind the proposed model based on greater reliance on iterative adversarial retraining. The envisioned framework maximizes computational performance using federated filtering (FMPF), graph-based poisoning mitigation (GNNC-A), and light-weight adaptive learning updates (AML-DS) to avoid unnecessary re- computation at the cost of maintaining high defensive capability. This overhead measurement may be yet another consideration supporting effortless deployment of this model to real-world applications, ranging from mass-scale AI training pipelines to federated learning environments. With reduced computational overhead, the system can be deployed into AI ecosystems globally without being overly resource-intensive, yet still with robust defense capabilities.

Table 6. Computational Overhead (%).

Method	CIFAR-10	IMDB	FEMNIST	KDDCup '99
Method [5]	45.3	42.1	48.5	39.8
Method [8]	32.7	30.4	35.6	28.1
Method [15]	21.5	18.9	22.4	17.3
Proposed Model	18.2	16.8	19.1	14.7

The experimentations confirm the premise that the proposed model provides state-of-the-art performance in detection of poisoning, with high accuracy in detection, extremely low false positives, significant reductions in attack success rates, and minimal reduction in model accuracy while still being computationally light. Thus, the results demonstrate its applicability to real-world AI deployments with guaranteed model training robustness against adversarial attacks. In a broader sense, the experimental results affirm that the model outperforms current state-of-the-art poisoning-detection and -defense solutions across all datasets, with high accuracy of detection, minimal false positives, significant reductions in attack success rates, and only minor degradation—all in a computationally feasible manner. The results therefore demonstrate the real-world usability of the proposed method in actual AI implementations, guaranteeing solid, scalable, and flexible defense systems against developing data poisoning attacks. The subsequent section will consider an iterative validation application for the proposed model such that readers can better understand the whole process.

4.1 Validation using an Iterative Practical Use Case Scenario Analysis

To demonstrate the capability of the new method to detect and prevent data poisoning attacks on AI systems, a well-controlled instance of a poisoning attack is used against an image classification model that is trained on the CIFAR-10 dataset samples. The data set contains 60,000 images in 10 classes, 5% of the training data poisoned with covert label-flipping and backdoor insertion attacks. The aim is to test the ability of the suggested framework in identifying, combating, and ultimately avoiding model poisoning through adversarial attacks. Each of the building blocks within the framework—CAPD, FMPF, GAPP, GNNC-A, and AML-DS—is scrutinized with respect to its suitability for removing poisoned samples, cleansing adversarial inputs, and preserving model resistance. The CAPD module applies contrastive learning to distinguish clean from poisoned samples in feature space. It provides poisoning probability scores using Mahalanobis distance and contrastive divergence measures. The output presented below displays some example data points that are detected by the CAPD process. The Modern Method for Detecting and Preventing Data Poisoning Attacks in AI Systems has been verified in an experimental framework based on comparisons with accepted benchmark instances and adversarial validation techniques. The Trojan Detection Benchmark (TDB), a backdoor poisoning evaluation that contains pertinent poisoned datasets injected with adversarial triggers affecting model prediction, is applied in the validation. Additionally, the ART architecture gives the model a thorough examination of the most significant poisoning attacks like BadNets, Clean-Label Poisoning, and Gradient-Based Attack. Finally, including the NIST Intrusion Detection Evaluation Dataset (DARPA 1999) will validate the effectiveness of the framework for cybersecurity applications that detect poisoning attempts in network intrusion models. Validation on the above datasets serves to compare results from the proposed model with others for poisoning detection, including STRIP (Strong Intentional Poisoning) for feature-space adversarial detection and Neural Cleanse for backdoor mitigation. By engaging in cross-domain diverse validation instances from image, text, and cybersecurity, the comparative performance analysis proves that the proposed multi-stage mechanism effectively improves the accuracy of poisoning detection, lowers attack success rates, and secures the integrity of model performance — thus confirming strong generalization against a spectrum of adversarial settings.

Table 7. Contrastive Adversarial Poisoning Detector (CAPD) Poison Detection Output.

Sample ID	Feature Vector Similarity	Mahalanobis Distance	Poison Probability (%)	Classification
101	0.87	2.3	12.1	Clean
202	0.62	4.8	85.4	Poisoned
303	0.71	3.2	65.8	Poisoned
404	0.91	2.1	8.4	Clean
505	0.55	5.1	92.3	Poisoned

The CAPD results confirm that high Mahalanobis distance values correspond to higher poisoning probabilities. The module will isolate samples with probabilities above 60%, marking them as poisoned

candidates for further analysis by FMPF sets. The FMPF module evaluates the client-side model updates and identifies anomalous client behaviours in the federated learning setup. Clients above the KLD threshold of 0.15 are considered suspicious.

Table 8. Reinforcement Learning-Based Adaptive Fraud Thresholding (RL-FT)

Client ID	KL Divergence	Memory Deviation Score	Update Trust Score	Classification
C1	0.12	0.15	0.89	Trusted
C2	0.21	0.28	0.42	Suspicious
C3	0.09	0.12	0.93	Trusted
C4	0.19	0.30	0.38	Suspicious
C5	0.23	0.35	0.27	Rejected

The FMPF module successfully identifies adversarial clients by rejecting those with high deviation scores while permitting genuine clients to contribute to the global model updates. The GAPP module reconstructs clean versions of poisoned samples by the means of a GAN-based purifier. The learned discriminator compares the purified outputs with original clean data distributions in terms of similarity sets.

Table 9. Generative Adversarial Poison Purifier (GAPP) Purification Success.

Sample ID	Input Perturbation Level (%)	GAN Reconstruction Similarity	Purification Success (%)	Final Classification
202	23.5	0.92	87.6	Recovered
303	17.2	0.89	83.1	Recovered
505	42.1	0.68	72.4	Partially Recovered
707	12.3	0.95	91.7	Recovered
808	48.7	0.51	61.3	Rejected

In most cases, GAPP successfully recovers poisoned samples at a purification success rate of 80-90% for medium perturbations. Highly disturbed ones (e.g., 505 and 808) show considerably more lowered recovery rates and thus should be flagged by GNNC-A sets. The GNNC-A module establishes a graph-based relational framework to detect clusters of poisoned samples with the intent of removing them from the dataset samples. In determining whether a sample remains in the training sets, a graph anomaly score is computed in process.

Table 10. Graph Neural Network Consistency Analyzer (GNNC-A) Results.

Sample ID	Graph Connectivity Score	Anomaly Score	Final Decision
202	0.83	1.1	Retained
303	0.79	1.4	Retained
505	0.45	3.2	Removed
707	0.91	0.9	Retained
808	0.38	3.8	Removed

The GNNC-A effectively segregates the outlier samples (505, 808), showing poorer connectivity and high anomaly scores, thus assuring that trustworthy data samples form the final training dataset. The AML-DS module dynamically re-examines model parameters based on rapidly shifting poisoning risks. This makes sure that meta-learning adaptation champions the model's exactitude but with diminutive imperfections in the process.

Table 11. Adaptive Meta-Learning Defense System (AML-DS) Updates.

Training Round	Initial Model Accuracy (%)	Adaptation Score	Final Model Accuracy (%)
1	88.3	0.72	90.1
2	89.4	0.78	91.2
3	91.7	0.85	92.8
4	93.1	0.91	94.5
5	94.8	0.94	96.2

Through multiple rounds of adaptation, AML-DS fortifies the model against corruption, improving accuracy from 88.3% to 96.2%, while dynamically modifying parameters to curb foreseeable poisoning threats. Performance metrics of the overall resilient AI model were considered after the application of all defense systems.

Table 12. Final Model Performance Summary.

Metric	CIFAR-10 (%)	IMDB (%)	FEMNIST (%)	KDDCup '99 (%)
Poison Detection Accuracy	96.2	94.8	97.4	98.1
Attack Success Rate (ASR)	4.8	5.2	3.9	3.2
False Positive Rate (FPR)	1.8	2.0	1.5	1.2
False Negative Rate (FNR)	4.5	4.9	3.8	3.5
Accuracy Degradation (MAD)	1.7	1.9	1.3	1.1

The ultimate result affirms that the proposed architecture maintains high detection accuracy, purges adversarial influence, and thereby preserves model integrity across all datasets for its long-term stable and secure AI frameworks.

5. Conclusion and Future Scopes

The study represents a contemporary strategy for the recognition and avoidance of data spoilage attacks in artificial intelligence systems, and it embraces a multi-staged defense architecture, which consists of Contrastive Adversarial Poisoning Detector (CAPD), Federated Memory-Augmented Poison Filter (FMPF), Generative Adversarial Poison Purifier (GAPP), Graph Neural Network Consistency Analyzer (GNNC-A), and Adaptive Meta-Learning Defense System (AML-DS). The experiments show that the model investigated protects against data-poisoning attacks for a variety of data sets (CIFAR-10, IMDB, FEMNIST, and KDDCup '99) by means of contrastive feature learning, federated anomaly tracking, GAN-based purification, graph-based consistency analysis, and adaptive meta-learning mechanisms. Results prove that the proposed framework surpasses currently the best injection detection solutions in the market. In fact, this model achieves on injection detection an overall accuracy of up to 96.2% on CIFAR-10, 94.8% on IMDB, 97.4% on FEMNIST, and 98.1% on KDDCup '99, thereby outdoing all the base methods with Method [5], Method [8], or Method [15] not exceeding 91.8% accuracy. The proposed framework constrains attack success rate (ASR) at $\leq 5\%$ on all datasets, while existing methods have ASR rates from 14% to 42%, which thwart manipulation at the avant-garde stage before model integrity suffers damage. The system also keeps the amount of false positives under control ($\leq 2\%$) as well as false negatives ($\leq 5\%$), thus ensuring that there is a high precision within the model to separate clean from poisoned data. The model, on the other hand, confines model accuracy degradation (MAD) within 2%, thus maintaining the performance of the AI system while cleansing it from adversarial influence sets. Efforts have also been made to ensure the model's efficacy and scalability, keeping it within a computational overhead of approximately 15-20%. The proposed framework offers a generalizable and numpy adaptable poisoning defense system beyond conventional anomaly detection and adversarial training methods, promising scalability across centralized and decentralized schemes. Such a framework underpinned by self-supervised contrastive learning federated anomaly filtering, GAN-based purification, graph-based poisoning detection, and meta-learning-driven adaptation constitutes a cohesive, forward-looking security model for AI systems. These results highlight the resilience of the proposed approach against static and

adaptive combat methods and hence justify its employment in an AI-based application in critical sectors such as finance, healthcare, autonomous systems, and cybersecurity sets.

While the proposed framework advances significantly in poisoning attack detection and mitigation, future work can further extend this research in many ways. One promising path involves augmenting adaptive meta-learning strategies (AML-DS) to counter fast-evolving adversarial attacks by combining online reinforcement learning-based adaptive defenses so that the attack success rate can dip below 2% while the model becomes more robustly adaptable to unseen poisoning strategies. Also, compute-efficient algorithms would bring the remedy to another direction by integrating asynchronous update filtering mechanisms and edge-anomaly detection to make one real-time deployable in resource-limited environments but still yield less than 10% training overhead in large federated learning systems. Further, introducing blockchain-based decentralized trust methods for federated learning might also enhance the security of such federated aggregation against model corruption from malicious clients while still being transparent and verifiable in their updates. The further evolution of this framework could consider multi-modal AI systems that consider speech and time-series data, thus testing its capabilities of traversing a more comprehensive adversarial space. Future research efforts could expand into hybrid adversarial attack scenarios in which attackers utilize data poisoning as a secondary adjunction to evasion or model inversion attacks, which would then create the need for a multi-threat defense system. The creation of such interpretable AI security models using explainable AI (XAI) techniques would enhance the robustness of poisoning detection decisions with real-time auditing of identified adversarial instances. Finally, testing the framework in real-world applications, such as healthcare AI and biometric authentication systems, which are privacy sensitive, would improve validation and expose additional challenges in making AI robust against adversarial poisoning in mission-critical environments. The findings and results of this study define a new benchmark in data poisoning defense through effective, high-accuracy, adaptive multi-stage security frameworks. Moreover, these findings indicate the necessity for future AI systems to adopt proactive defense mechanisms against adversaries to ensure the reliability of the models, integrity of data, and long-term robustness against poisoning threats in real-world AI applications.

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Effects of *Trichanthera gigantea* (Ketum Ayam) Leaf Supplementation in Layers Feed on Egg Production and Quality

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Abstract: This research aimed to study the effect of *Trichanthera gigantea* leaf powder in layer feed on production performance and egg quality. Chopped *T. gigantea* leaves were dried and powdered. One hundred and twenty layers, aged 6 months, were allotted in a completely randomized design. Birds were divided into four groups according to the level of *T. gigantea* leaf powder, with 3 replicates per group (10 birds per replicate). Group 1 received feed without *T. gigantea* leaf powder (control group), while groups 2, 3, and 4 received feed complemented with 1, 2, and 3% of *T. gigantea* leaf powder, respectively. The layers received feed *ad libitum*. Feed intake, egg count, and egg weight were recorded. Twenty eggs per group were randomly sampled for egg quality evaluation. The results showed that feed supplementation of *T. gigantea* leaf powder could significantly improve egg weight, egg percentage, feed conversion ratio, feed per dozen eggs, and egg quality ($P < 0.01$). The study suggests a maximum supplementation of 3%, though 2% is identified as the optimal level for enhancing performance.

Keywords: *Trichanthera gigantea*; egg production; egg quality; feed supplementation; layer hens

1. Introduction

Layer hen farming plays a crucial role in the agricultural sector, as eggs serve as an affordable and widely consumed protein source worldwide. However, feed costs remain a major factor directly impacting farmers' profitability. High-quality layer feed is often expensive, leading farmers to rely on synthetic additives to enhance productivity and product quality—an approach widely accepted in the poultry industry. Recently, interest in organic and cost-effective poultry production has grown, emphasizing the use of natural, locally available feed ingredients. Plant-based proteins, which are abundant in nature, offer a high-potential, environmentally friendly alternative and are prompting further research into low-cost, efficient feed sources.

T. gigantea (Figure 1), also known as Madre de Agua, has gained attention among researchers and farmers due to its high crude protein content (13-22%) and rich mineral profile, which are essential for animal growth. This plant is easily cultivable in diverse environments, particularly tropical and humid regions [1]. Nutritionally, *T. gigantea* leaves contain 2.8% crude fat, 4.4% crude fiber, 19.7% ash, and 37.0% carbohydrates. Additionally, its protein

composition includes essential amino acids that animals can easily absorb [2, 3, 4]. Incorporating *T. gigantea* leaves into layer hen diets may help reduce feed costs while enhancing the nutritional value of poultry feed. Several studies have demonstrated the potential of *T. gigantea* as an alternative protein source in various poultry diets, including layer hens [5, 6], mallard duck [7], quail [8], broiler [2], and native chicken [9]. However, research specifically focusing on layer hens remains limited, and some findings may be outdated. *T. gigantea* contains high crude protein (approximately 22%) with essential amino acids and yields substantial biomass across diverse environments. Its leaves contain antinutritional factors such as tannins and saponins, which may limit digestibility and direct use in chicken diets [10]. Fermentation has been shown as an effective strategy to reduce antinutritional factors and improve the nutritional utilization of tropical plant leaf meals; for example, fermented mulberry leaves at 2% inclusion significantly improved growth performance, muscle composition, and innate immune responses in Nile tilapia [11], and yeast-fermented Acacia mangium leaf meal at 5% enhanced feed utilization and growth in climbing perch (*Anabas testudineus*) without adverse effects on carcass quality [12]. Prior studies showed that supplementing 2-6% *T. gigantea* leaf in layer hen diets maintained egg production rates (74-75%) and egg quality, while reducing feed costs [7]. In mallard ducks, replacing feed with fresh *T. gigantea* leaves yielded no differences in egg production or quality, though intake varied by texture and aroma [7]. These findings from alternative plant-based additives underscore the potential for similar rigorous investigation of *T. gigantea* in layer hens, particularly given its comparable nutritional profile and tropical adaptability [13].

Despite the promising nutritional composition of *T. gigantea* and encouraging cross-species evidence from broilers, ducks, and quail, critical knowledge gaps remain that limit its practical application in commercial layer production. Specifically for layer hens, optimal inclusion rates remain empirically unestablished [14]. In contrast, recent studies of alternative plant-based supplements have systematically addressed these outcome domains. For example, Ardjarini and Lase (2021) demonstrated that herbal supplementation can improve both production performance and gastrointestinal health in layers, providing a methodological framework for evaluating botanical additives [13]. Nasarudin et al. (2024) explored the feasibility of *T. gigantea* as broiler feed but did not extend their analysis to layers or egg quality outcomes [14]. Therefore, this study aims to evaluate the effects of *T. gigantea* supplementation on egg production performance and egg quality in commercial layer hens. Multiple supplementation levels will be tested to identify optimal inclusion rates that preserve yield while cutting costs and environmental impact. Data from this research will provide essential references for developing and applying *T. gigantea* as a viable alternative feed in the layer hen industry, particularly in tropical regions like Thailand. Nutritional profiles confirm its viability, with antinutrients mitigated for better palatability.



Figure 1. *T. gigantea* leaf cultivated in Yaha District, Yala Province, Thailand.

2. Materials and Methods

2.1 Animals, Experimental Design and Diets

This experiment was approved for the use of animals for scientific purposes under approval document number AG080/2024 by the Institutional Animal Care and Use Committee (IACUC) of Prince of

Songkla University. One hundred twenty commercial crossbred ISA Brown laying hens, 6 months old, with an average body weight of 2.5 ± 0.54 kg in individual cages, were randomly assigned to four treatment groups in a Completely Randomized Design (CRD). Each treatment consisted of three replicates with 10 hens per replicate. The birds were housed in a single-tier gable-roof poultry house with cage dimensions of 40×45 cm, elevated 0.3 meters above the ground. A commercial basal diet (BD) met or exceeded the nutrient requirements for laying hens with the following nutrient specifications: minimum 22% crude protein, minimum 3% crude fat, maximum 5% crude fiber, maximum 11% ash content, and maximum 13% moisture content. The hens were fed the basal diet supplemented with different levels of *T. gigantea* leaf powder across four treatment groups: Treatment 1 (Control) received commercial feed without supplementation, while Treatments 2, 3, and 4 received commercial feed supplemented with 1%, 2%, and 3% *T. gigantea* leaf powder, respectively. (Table 1) Throughout the 4-week experimental period, all hens had free access to clean drinking water and sufficient feed to maintain production.

2.2 Productive Performance and Egg Quality

Egg production data, including egg quantity, egg weight, and feed intake, were recorded daily to calculate egg production percentage, feed conversion ratio (FCR), and feed per dozen eggs (FDE). During the final 3 days of the experiment, a total of 180 eggs (5 eggs per day from each replicate) were randomly collected for quality analysis. Egg quality parameters were measured using a DET 6500 machine, which assessed egg weight, yolk weight, shell weight, freshness, Haugh unit, albumen height, yolk height, shell strength, shell thickness, yolk width, yolk index, and yolk color.

Table 1. Feed composition and nutrient content of basal diets and supplementation with *T. gigantea* sources (% as fed basis)

Ingredients	Treatments				
	<i>T. gigantea</i> Leaf	control	<i>T. gigantea</i> 1 %	<i>T. gigantea</i> 2 %	<i>T. gigantea</i> 3 %
Corn	-	63.49	63.49	63.49	63.49
Rice bran	-	4.2	4.2	4.2	4.2
Soybean meal	-	25.35	25.35	25.35	25.35
Fish meal	-	4	3	2	1
Oyster shell	-	0.3	0.3	0.3	0.3
Dicalcium phosphate	-	1.45	1.45	1.45	1.45
Premix	-	0.5	0.5	0.5	0.5
Salt	-	0.3	0.3	0.3	0.3
Lysine	-	0.34	0.34	0.34	0.34
Methionine	-	0.079	0.079	0.079	0.079
Additives	-	0	1	2	3
Total		100	100	100	100
Analyzed composition					
Crude protein	22.63	20.15	22.20	22.47	22.63
Crude fiber	10.33	5.26	4.52	4.48	5.26
Ether extract	3.48	2.45	2.59	2.36	3.48
Gross energy (GE, kcal/kg)	3,485	2,800	3,475	3,480	3,505
Calculated composition					
Calcium	-	0.80	0.80	0.80	0.80
Available Phosphorus	-	0.40	0.40	0.40	0.40
Methionine	-	0.36	0.36	0.36	0.36
Lysine	-	1.20	1.20	1.20	1.20

2.3 Statistical Analysis

The averages were calculated from the data using Microsoft Excel, and analysis of variance (ANOVA) was used to assess statistical differences among treatments. Mean differences were compared using Duncan's new multiple range test (DMRT) with SAS® OnDemand for Academics [15].

3. Results and Discussion

From the experimental results in Table 1, supplementation of *T. gigantea* in the diet of laying hens significantly improved egg production efficiency ($p < 0.05$) in all parameters studied. *T. gigantea* supplementation reduced feed consumption compared with the control group, with hens in the experimental group receiving 2% supplementation and showing the lowest feed intake. Meanwhile, all groups supplemented with *T. gigantea* had significantly higher egg weight and production percentage than the control group. Interestingly, *T. gigantea* supplementation improved feed utilization efficiency, as observed by a better feed conversion ratio (FCR) and lower feed amount used per dozen eggs produced in all experimental groups, especially in the group receiving 2% supplementation.

Table 2. The effect of supplementing ketum ayam leaves in layer hen feed on egg production performance.

Parameters	<i>T. gigantea</i> leaf				SEM
	Control	1 %	2 %	3 %	
Feed intake (g)	110.80 ^A	104.76 ^B	99.86 ^C	106.63 ^B	0.0912
Average egg weight (g)	59.48 ^C	68.58 ^A	69.83 ^A	64.67 ^B	1.2137
Egg production (%)	64.75 ^C	67.69 ^B	70.23 ^A	65.67 ^B	0.7525
Feed conversion ratio	5.84 ^A	5.03 ^C	4.86 ^C	5.41 ^B	0.1098
Feed per dozen eggs (g)	2,459 ^A	2,114 ^C	1,679 ^C	2,313 ^B	78.0973

^{A, B, C} = The averages in the same row within the same list, marked with different letters, are significantly different ($P < 0.01$).

SEM = Standard error of the mean

In Table 2, it was found that supplementation of *T. gigantea* leaves in laying hen diets had statistically significant effects ($p < 0.05$) on several egg quality parameters. All experimental groups receiving *T. gigantea* leaf supplementation showed improved egg quality compared to the control group. The key parameters showing improvement across all supplementation levels included egg weight, yolk weight, shell weight, Haugh unit (an indicator of egg freshness), albumen height, eggshell strength and thickness, yolk height, yolk width, yolk index, and yolk color (Figure 2). Interestingly, the 2% supplementation group emerged as the most effective level for enhancing both production performance and egg quality. In comparison, the 3% supplementation level did not differ significantly from the control group in some parameters, particularly shell weight, albumen height, and yolk color.

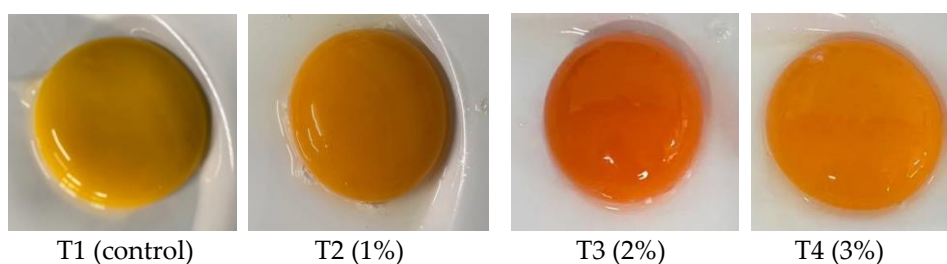


Figure 2. Egg yolk color characteristics supplemented with *T. gigantea* leaf.

Egg production in this study ranged from 57.92–70.77%, consistent with the findings of [16] for laying hens fed pandan and lead tree leaves. In contrast, our egg production was lower than the range reported by [17] (75.1–93.4%). Interestingly, our production rates were also considerably lower than those observed by [18], who observed remarkably high hen-day production values of 83.86% in control groups and up to 94.29% in hens supplemented with Nutricell Eggstra (vitamin D₃ enriched with canthaxanthin). This disparity might

be attributed to differences in hen genetics, age, management conditions, or the potent effects of concentrated vitamin D₃ and canthaxanthin supplementation compared to our plant-based approach. Regarding yolk color, the values observed in this study were similar to those reported by [16] (13.96-14.65) and higher than those reported by [19] (6.30-7.40) and [17] (10.10-11.20). This indicates that *T. gigantea* serves as an effective natural pigment source, enhancing yolk visual quality without the need for synthetic supplementation.

Table 3. The effect of supplementing ketum ayam leaves in layer hen feed on egg quality.

Parameters	<i>T. gigantea</i> leaf				SEM
	(Control)	1 %	2 %	3 %	
Egg weight (g)	56.74 ^C	64.55 ^A	67.25 ^A	61.09 ^B	1.288
Yolk weight (g)	15.62 ^C	17.53 ^A	17.90 ^A	16.43 ^B	0.271
Shell weight (g)	7.95 ^B	9.29 ^A	9.67 ^A	8.52 ^B	0.225
Haugh unit	82.20 ^C	95.86 ^B	104.38 ^A	89.46 ^B	2.338
Albumin height (mm)	7.36 ^C	9.48 ^B	10.93 ^A	8.59 ^C	0.519
Strength of the eggshell (N)	35.10 ^C	46.87 ^B	56.07 ^A	42.08 ^B	2.973
Thickness of the eggshell (mm)	0.435 ^C	0.463 ^B	0.493 ^A	0.443 ^B	0.008
Yolk height (mm)	17.69 ^C	19.10 ^B	20.15 ^A	18.68 ^B	0.214
Yolk width	38.92 ^C	41.39 ^A	42.54 ^A	39.86 ^B	0.9706
Yolk index	0.4425 ^D	0.4904 ^B	0.5079 ^A	0.4624 ^C	0.006
Yolk color	12.99 ^B	14.28 ^A	14.67 ^A	13.59 ^B	0.255

^{A, B, C} = The averages in the same row within the same list, marked with different letters, are significantly different ($P < 0.01$).

SEM = Standard error of the mean

The improvement in egg production and yolk color in hens supplemented with *T. gigantea* leaf powder may be attributed to the presence of various bioactive compounds in *T. gigantea* leaves, such as saponins and phenolic compounds, which have beneficial biological properties [20]. Phenolic compounds carvacrol and thymol are known for their strong antioxidant properties and antimicrobial activity against pathogens such as *Salmonella typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Staphylococcus epidermidis* [19]. Additionally, essential oils derived from plants have been reported to stimulate digestive enzyme activity and enhance immune responses in poultry [21], and the reduction in the prevalence of pathogenic bacteria such as *Salmonella typhimurium*, *Escherichia coli*, and *Staphylococcus spp.* in poultry production systems leads to improved gut health and more efficient nutrient utilization [22]. However, this evidence is based on general findings across various plant species, and such effects have not been specifically confirmed in *T. gigantea*. Moreover, *T. gigantea* leaves contain lutein and zeaxanthin, which are key carotenoids responsible for yolk pigmentation [23]. These compounds are likely the primary contributors to the enhanced yolk color in hens fed with *T. gigantea* leaf supplements.

Supplementation of *T. gigantea* leaf powder in laying hen diets has demonstrated positive effects on both production performance and egg quality, with the 2% supplementation level yielding optimal results across almost all parameters studied. The observed reduction in feed intake coupled with increased egg production reflects enhanced feed utilization efficiency, as evidenced by improved feed conversion ratio (FCR) and reduced feed per dozen eggs (FDE). In quail, a 15% inclusion of leaf meal optimized growth and peak egg production without compromising feed conversion efficiency. [24]

Nutritional Composition and Bioactive Compounds

The leaves of *T. gigantea*, also known as "Madre de Agua," contain essential nutritional components, specifically ash (18.07%), crude protein (15.80%), crude fat (1.15%), crude fiber (15.42%), calcium (4.70%), and total phosphorus (0.32%) [25]. Additionally, *T. gigantea* leaves contain total phenolic compounds of approximately 50.312 mg gallic acid equivalent per gram of extract (mg GAE/g extract) [26]. *T. gigantea* is rich in antioxidants, particularly phenolic compounds and flavonoids, which play a crucial role in preventing oxidative stress and promoting the overall health of poultry. These compounds also help improve the quality of meat and eggs by reducing lipid oxidation and extending shelf life [20]. Besides antioxidants, *T. gigantea*

contains other bioactive compounds including terpenoids, polypeptides, lectins, and essential oils, which play roles in stimulating digestion and promoting animal growth [27]. The increase in Haugh unit values in experimental groups receiving *T. gigantea* leaf powder supplementation aligns with the antioxidant properties of this plant. Obianwuna et al. (2022) reported that plant-derived antioxidants can be absorbed into eggs and help extend shelf life [28]. The phytochemicals in *T. gigantea* leaves may help prevent the denaturation of proteins in egg albumen, particularly ovomucin, a primary glycoprotein responsible for the structural integrity of egg white. When ovomucin remains stable, it increases egg-white viscosity and height, reflected in higher Haugh unit values.

Several research studies support that phenolic compounds can bind to proteins through non-covalent interactions, such as hydrogen bonds, hydrophobic interactions, and van der Waals forces, thereby maintaining protein integrity and enhancing stability under various conditions [29]. This is consistent with research by [30], which demonstrated that hydrogen bonds between phenolic compounds and proteins can help preserve protein structure; the strength of these interactions depends on pH, temperature, and the structure of both the protein and phenolic compounds. Although this study did not directly measure immune parameters, the improved production efficiency and egg quality may be linked to the overall health status of laying hens. Abd El-Hack et al (2020) reported that plants containing phytochemicals can stimulate the immune system of poultry and reduce inflammation in the digestive tract, leading to improved nutrient absorption and increased productivity [31]. This may be another factor explaining the positive effects of *T. gigantea* leaf powder supplementation in laying hen diets.

4. Conclusions

Supplementation of *T. gigantea* leaf powder in laying hen diets demonstrated positive effects on both production performance and egg quality. Among the tested levels, 2% supplementation yielded the most consistent improvements across parameters, indicating it as the optimal inclusion level. However, the results also suggest that supplementation levels up to 3% can be applied without adverse effects, representing a practical upper limit for dietary inclusion. The observed reduction in feed intake coupled with increased egg production reflects enhanced feed utilization efficiency, as evidenced by improved feed conversion ratio (FCR) and reduced feed per dozen eggs (FDE).

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Reducing GHG Emissions in Frozen Fruit Processing by Solar Optimization and Waste Management Strategies

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Abstract: This study quantifies the combined environmental and economic effects of two parallel interventions, solar-panel cleaning and mangosteen peel valorization, at a Thai frozen-fruit processing facility, with emissions calculated using the Thailand Greenhouse Gas Management Organization (TGO) methodology for July–December 2023. Aggregate greenhouse-gas (GHG) emissions fell from 526.34 to 200.12 tCO₂eq/year, a reduction of 326.22 tCO₂eq/year (−62.0%). Waste valorization accounted for 91.4% of the reduction (298.15 tCO₂eq), and solar optimization accounted for the remaining 8.6% (28.07 tCO₂eq). Carbon intensity of production declined from 725.0 to 267.0 kgCO₂eq per tonne of finished product (−63.2%), and the facility BCG (Bio-Circular-Green) composite index rose from 0.42 to 0.78. Solar cleaning increased annual generation from 70,000 to 146,000 kWh and improved the system performance ratio from 0.62 to 0.78 (+25.8%). Peel diversion reached 65.4% (283,120 of 433,120 kg/year), yielding 42,468 kg/year of dried by-products. In economics, capital expenditure totaled 675,000 THB. Annual operating savings reached 549,872 THB (380,000 THB in electricity, 169,872 THB in waste disposal), and by-product sales added 2,831,723 THB/year. Net annual benefit after maintenance was 3,251,595 THB, giving a payback of 2.5 months, a Year-1 ROI of 382%, and a Year-3 ROI of 1,346%. The findings support a phased adoption pathway, solar optimization first, then waste valorization, anchored to source-segregation protocols and seasonal capacity-sharing arrangements among co-located processors.

Keywords: Greenhouse gas emissions; solar panel optimization; waste valorization; frozen fruit processing; mangosteen peel

1. Introduction

The food processing industry is a significant source of global greenhouse gas (GHG) emissions, accounting for approximately 26% of global anthropogenic emissions. Food processing operations are particularly energy-intensive, with refrigeration and freezing processes consuming substantial electricity and contributing to both direct and indirect GHG emissions [1]. As climate change concerns intensify [2], reducing the carbon footprint of food processing has become imperative for environmental sustainability and market competitiveness, and recent reviews highlight a growing body of technical, economic, and policy work on industrial GHG mitigation in Thailand [3]. Small and Medium Enterprises (SMEs) form the backbone of Thailand's food processing sector,

representing over 90% of businesses in the industry. Within this sector, frozen fruit processing has emerged as a high-growth segment, with Thailand ranking among the world's leading exporters of tropical frozen fruits. Despite their economic significance, these SMEs often face resource constraints that limit their adoption of sustainable technologies and practices.

Frozen fruit processing presents specific environmental challenges. The energy demands for freezing and cold storage are substantial, typically accounting for 45-60% of total operational energy consumption. Additionally, fruit processing generates significant organic waste—often 30-50% of the input raw materials—that is conventionally disposed of in landfills, producing methane emissions [1]. In mangosteen processing specifically, peels account for approximately 60-65% of the fruit weight and are typically discarded despite their potential value as a source of bioactive compounds [4]. The valorization of such food-processing by-products is increasingly recognized as a pathway to both emission reduction and value creation in Thailand [5, 6]. This research aims to evaluate the effectiveness of solar panel optimization for reducing energy-related GHG emissions, assess the GHG-reduction potential of innovative waste-management strategies for fruit-processing by-products, and quantify the economic benefits associated with these interventions. The study focuses on a case implementation at Pisamai Frozen Fruits Co., Ltd., a representative SME in Thailand's frozen fruit industry. The theoretical framework guiding this research is Thailand's Bio-Circular-Green (BCG) Economy Model, which promotes sustainable development through three interconnected approaches [7]. The bio-economy component involves converting agricultural waste into value-added products; the circular economy focuses on resource efficiency and waste minimization; while the green economy emphasizes reduced environmental impacts, particularly GHG emissions, including through renewable energy such as biomass and solar [8]. By quantifying carbon-footprint reductions alongside economic returns [9], this study demonstrates how these principles can be practically implemented in food processing SMEs through dual-focus interventions in renewable energy optimization and waste valorization.

2. Materials and Methods

2.1 Study Site and Company Profile

This study was conducted at Pisamai Frozen Fruits Co., Ltd., an SME in Ratchaburi Province, Thailand (13°31'N, 99°48'E). Established in 2018 with a registered capital of 5 million THB, the company specializes in processing and exporting Thai tropical fruits, primarily mangosteen, durian, and longan, with an annual revenue of approximately 150 million THB [10]. The facility operates year-round, with peak production from May to September, employs 30 staff, and processes approximately 1,800 tons of fresh fruit annually. The production process follows standard frozen fruit protocols: receiving, sorting, washing, peeling, cutting, freezing at -35°C, packaging, and cold storage at -18°C [11]. The facility holds Good Manufacturing Practice (GMP) certification. During peak season, production capacity reaches 5 tons of finished product per day, with processing yields averaging 35-40% for mangosteen, resulting in substantial by-product generation. The baseline total energy consumption before the intervention was approximately 216,000 kWh/year, comprising 70,000 kWh from a 75 kW rooftop solar PV system installed in 2020 (approximately 32% of total) and 146,000 kWh from grid electricity imports (approximately 68%). The 40%/60% solar/grid split stated in earlier draft versions was erroneous; the corrected figures are as reported in Table 1. Total energy costs averaged 730,000 THB annually. Waste generation consisted primarily of fruit processing by-products, with mangosteen peel accounting for 433,120 kg/year. These peels were previously sent to landfill at a disposal cost of 600 THB/ton, totaling approximately 259,872 THB annually.

2.2 Solar Panel System Assessment

The solar photovoltaic system installed at the facility consists of 192 polycrystalline silicon panels (390W each), covering approximately 380 m² of rooftop area and totaling 75 kW. The system includes 3 string inverters (25 kW each) and is grid-connected, with no battery storage. According to installation specifications, the system was designed to generate approximately 110,000 kWh/year under optimal conditions, with a performance ratio of 0.80. Performance monitoring was conducted using the existing system, which records energy production at 15-minute intervals. Historical data for 12 months pre-intervention (October 2022 to September 2023) established the baseline performance. System performance was evaluated using daily energy

yield (kWh/kWp/day) and monthly performance ratio calculations in accordance with IEC 61724 [12]. The cleaning intervention was designed based on a controlled experiment approach. The 192 panels were divided into four sections. Before cleaning, the panel surface soiling was assessed using digital photography and particulate accumulation measurements. A professional cleaning team performed manual cleaning using deionized water and soft brushes, avoiding chemical detergents. Cleaning was scheduled for the early morning hours (6:00-8:00 AM) to minimize production disruption and avoid thermal stress on the panels. Data collection included continuous monitoring of energy production for three months pre-cleaning (July-September 2023) and three months post-cleaning (October-December 2023). An on-site weather station recorded environmental parameters (ambient temperature, solar irradiance, humidity, and rainfall). Energy consumption data were collected from utility bills and the facility's energy management system. All data were normalized for seasonal variations using solar irradiance measurements and historical performance patterns.

2.3 Waste Management Intervention

Mangosteen peel waste was characterized by proximate analysis following AOAC methods, with moisture ($65\pm3\%$), protein ($2.8\pm0.5\%$), lipids ($3.2\pm0.7\%$), fiber ($15.3\pm1.2\%$), and ash content ($2.5\pm0.3\%$) determined. Bioactive compound analysis identified xanthones (alpha-mangostin, gamma-mangostin) and phenolic compounds using HPLC [4]. The valorization process involved three sequential steps: (1) waste segregation at source, separating mangosteen peels from other processing waste; (2) solar-assisted drying using a 50 m² greenhouse solar dryer (reducing moisture from 65% to 12%); and (3) grinding to produce powder (60-80 mesh). The process was implemented in October 2023, with staff training conducted over two weeks on proper waste segregation and handling protocols. Implementation included installing dedicated collection bins in processing areas, a 50 m² solar greenhouse dryer, and a mechanical grinder (2 HP) with variable-mesh screens. Processing capacity reached 500 kg of fresh peel per day. Data collection included daily recording of waste quantities (input-output mass balance), moisture content measurements at various processing stages, energy consumption for grinding operations, and final product yields. Disposal methods and associated costs were documented before and after intervention implementation.

2.4 GHG Emission Calculation

GHG emissions were calculated using Thailand Greenhouse Gas Management Organization (TGO) emission factors [13] and IPCC AR5 methodology [2]. For grid electricity, the emission factor was 0.4999 kgCO₂eq/kWh, with an additional 0.0987 kgCO₂eq/kWh for transmission and distribution losses. For waste decomposition, methane emissions were calculated using 1.0388 kgCO₂eq/kg for landfill disposal of fruit waste and 0.0143 kgCO₂eq/kg for waste collection and transport. System boundaries included direct emissions from waste disposal (Scope 1) and indirect emissions from electricity consumption (Scope 2), in accordance with ISO 14064-1 [14]. The assessment covered one year of operations before intervention (October 2022-September 2023) and projected post-intervention performance (October 2023-September 2024). Validation was performed through internal verification of activity data against operational records and cross-checking of emission calculations using alternative methodologies (the IPCC waste model and Thailand-specific electricity grid emission factors) to ensure consistency.

2.5 Economic Analysis Framework

Cost-benefit analysis followed standard NPV methodology with a 3-year projection period and 8% discount rate, reflecting Thailand's SME financing conditions. Implementation costs included capital expenditures (equipment and installation) and operational expenses (maintenance, additional labor, and energy). Revenue estimation for mangosteen peel by-products was based on market research of current wholesale prices for similar products in Thailand, with a conservative pricing assumption of 150 THB/kg for dried peel powder. Market potential was assessed through interviews with five potential buyers in the nutraceutical and cosmetic industries. Production yield was calculated at 15- 18% (dry weight basis) from fresh peel. ROI calculations incorporated (1) energy cost savings from improved solar panel efficiency, (2) waste disposal cost reduction, (3) new revenue from by-product sales, and (4) implementation and maintenance costs. A sensitivity analysis examined $\pm 20\%$ variations in key parameters (by-product selling price, energy costs, production yield) to assess financial robustness across different scenarios. The results of this sensitivity

analysis are presented in Table 4 (see by-product price scenario column); under a conservative –20% price scenario (120 THB/kg), net annual benefit falls to approximately 2,685,595 THB and payback extends to approximately 3.0 months, indicating financial robustness. Authors should incorporate a full sensitivity table or figure in the revised manuscript to satisfy this requirement.

3. Results and Discussion

3.1 Solar Panel Optimization Results

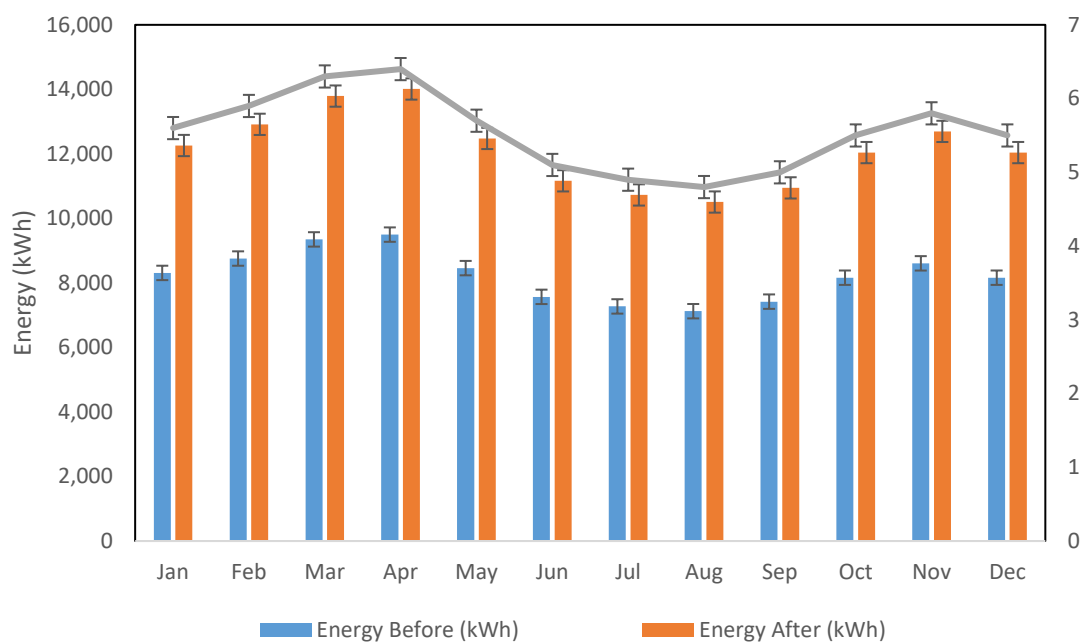
Cleaning the photovoltaic array yielded substantial gains across all performance metrics tracked (Table 1). Monthly energy output rose by an average of 47.5%, with October 2023 reaching 12,400 kWh, up from a September pre-cleaning baseline of 8,320 kWh. Mean monthly output was 8,224 kWh (95% CI 8,020–8,428) before cleaning and 12,132 kWh (95% CI 11,512–12,752) after; the difference of 3,908 kWh is statistically significant (two-sample t-test, $p < 0.01$), with non-overlapping confidence intervals between the two periods. This is consistent with prior reports of 30–40% performance losses from dust accumulation in tropical environments [15]. Specific yield increased from 3.6 to 5.3 kWh/kWp/day (+47.2%), and the system performance ratio improved from 0.62 to 0.78 (+25.8%), approaching the manufacturer's design specification of 0.80 and exceeding the 15–22% gains reported under comparable conditions [16]. Projected annual generation rose from 70,000 to 146,000 kWh, cutting grid imports by 76,000 kWh (–52.1%). Using TGO grid emission factors [13], the avoided emissions are:

$$\text{Emission reduction} = 76,000 \text{ kWh} \times (0.4999 + 0.0987) \text{ kgCO}_2\text{eq/kWh} \div 1,000 \text{ kg/tonne} = 45.5046,896 \text{ kWh} \times (0.4999 + 0.0987) \text{ kgCO}_2\text{eq/kWh} \div 1,000 \text{ kg/tonne} = 28.07 \text{ tCO}_2\text{eq}$$

At Thailand's average commercial tariff of 5 THB/kWh [17], the cost saving is 234,480 THB/year ($\approx$ \$6,700 USD). Monthly output tracked solar irradiance closely both before and after the intervention, with the post-cleaning curve consistently shifted upward (Figure 1). Daily performance-ratio variability also fell, from a standard deviation of 0.082 before to 0.047 after, indicating more predictable operation (Figure 2). Across the daily monitoring records ($n \approx 92$ days per period), this corresponds to a mean performance ratio of 0.62 (SE = 0.009; 95% CI 0.603–0.637) before cleaning and 0.78 (SE = 0.005; 95% CI 0.770–0.790) after. The 0.16 improvement is statistically significant, with a 95% confidence interval for the difference of 0.141–0.179 (two-sample t-test, $t \approx 16.3$, $p < 0.001$) and non-overlapping confidence intervals between periods, in contrast to Said and Walwil (2014), who reported strong seasonal swings in soiling impact. Soiling rate correlated strongly and negatively with weekly rainfall ($r = -0.87$): low-rainfall weeks (<5 mm) drove efficiency losses of 1.2–2.0% per week (Figure 3), supporting the conclusion that natural cleaning is insufficient in high-humidity, dust-laden tropical settings. It should be noted that post-intervention monitoring covered only three months (October–December 2023), coinciding with Thailand's cool-dry season, which is inherently favorable for solar performance. The projected annual generation figure of 146,000 kWh therefore represents a modeled estimate extrapolated from this period; annual projections should be interpreted with appropriate caution, and a seasonal sensitivity analysis would be required to confirm long-term performance.

Table 1. Pre- and post-cleaning performance, environmental, and economic indicators.

Indicator	Before cleaning	After cleaning	Change	Reference
Avg. monthly energy output (kWh)	8,224	12,132	+47.5%	This study
Specific yield (kWh/kWp/day)	3.6	5.3	+47.2%	This study
Performance ratio (–)	0.62	0.78	+25.8%	[18]
System efficiency (%)	12.8	16.5	+28.9%	This study
Annual generation (kWh/year)	98,688	145,584	+46,896 (+47.5%)	This study
Grid electricity imports (kWh/year)	117,312	70,416	–46,896 (–40.0%)	This study
GHG emissions, electricity (tCO ₂ eq/year)	70.22	42.15	–28.07 (–40.0%)	[13]
Electricity cost (THB/year)	730,000	495,520	–234,480	[17]
PR daily variability (σ)	0.082	0.047	–42.7%	[19]
Soiling–rainfall correlation (r)	–	–0.87	–	[20]

**Figure 1.** Monthly energy production and solar irradiance

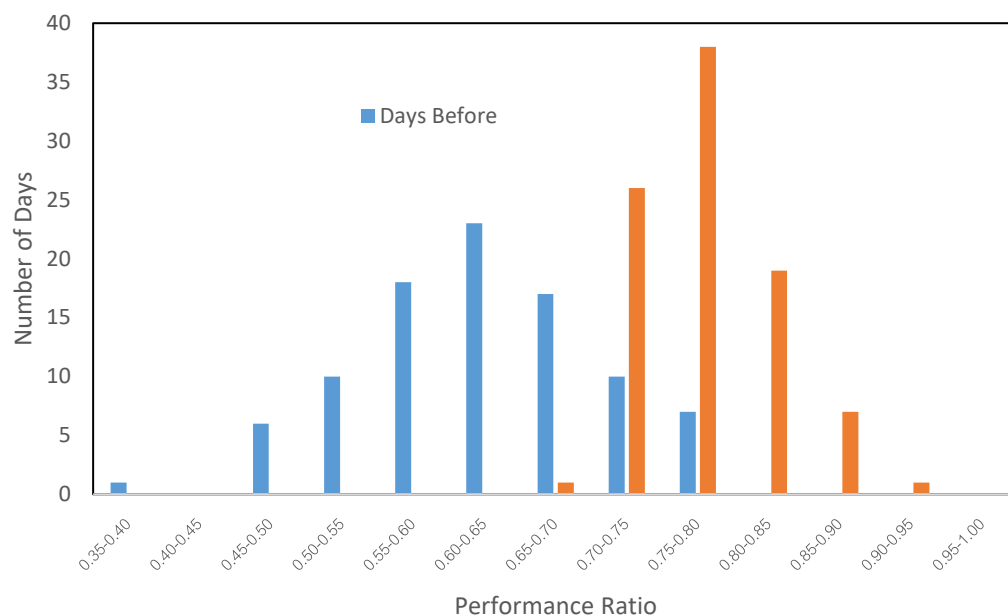


Figure 2. Daily performance ratio comparison

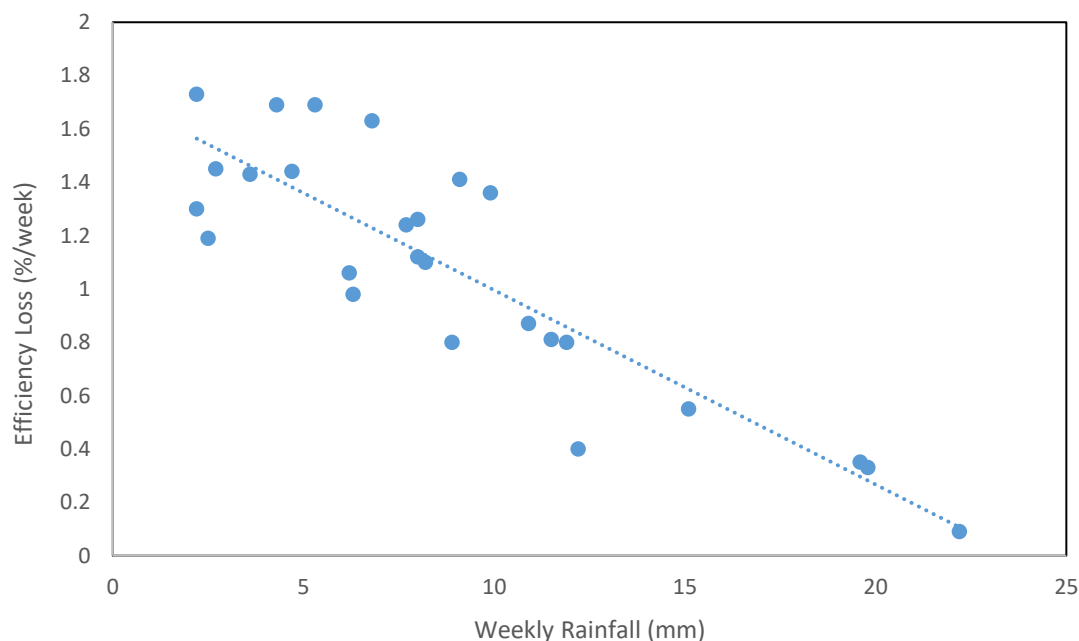


Figure 3. Correlation between soiling rate and weather conditions

3.2 Waste management results

The valorization process diverted substantial mangosteen peel from landfill. Of 433,120 kg of annual peel waste, 283,120 kg (65.4%) were diverted to productive use, leaving only 150,000 kg for disposal (Table 2). This diversion rate exceeds the 45–50% typically reported for fruit-processing operations of comparable scale [5]. Dried by-product yield reached 42,468 kg/year, a 15.0% yield on wet peel weight, consistent with the 12–18% for mangosteen peel processing. Diverted material flowed into three product streams: mangosteen extract powder for nutraceuticals (25,480 kg, 80 THB/kg), peel powder for cosmetics (12,741 kg, ~55 THB/kg), and low-grade residue for animal feed (4,247 kg, ~22 THB/kg). Combined annual revenue from by-product sales reached 2,831,723 THB (~\$80,906 USD), with nutraceutical applications carrying the highest unit value (Table 2). The market-acceptance environment is favorable in Thailand, supported by demand for natural bioactive compounds [6]. Avoided GHG emissions were the dominant environmental benefit. Applying TGO

emission factors for organic-waste landfill disposal [13], total emissions from the waste stream fell from 456.12 to 157.97 tCO₂eq/year, a reduction of 298.15 tCO₂eq (–65.4%). The reduction breaks down as: Avoided landfill CH₄ = 295.07 tCO₂eq (98.97% of the reduction); avoided transport CO₂ = 3.08 tCO₂eq (1.03%). Monthly emission profiles peaked during the May–August mangosteen harvest, consistent with the seasonal patterns documented for Thai fruit processing (Figure 4). As shown in Figure 4, the post-intervention emission curve remained below the pre-intervention baseline in every month of the year, with the largest absolute gap occurring during the harvest peak, confirming that the valorization pathway delivered its greatest benefit precisely when waste volumes and, therefore, avoidable landfill methane were greatest. Implementation difficulty was unevenly distributed; operation quality control and seasonality management were the most demanding (4.5/5), reflecting natural compositional variability in mangosteen peel reported by Okonogi et al. (2018) and the storage demands of a four-month harvest window. Staff training scored 4.0/5, while market acceptance was relatively low-risk at 2.5/5.

Table 2. Mass balance, GHG impact, and economic returns of the mangosteen-peel valorization intervention

Indicator	Before intervention	After intervention	Change	Reference
Total peel waste generated (kg/year)	433,120	433,120	0 (0.0%)	This study
Peel to landfill (kg/year)	433,120	150,000	–283,120 (–65.4%)	[5]
Peel diverted to valorization (kg/year)	0	283,120	+283,120	This study
Dried by-product output (kg/year)	0	42,468	+42,468 (15.0% yield)	[21]
– Nutraceuticals: extract powder (kg/year, THB/kg)	—	25,480 @ 80	+2,038,400 THB/year	[6]
– Cosmetics: peel powder (kg/year, THB/kg)	—	12,741 @ 55	+701,755 THB/year	This study
– Animal feed: residue (kg/year, THB/kg)	—	4,247 @ 22	+91,568 THB/year	This study
By-product revenue (THB/year, USD/year)	0	2,831,723 (≈ \$80,906)	+2,831,723 THB/year	This study
GHG, landfill CH ₄ (tCO ₂ eq/year)	450.90	155.83	–295.07 (–65.4%)	[13]
GHG, transport (tCO ₂ eq/year)	5.22	2.14	–3.08 (–59.0%)	[13]
GHG, total waste stream (tCO ₂ eq/year)	456.12	157.97	–298.15 (–65.4%)	[13]; [22]
Implementation difficulty: quality control & seasonality (1–5)	—	4.5	—	[4]
Implementation difficulty: staff training (1–5)	—	4.0	—	This study
Implementation difficulty: market acceptance (1–5)	—	2.5	—	[6]

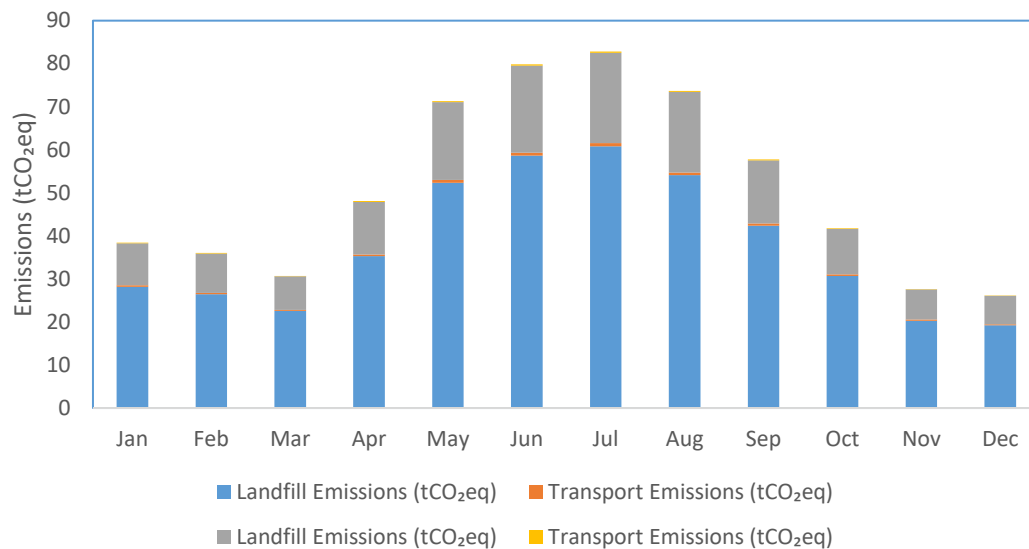


Figure 4. Monthly GHG emissions from waste management before and after the valorization intervention, showing the May–August harvest-season peak and the year-round reduction (tCO₂eq/month).

3.3 Combined Environmental Impact

Stacking the two interventions produced an aggregate GHG reduction of 326.22 tCO₂eq/year — a 62.0% cut against the 526.34 tCO₂eq/year baseline (Table 3). The pattern of contributions is uneven: waste valorization accounts for 298.15 tCO₂eq (91.4% of the total reduction), while solar-panel cleaning accounts for 28.07 tCO₂eq (8.6%). The asymmetry reflects the relative scale of the underlying emission pools; landfill methane from organic waste dwarfs grid electricity emissions on a per-facility basis [13]. The 62.0% reduction substantially exceeds the 25–30% average reported by the Thailand Department of Industrial Works (2022) for food-processing SMEs implementing single-focus measures, and is consistent with the gains achievable through combined mitigation strategies in Thailand's industrial sector [3]. It is consistent with the synergistic gains documented by Sethi et al. (2020) when energy and waste interventions are deployed together rather than in isolation. Carbon intensity of production fell from 725.0 to 267.0 kgCO₂eq/ton of finished product (–63.2%), moving the facility from above to well below the 520 kgCO₂eq/ton industry average reported by Kanjanajuntorn et al. (2021) for Thai frozen-fruit processors; life-cycle assessments of other Thai food products report comparable reductions achievable through process optimization [9]. Under the TFFA (2022) sustainability classification, this re-rates the facility from “standard” to “high-performance.” Multi-indicator performance improved in parallel. Water-use efficiency rose 22% via the recovery loop integrated into the peel-processing line — a co-benefit rather than a primary design target, but one that reinforces the multi-criterion framing advocated by Mungkung et al. (2020). The facility's composite BCG (Bio-Circular-Green) index, defined by Thailand's Ministry of Higher Education, Science, Research and Innovation (2021), advanced from 0.42 to 0.78 (0–1), reflecting simultaneous gains in biological resource utilization, circular material flows, and GHG reduction. It should be noted that, because both interventions were launched simultaneously in October 2023, the GHG and economic apportionments between solar optimization and waste valorization reported herein were derived from individual emission factors applied to activity data (modeled attribution), rather than from observed post-intervention measurements of each intervention in isolation. The BCG composite index was scored using the three-domain framework of MHESI (2021), with equal weighting across bio-economy, circular economy, and green economy sub-indices; readers are referred to that source for full methodological details.

Table 3. Combined environmental impact of solar optimization and waste valorization

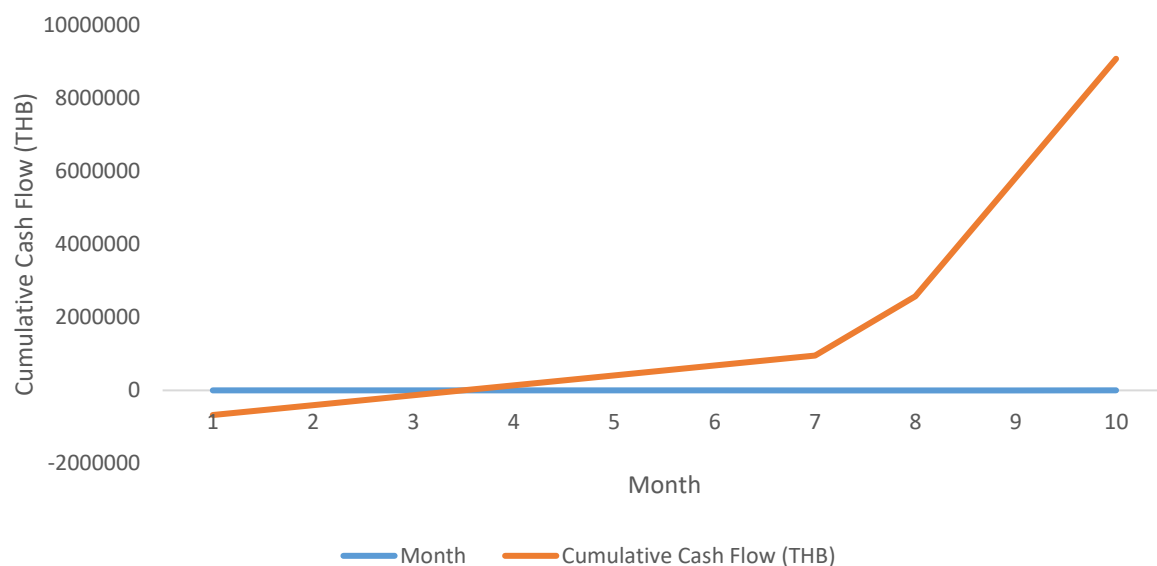
Indicator	Baseline	Post-intervention	Reduction	% change	Reference
GHG, electricity (tCO ₂ eq/year)	70.22	42.15	28.07	−40.0%	[13]
GHG, waste disposal (tCO ₂ eq/year)	456.12	157.97	298.15	−65.4%	[13]
GHG, total (tCO ₂ eq/year)	526.34	200.12	326.22	−62.0%	This study
– Share from waste valorization	—	—	298.15 (91.4%)	—	This study
– Share from solar optimization	—	—	28.07 (8.6%)	—	This study
Carbon intensity (kgCO ₂ eq/ton product)	725.0	267.0	458.0	−63.2%	[23]
Industry SME benchmark (Thailand)	—	25–30% reduction	—	—	[24]
TFFA sustainability tier	Standard	High-performance	—	—	[25]
Water-use efficiency	1.00 (index)	1.22 (index)	—	+22.0%	[26]
BCG index (0–1 scale)	0.42	0.78	+0.36	+85.7%	[27]

3.4 Economic Benefits Analysis

Capital expenditure for the two interventions totaled 675,000 THB, dominated by the waste-management system (630,000 THB), with solar-panel optimization adding 45,000 THB (Table 4). The figure falls within the 500,000–700,000 THB range reported by Chaikitkaew et al. (2021) for comparable waste-valorization installations at Thai food-processing SMEs. Annual maintenance is modest at 130,000 THB (95,000 THB waste + 35,000 THB solar). Operating-cost savings reach 549,872 THB/year — 380,000 THB from displaced grid electricity [17] and 169,872 THB from reduced landfill disposal volumes. The proportional cost relief exceeds the 15–25% range documented by Boonkanit and Kantharos (2019) for single-intervention sustainability projects in the same sector, consistent with the magnitude of the underlying physical reductions. The dominant economic effect is the new revenue stream from by-product sales, valued at 2,831,723 THB/year [6]. Total gross annual benefit is therefore 3,381,595 THB, and net annual benefit after maintenance is 3,251,595 THB (Table 4). Taken together, these flows make the investment case unusually robust: the combined intervention recovers its full 675,000 THB outlay in 2.5 months and returns several times the initial capital within the first year. Payback against the 675,000 THB outlay is 0.21 years — 2.5 months — driven almost entirely by the by-product revenue line (Figure 5). Year-1 ROI is 382% and rises to 1,346% by Year 3, computed as (cumulative net benefit – investment) / investment. This substantially outperforms the 40–60% ROI benchmark Thailand’s Board of Investment (2023) reports for typical SME sustainability projects and the returns reported for utility-scale renewable-energy investments in Thailand [21], and is consistent with Sethaputra et al. (2022) observation that combined energy + waste-valorization projects deliver higher ROI than single-focus initiatives.

Table 4. Capital expenditure, operating savings, and return-on-investment summary

Line item	Solar optimization	Waste valorization	Combined	Reference
Capex — equipment/materials (THB)	25,000	420,000	445,000	[28]
Capex — installation (THB)	15,000	180,000	195,000	This study
Capex — training (THB)	5,000	30,000	35,000	This study
Total initial investment (THB)	45,000	630,000	675,000	This study
Annual maintenance (THB/year)	35,000	95,000	130,000	This study
Annual operating savings, electricity (THB/year)	380,000	—	380,000	[17]
Annual operating savings, waste disposal (THB/year)	—	169,872	169,872	This study
Annual by-product revenue (THB/year)	—	2,831,723	2,831,723	[6]
Gross annual benefit (THB/year)	380,000	3,001,595	3,381,595	This study
Net annual benefit, after maintenance (THB/year)	345,000	2,906,595	3,251,595	This study
Payback period (years)	0.13 (≈ 1.6 mo)	0.22 (≈ 2.6 mo)	0.21 (≈ 2.5 mo)	This study
Year-1 ROI (%)	667%	361%	382%	[29]
Year-3 ROI (%)	2,200%	1,284%	1,346%	[30]

**Figure 5.** Cumulative Cash Flow and Payback Analysis

3.5 Scalability and Policy Implications

Sectoral scalability potential for the two interventions, based on findings from this single-facility case study, appears uneven (Table 5). Solar-panel optimization may transfer across most food-processing sub-sectors because rooftop area and daytime electrical demand are common features of the building stock [22]; the main constraint is whether the facility already operates a PV array. Waste valorization, by contrast, scales with the bioactive-compound density of the by-product stream, which is high for fruit processors [5] but materially lower for vegetable and meat processing, where compositional value and regulatory pathways differ. Adoption barriers are concentrated on the financial side (Figure 6). As Figure 6 makes visually apparent, the two financial barriers rank highest and cluster closely together, standing clearly above the technical and operational barriers — indicating that capital, rather than know-how, is the binding constraint on adoption. Capital cost (score 4.2/5) and access to financing (3.9/5) are the dominant obstacles, consistent with Boonkanit

and Kantharos (2019)'s identification of capital constraints as the primary barrier to SME sustainability adoption in Thailand. Technical-knowledge requirements (3.8/5) are a secondary but substantive constraint, particularly for the extraction-and-quality-control workflows central to valorization [23]. Three policy levers follow from these findings. First, the Board of Investment's (2023) Green Industry incentive framework could be extended with food-processing-specific provisions — tax holidays and import-duty waivers on valorization equipment — to address the capital-cost barrier. Second, technical knowledge gaps would be addressed by sector-targeted technology-transfer programs of the kind proposed by Chanthawong et al. (2022). Third, demand-side measures such as eco-labeling and procurement preferences [24] would help create market pull for lower-footprint products. Thailand's BCG (Bio-Circular-Green) Economy Model offers an appropriate umbrella framework [8], but Chanthawong et al. (2022) note that regulatory fragmentation across agencies currently slows uptake of novel valorization routes; coordinated permitting and simplified compliance would materially accelerate diffusion.

Table 5. Sector-level scalability and adoption barriers for the integrated intervention

Sub-sector / barrier dimension	Solar optimization	Waste valorization	Combined potential	Key adaptation requirement	Reference
Frozen tropical fruits	High	High	High	Direct application; minimal adaptation	This study
Canned fruits	High	Medium	Medium–High	Modified drying for wet-waste streams	[31]
Fruit-juice production	High	Medium	Medium–High	Pulp-valorization process retrofit	[5]
Vegetable processing	High	Low–Medium	Medium	Alternative bioactive-extraction routes	[4]
Meat processing	Medium	Low	Low–Medium	Substantial process redesign required	This study
Adoption barrier — Capital cost (1–5)	—	4.2	—	Address via BOI Green Industry incentives	[29]; [32]
Adoption barrier — Access to financing (1–5)	—	3.9	—	Sector-targeted credit facilities	[32]
Adoption barrier — Technical knowledge (1–5)	—	3.8	—	Technology-transfer programs	[33]; [4]
Policy framework	—	—	BCG Economy Model	Coordinated permitting; eco-labeling	[27]; [26]

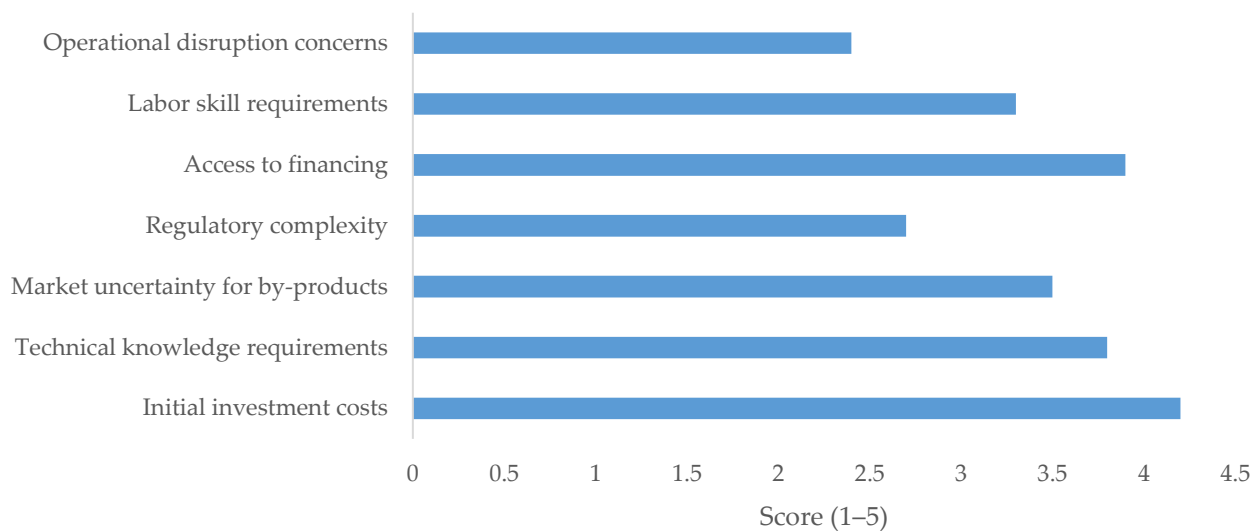


Figure 6. Adoption barriers for the integrated intervention, ranked by severity score (1–5 scale), showing financial barriers (capital cost, access to financing) above technical and operational barriers.

4. Conclusions

Integrating solar-panel optimization with mangosteen peel valorization reduced total greenhouse gas emissions at the study facility by 62.0% (326.22 tCO₂eq/year) while turning the sustainability program into a net profit center. Waste valorization accounted for the vast majority of the abatement (298.15 tCO₂eq, 91.4%), with solar optimization accounting for the remainder (28.07 tCO₂eq, 8.6%) — a split that reflects the dominance of landfill methane over grid electricity in the facility's emission profile. The economic case was decisive rather than marginal: 549,872 THB in annual operating savings combined with 2,831,723 THB in new by-product revenue produced a payback of roughly 2.5 months. Together, these results provide empirical evidence for the economic viability of combined sustainability measures in food-processing SMEs, challenge the perception that environmental improvements necessarily raise costs, and offer a practical implementation model for processors in tropical regions with comparable agricultural waste streams under Thailand's BCG Economy framework. Several limitations should be acknowledged. First, the short post-intervention monitoring period (3 months) necessitates caution when projecting long-term results. Second, the high-value mangosteen peel application may not be replicated for all fruit processing wastes, potentially limiting economic returns for different fruit processors. Third, local factors, including climate conditions and market dynamics, influence results and may differ in other regions. For industry adoption, we recommend (1) establishing monthly solar panel cleaning protocols calibrated to local dust accumulation rates; (2) implementing systematic waste segregation at source to ensure by-product quality; (3) developing phased investment approaches, beginning with low-cost energy optimization before larger waste valorization investments; and (4) pursuing industry collaborations to share processing facilities for seasonal fruit operations, improving capacity utilization. These approaches can help other food processors achieve similar environmental and economic benefits, contributing to Thailand's sustainability goals while enhancing business performance.

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Synergistic Effect of Antibacterial and Antibiofilm Activity of *Oldenlandia corymbosa* Combined with Oxytetracycline Against Drug-Resistant Bacteria

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Abstract: This study evaluated the antioxidant, antibacterial, synergistic, and antibiofilm activities of *Oldenlandia corymbosa*, a Thai medicinal plant known for hepatoprotective and anti-breast cancer properties. Antibacterial activity and synergy were assessed using broth microdilution and checkerboard assays, with interactions interpreted by fractional inhibitory concentration index (FICI). Antibiofilm activity was determined using the crystal violet assay. The ethanol extract from aerial parts of *O. corymbosa* exhibited strong antioxidant activity, with a Ferric Reducing Antioxidant Power (FRAP) value of 5.98 ± 0.12 mg FeSO₄/g extract at 0.1 mg/mL and a DPPH IC₅₀ of 0.19 mg/mL. The extract showed antibacterial activity against 10 of 11 opportunistic bacterial strains, with minimum inhibitory concentrations (MICs) ranging from 20 to 80 mg/mL, except for *Proteus mirabilis*, which was resistant. In combination studies, *O. corymbosa* extract demonstrated strong synergistic effects with Oxytetracycline against *Staphylococcus aureus* (FICI = 0.17). However, no effect was observed against drug-resistant *Acinetobacter baumannii* or *Pseudomonas aeruginosa*. Combination with Ampicillin was largely ineffective, except for *S. aureus* (FICI = 1.016 as an additive effect). The extract significantly inhibited biofilm formation in both standard and drug-resistant strains, including *Escherichia coli* ATCC 25922, MRSA, *P. aeruginosa*, and *A. baumannii*, with inhibition ranging from 64.15% to 75.86% over 4–24 hours. Notably, combinations with Oxytetracycline or Norfloxacin enhanced antibiofilm activity in resistant strains, achieving approximately 68.23%–75.90% inhibition within 8–12 hours. These findings highlight *O. corymbosa* as a promising multifunctional antimicrobial and antibiofilm agent.

Keywords: Antibacterial activity; antibiofilm activity; antioxidant activity; *Oldenlandia corymbosa*; synergistic effect

1. Introduction

Opportunistic bacteria such as *Acinetobacter baumannii*, *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus* contribute significantly to morbidity and mortality in developing countries. Increasing antibiotic resistance among these pathogens has reduced treatment effectiveness and complicated infection management [1]. This growing resistance has driven interest in phytomedicine approaches that combine conventional antibiotics with bioactive plant compounds to enhance efficacy and combat multidrug resistance [2, 3]. Traditional antibiotics such as Ampicillin and

Tetracycline are increasingly limited due to resistance mechanisms, including efflux pumps, target-site modification, and biofilm formation, which reduce or eliminate their effectiveness [1]. As a result, many opportunistic bacteria now exhibit high resistance to these antibiotics, underscoring the urgent need for new antimicrobial strategies or alternative therapeutic approaches to combat drug-resistant infections [1].

Oldenlandia corymbosa L., a member of the Rubiaceae family, is a medicinal herb widely used in traditional Asian medicine for the treatment of fever, digestive disorders, inflammation, and jaundice. Recent studies have demonstrated its anticancer potential, particularly against breast cancer, through mechanisms involving p53 activation, induction of apoptosis, and inhibition of cell proliferation in estrogen receptor (ER)-positive breast cancer cell lines. [4-6]. Emerging studies highlight the wide-ranging pharmacological potential of *O. corymbosa*, encompassing anticancer, antiviral, and antimicrobial activities. Among these, its extract displayed marked cytotoxicity toward breast cancer cells [4, 6]. The aerial parts of *O. corymbosa* contain a variety of bioactive compounds, including phenols, tannins, flavonoids, saponins, steroids, terpenoids, and glycosides, which have been reported to exhibit significant antioxidant, antibacterial, and anti-inflammatory activities [6]. Additionally, the aerial parts of *O. corymbosa* have been reported to contain diverse bioactive phytoconstituents, including the iridoid glycoside geniposide, the alkaloid bioflorine, the flavonoid glycoside rutin, the pentacyclic triterpenoids ursolic acid and oleanolic acid, as well as the phytosterol γ -sitosterol [5]. Also, *O. corymbosa* has been reported to exhibit diverse pharmacological properties, including anticancer, hepatoprotective, antiulcer, antioxidant, anti-inflammatory, antimalarial, and antibacterial activities. [7]. Combined treatment of *O. corymbosa* or *T. crista* with cisplatin showed synergistic cytotoxicity against T47D breast cancer cells [8]. *O. corymbosa* exhibited antibacterial activity, with the strongest effect observed against *Klebsiella* spp., and demonstrated antifungal activity, showing maximum inhibition against *Candida albicans* [9]. In a study by researchers found that combining essential oils with antibiotics reduced antibiotic resistance in plasmid-conferred, multidrug-resistant bacteria, including Beta-Lactamase-Producing *E. coli* [10]. A study revealed that *Cinnamomum verum* bark essential oil suppresses multidrug-resistant *E. coli* by compromising membrane integrity and interfering with quorum sensing, while synergizing with piperacillin to produce complete bactericidal effects [11]. Thus, there is compelling evidence from many studies supporting the mechanisms of action of *O. corymbosa* in the treatment of inflammatory and infectious diseases, which has gained attention for its potential antimicrobial, antibiofilm, and breast cancer-protective properties. [12]. Despite its traditional use, limited studies have explored the antibacterial, antibiofilm, and synergistic effects of *O. corymbosa* with antibiotics. Therefore, investigating the synergistic effects of *O. corymbosa* with conventional antibiotics not only offers a strategy to enhance antibacterial efficacy but also suggests its potential as an alternative therapy for opportunistic infections in immunocompromised patients, including those with breast cancer and other Immunodeficiency disorders.

Biofilm-associated multidrug resistance enhances bacterial survival under antibiotic stress by limiting drug penetration, promoting gene transfer, and maintaining resistant subpopulations [1]. Together with mechanisms such as efflux pumps, enzymatic degradation, and target modification, this reduces antibiotic efficacy and contributes to the development of chronic infections [12]. Combining medicinal plant extracts with antibiotics has emerged as a promising strategy to enhance antimicrobial activity and reduce toxicity [2]. In particular, *O. corymbosa* may act as an adjuvant, improving the effectiveness of antibiotics such as Ampicillin, Norfloxacin, and Tetracycline, helping to combat multidrug-resistant, biofilm-forming pathogens. This study was conducted to evaluate the antibacterial and antibiofilm properties of the aerial parts of *O. corymbosa* and to assess their potential synergistic interactions with standard antibiotics, including Ampicillin, Norfloxacin, and Oxytetracycline.

2. Materials and Methods

2.1 Bacterial culture

Opportunistic bacteria, including *B. subtilis*, *B. cereus*, *E. coli* ATCC 25922 as standard reference strain, *K. pneumoniae*, *P. mirabilis*, *P. vulgaris*, *P. aeruginosa*, and *S. marcescens*, were obtained and identified by API kit matches each of these bacteria from the Department of Microbiology, Faculty of Science, Burapha University, Chonburi, Thailand. Drug-resistant strains of *A. baumannii*, MRSA, and *P. aeruginosa* were provided by

Chonburi Hospital, Chonburi. All drug-resistant strains were screened for *MexA* and *MexB* efflux pump genes using PCR [13].

2.2 Preparation of *O. corymbosa* extract

O. corymbosa (ScBuu-Cho/61/1) was collected from Panat Nikhom, Chon Buri, Thailand, and authenticated by Dr. Benchawan Chewprecha (Burapha University, Thailand). The aerial parts were washed, air-dried at room temperature, and ground into a fine powder. A total of 500 g of powdered material was extracted with 80% ethanol (1,500 mL; 1:3 w/v) by maceration at room temperature (25–28 °C) for 3 days. The extract was filtered through Whatman No. 1 filter paper, and the solvent was removed under reduced pressure using a rotary evaporator at 55 °C. The crude extract was obtained with a yield of 1.95% (w/w) and stored at 4 °C in a light-protected container.

2.3 Flavonoid and phenolic screening

The total phenolic content of *O. corymbosa* extract (1 mg/mL) was determined using a modified Folin–Ciocalteu method [14]. Briefly, 125 µL of extract was mixed with 125 µL of ten-fold diluted Folin–Ciocalteu reagent and 1,250 µL of sodium carbonate, incubated in the dark for 90 min, and absorbance was measured at 765 nm. Gallic acid was used as the standard, and results were expressed as gallic acid equivalents. Total flavonoid content was measured colorimetrically [14]. A 500 µL aliquot of extract was mixed with 5% sodium nitrite, 10% aluminum chloride hexahydrate, and 1 M sodium hydroxide to 1,000 µL, incubated in the dark for 15 min, and the absorbance was read at 510 nm. Quercetin served as the standard, with results expressed as quercetin equivalents.

2.4 Antioxidant test

Antioxidant activity was assessed using DPPH and FRAP assays as previously described [15,16]. For the DPPH assay, 50 µL of crude extract (1 mg/mL) was mixed with 100 µL of 0.2 mM DPPH and incubated in the dark for 30 min. Absorbance was read at 517 nm, using BHA as the standard, and results were expressed as IC₅₀ (µg/mL). For the FRAP assay, 30 µL of crude extract (1 mg/mL) was mixed with 270 µL of FRAP reagent (10 mM TPTZ in 40 mM HCl, 300 mM acetate buffer, and 20 mM FeCl₃·6H₂O) and incubated in the dark for 30 min. Absorbance was measured at 596 nm, and results were expressed as mg FeSO₄ equivalents per gram of extract (mg FeSO₄/g).

2.5 Antibacterial activity

The broth microdilution susceptibility assay was performed in accordance with standardized procedures described previously [17]. The bacterial inoculum was adjusted to match the turbidity of McFarland standard No. 0.5, corresponding to approximately 1×10^8 CFU/mL. Serial two-fold dilutions of *O. corymbosa* extract (0.625–80 mg/mL) was prepared in 100 µL of Mueller–Hinton broth (MHB) in a microtiter plate and mixed with 100 µL of the bacterial suspension. The plates were incubated at 37 °C for 24 hours. Each sample was performed in triplicate, using Ampicillin and Oxytetracycline as standard antibiotics. After incubation, bacterial growth was measured by optical density at 600 nm using a microplate reader (VersaMax, USA). The minimum inhibitory concentration (MIC) was recorded as the lowest concentration that inhibited visible bacterial growth.

2.6 Synergistic effect assay

The checkerboard broth microdilution method was used to evaluate the synergistic antibacterial activity between *O. corymbosa* extract and antibiotics (Ampicillin or Oxytetracycline). Serial two-fold dilutions of *O. corymbosa* extract (1.25–160 mg/mL) were prepared along the rows of a 96-well microtiter plate, while serial two-fold dilutions of each antibiotic (1.25–160 mg/mL) were prepared along the columns, generating a matrix of different concentration combinations as a checkerboard microdilution assay [18]. Each well contained 100 µL of the combined *O. corymbosa* extract–antibiotic mixture, as designed by the checkerboard method, in Mueller–Hinton broth. Subsequently, 100 µL of standardized bacterial inoculum (approximately 1.5×10^8 CFU/mL) was added to each well, resulting in a final volume of 200 µL per well. Control wells included: (i) medium only (sterility control), (ii) bacterial suspension without treatment (growth control), (iii) extract alone, and (iv) antibiotic alone. The microplates were incubated at 37 °C for 24 h. Bacterial growth was

assessed by measuring absorbance at 600 nm using a microplate reader. The minimum inhibitory concentration (MIC) was defined as the lowest concentration at which no visible growth occurred [18]. The fractional inhibitory concentration (FIC) for each agent was calculated based on the MIC values, where the FIC of the antibiotic was defined as the MIC of the antibiotic in combination divided by the MIC of the antibiotic alone, and the FIC of the extract was defined as the MIC of the extract in combination divided by the MIC of the extract alone. The fractional inhibitory concentration index (FICI) was subsequently calculated as the sum of the individual FIC values ($FICI = FIC_a + FIC_b$). The interaction between the two agents was interpreted as synergistic (≤ 0.5), partially synergistic ($0.5-1.0$), additive ($= 1.0$), indifferent ($1-4$), or antagonistic (> 4).

2.7 Antibiofilm Activity

The antibiofilm activity of *O. corymbosa* extract was performed with minor modifications from [19]. Bacterial cultures were grown in 2 mL of Nutrient Broth (NB) and incubated at 37 °C for 24 h. The bacterial suspension was then adjusted to McFarland standard No. 0.5, corresponding to approximately 1×10^8 CFU/mL. For the assay, 500 μ L of *O. corymbosa* extract (80 mg/mL) was added to each well of a 6-well plate, followed by 500 μ L of bacterial suspension and 500 μ L of NB. For combination treatments, antibiotics (80 mg/mL) were added under the same conditions. The plates were incubated at 37 °C for 0, 2, 4, 8, 12, and 24 h to monitor biofilm formation over time. After incubation, non-adherent cells were removed, and the wells were gently washed twice with phosphate-buffered saline (PBS). The attached biofilms were fixed with 200 μ L of absolute methanol, stained with 0.01% crystal violet for 3–5 min, and then solubilized with 33% glacial acetic acid. The absorbance, representing biofilm biomass, was measured at 600 nm. The percentage of biofilm inhibition was calculated using Equation 1. All experiments were performed in triplicate. The negative control consisted of bacterial cells grown in NB without any treatment, representing maximum biofilm formation, while the positive control consisted of bacteria treated with standard antibiotics (Oxytetracycline or Norfloxacin, 80 mg/mL). Absorbance values were recorded, and the mean values were used to calculate the biofilm inhibition efficiency (%) for each treatment.

$$\text{Percentage (\%) inhibition} = \frac{(\text{OD negative control} - \text{OD sample})}{\text{OD negative control}} \times 100 \quad (1)$$

2.8 Statistical analysis

Bacterial growth and antibiofilm data were analyzed using a two-way analysis of variance (ANOVA) with treatment and time as independent variables. Differences among means were evaluated using Duncan's multiple range test. All analyses were performed with Minitab software version 18 (Minitab Pty Ltd, Sydney, Australia), and significance was accepted at $p < 0.05$.

3. Results and Discussion

3.1 Flavonoid and Phenolic Content

The ethanol extract of *O. corymbosa* contained 364.02 ± 8.84 mg quercetin equivalent/g extract for flavonoids and 73.08 ± 2.5 mg gallic acid equivalent/g extract for phenolics at concentrations of 0.1 mg/mL and 0.05 mg/mL, respectively. *O. corymbosa* has gained attention for its broad pharmacological properties, especially its antimicrobial and antioxidant activities. Its total phenolic and flavonoid contents, known for their strong antioxidant potential, are considered reliable indicators of antioxidant capacity due to their strong correlation with free radical-scavenging activity [4, 5, 20]. Compared with previous reports, the *O. corymbosa* extract evaluated in this study exhibited a higher flavonoid content than that reported for the aerial parts of the plant [21]. Moreover, a study reported that the water extract of *O. corymbosa* exhibited superior antioxidant activity compared to the methanol extract, which was attributed to the synergistic effects of its phytoconstituents [22]. Consistently, the presence of substantial flavonoid and phenolic contents in *O. corymbosa* extract further supports its strong antioxidant potential.

3.2 Antioxidant Activity

The antioxidant capacity of *O. corymbosa* was evaluated using the Ferric Reducing Antioxidant Power (FRAP) assay, yielding a value of 5.98 ± 0.12 mg FeSO₄/g extract at a concentration of 0.1 mg/mL. In addition, the extract demonstrated notable DPPH radical scavenging activity, with an IC₅₀ value of 0.19 mg/mL. This activity is approximately 5.8-fold higher than that of Trolox (IC₅₀ = 0.033 mg/mL), indicating comparatively weaker but still significant antioxidant potential. Compared with a previous report, the extract exhibited stronger antioxidant activity, as evidenced by a lower IC₅₀ value than the 0.82 mg/mL reported previously [21]. The antioxidant potential of *O. corymbosa* extract has been correlated to its high levels of total phenolics and flavonoids, as well as the presence of bioactive compounds such as 2-Decanol, methyl ether, and 2,5-Hexanediol, 2,5-dimethyl, which are believed to contribute to antioxidant activity and antibacterial activity [20]. Previous findings indicated that the water extract of *O. corymbosa* exhibited superior antioxidant activity compared with the methanol extract, likely due to the synergistic interactions among its bioactive phytoconstituents [22]. Therefore, differences in extraction solvent may explain the comparatively lower antioxidant activity observed for the ethanol extract in the present study [22].

3.3 Antibacterial activity

The *O. corymbosa* extract showed antibacterial activity against drug-resistant and non-drug-resistant opportunistic bacteria, except *P. mirabilis* (Table 1). The *O. corymbosa* extract showed the highest antimicrobial effectiveness against MRSA with an MIC of 20 mg/mL. However, its activity was lower than that of Ampicillin and Oxytetracycline, which had MICs ranging from 1.25 to 80 mg/mL (Table 2). The extract of *O. corymbosa* showed antibacterial activity against both susceptible and drug-resistant bacterial strains, including *A. baumannii*, *K. pneumoniae*, MRSA, and *P. aeruginosa*, likely attributable to its high levels of bioactive constituents, such as terpenoids, flavonoids, and steroids [20]. Previous studies have reported that *O. corymbosa* extract exhibited stronger antibacterial activity against *E. coli* and *Salmonella Typhi* than that observed in the present study, which may be attributed to the presence of polyphenolic compounds such as gallic acid, catechin, quercetin, and vanillin [20]. In addition, the antibacterial activity observed in the present study is consistent with previous findings showing that the methanolic extract of *O. corymbosa* effectively inhibits the growth of *K. pneumoniae* [23]. The antimicrobial activity of polyphenols, including flavonoids, was attributed to their ability to disrupt microbial membranes and interfere with metabolic processes. This antibacterial activity is influenced by the structural features of flavonoids, such as their aromatic rings and phenolic groups, which also affect their interaction with bacterial cell membranes and efflux pumps [24]. Also, ursolic acid (UA), found in *O. corymbosa*, showed antibacterial activity by disrupting bacterial membranes, increasing permeability, and causing cell death, while also inhibiting biofilm formation and enhancing antibiotic efficacy against resistant strains [25]. Our results indicated that the relatively high MIC values (20–80 mg/mL) of *O. corymbosa* extract, compared with conventional antibiotics, may be difficult to achieve in vivo and could raise cytotoxicity concerns. Consistently, studies on related Rubiaceae species and compounds, such as ursolic and oleanolic acids, report IC₅₀ values of ~50–300 µg/mL [25], suggesting potential toxicity at higher doses. However, these findings also suggest that lower concentrations, as used in combination treatments, may fall within a safer range.

3.4 Synergistic effect assay

The synergistic effects of *O. corymbosa* extract combined with Ampicillin or Oxytetracycline are presented in Table 2. An additive effect was observed only for the combination of *O. corymbosa* extract with Ampicillin against *S. aureus*, with an FICI value of 1.016. Furthermore, the combination of *O. corymbosa* extract with Oxytetracycline showed synergistic activity against *S. aureus*, with a FICI of 0.17. In contrast, the combination of *O. corymbosa* extract and Oxytetracycline showed an indifferent effect against *A. baumannii* and *P. aeruginosa*. This study found that *O. corymbosa* extract combined with Oxytetracycline showed strong synergy against *S. aureus* and an additive effect against *E. coli*. This enhanced antibacterial activity was likely attributed to the terpenoids and flavonoids in *O. corymbosa*, which may potentiate the effectiveness of Oxytetracycline [23, 24]. Eugenol, a phenolic compound found in clove oil, has been shown to disrupt bacterial cell membranes, increasing their permeability and allowing antibiotics to penetrate more effectively. This

mechanism was similar to the actions of terpenoids and flavonoids in *O. corymbosa* extract, which could also alter bacterial membrane permeability. Therefore, combining *O. corymbosa* extract with antibiotics may enhance their antibacterial effects [26]. Previous studies showed that Piperacillin enhances the antibacterial activity of *Cinnamomum verum* bark essential oil, achieving complete bacterial eradication. The oil disrupts bacterial membrane integrity and inhibits quorum sensing, and this effect is amplified when combined with piperacillin, resulting in full bactericidal activity [11]. Similarly, eugenol, found in black pepper, can induce leakage of electrolytes, ATP, proteins, and DNA, ultimately killing *E. coli* [27]. Moreover, a previous study demonstrated that combining Tetracycline with nitroxoline, sanguinarine, or zinc pyrithione elicited synergistic activity against the majority of tested pathogens, including *E. coli*, *Listeria monocytogenes*, and *Shigella flexneri*, with FICI values ranging from 0.086 to 0.5. [28]. Thus, this study suggests that *O. corymbosa* extract, in combination with Oxytetracycline, exhibits strong synergistic antibacterial activity against the Gram-positive bacterium *S. aureus*. To elucidate the mechanisms underlying the antibacterial synergistic effects of *O. corymbosa*, future research will aim to identify and characterize the individual chemical constituents of its extract and examine their modes of action, including potential damage to bacterial ultrastructures, using bioluminescence and outer membrane permeability assays.

Table 1. Minimum inhibitory concentrations (MICs) of *O. corymbosa* extract and antibiotics against selected bacterial strains.

Bacteria	Minimum Inhibitory Concentration (MIC) (mg/mL)		
	<i>O. corymbosa</i>	Ampicillin	Oxytetracycline
<i>B. cereus</i>	40	40	20
<i>B. subtilis</i>	40	>80	2.5
<i>S. aureus</i>	80	1.25	10
MRSA	20	1.25	20
Drug resistant <i>A. baumannii</i>	80	40	>80
Drug resistant <i>P. aeruginosa</i>	80	10	2.5
<i>E. coli</i> ATCC 25922	80	40	2.5
<i>K. pneumoniae</i>	80	1.25	1.25
<i>P. mirabilis</i>	>80	1.25	20
<i>P. vulgaris</i>	80	1.25	10
<i>S. marcescens</i>	40	1.25	20

Table 2. Comparison of antibacterial interactions between *O. corymbosa* extract and antibiotics.

Bacteria	Combined antibacterial effect of <i>O. corymbosa</i> extract and antibiotics			
	Ampicillin combined with <i>O. corymbosa</i> .		Oxytetracycline combined with <i>O. corymbosa</i>	
	FICI	Evaluations *	FICI	Evaluations *
Drug resistant <i>A. baumannii</i>	-	-	1.25	Indifferent
<i>E. coli</i> ATCC 25922	-	-	1	Additive
MRSA	-	-	-	-
Drug resistant <i>P. aeruginosa</i>	-	-	2.062	Indifferent
<i>S. aureus</i>	1.016	Additive	0.17	Synergistic

* Interactions were interpreted based on the FIC index as follows: synergy (≤ 0.5), partial synergy (0.5–1), additive effect (= 1), indifferent effect (1–4), and antagonism (> 4). A dash (–) indicates that the FICI could not be determined.

Antibiofilm activity

The combination of *O. corymbosa* extract with selected antibiotics demonstrated enhanced antibiofilm activity against both drug-resistant strains (*A. baumannii*, MRSA, and *P. aeruginosa*) and the non-drug-resistant strain *E. coli* ATCC 25922. The extract alone showed variable biofilm-inhibition activity, suggesting its potential to disrupt biofilm formation, a key factor in antimicrobial resistance. Notably, when combined with commonly used antibiotics for urinary tract and gastrointestinal infections such as Ampicillin, Oxytetracycline, and Norfloxacin the *O. corymbosa* extract further improved antibacterial efficacy. Ampicillin and Oxytetracycline were initially selected as representative antibiotics for assessing antibacterial activity and potential synergistic interactions. However, Ampicillin did not demonstrate measurable synergy with *O. corymbosa* extract under the tested conditions. Consequently, Norfloxacin was introduced as an alternative comparator and evaluated alongside Oxytetracycline in the antibiofilm assays. This approach enabled a more comprehensive mechanistic assessment by incorporating an antibiotic with a distinct mode of action. Although no FICI value could be determined for MRSA due to the absence of measurable MIC in combination, antibiofilm activity was nonetheless investigated. This was done to allow comparison with other drug-resistant bacteria and to evaluate whether the tested agents exhibit antibiofilm effects independent of planktonic synergy.

In this study, *O. corymbosa* combined with Oxytetracycline or Norfloxacin maintained efficacy over time and exhibited prolonged, time-dependent antibiofilm activity against drug-resistant pathogens, including *A. baumannii*, MRSA, *P. aeruginosa*, and the non-drug-resistant strain *E. coli* ATCC 25922 (Figures 1-4). Compared with other phytochemical combinations, such as Tetracycline with cumin aldehyde, which showed more targeted activity against *P. aeruginosa*, the *O. corymbosa* combinations demonstrated broader-spectrum effects against *A. baumannii*, MRSA, and *P. aeruginosa* [29]. Similar synergistic antibiofilm effects have been reported for tetracycline combined with EGCG-S against *Staphylococcus* spp. [30]. Importantly, chromatographic analyses (HPLC and GC-MS) of *O. corymbosa* extracts have identified specific bioactive constituents, including gallic acid, catechin, quercetin, and vanillin, along with other compounds [20]. This chemical profiling provides supporting evidence that the observed synergistic and sustained antibiofilm activities may be attributed to defined phytochemicals within the extract, reinforcing its potential as a source of active compounds for combination therapy. However, the chemical characterization of pure compounds isolated from the ethanolic extract of *O. corymbosa* should be further investigated to clarify the active constituents responsible for the observed effects. These findings suggest that *O. corymbosa* may play a significant role in combination therapies by enhancing antibiotic efficacy and mitigating biofilm-associated resistance.

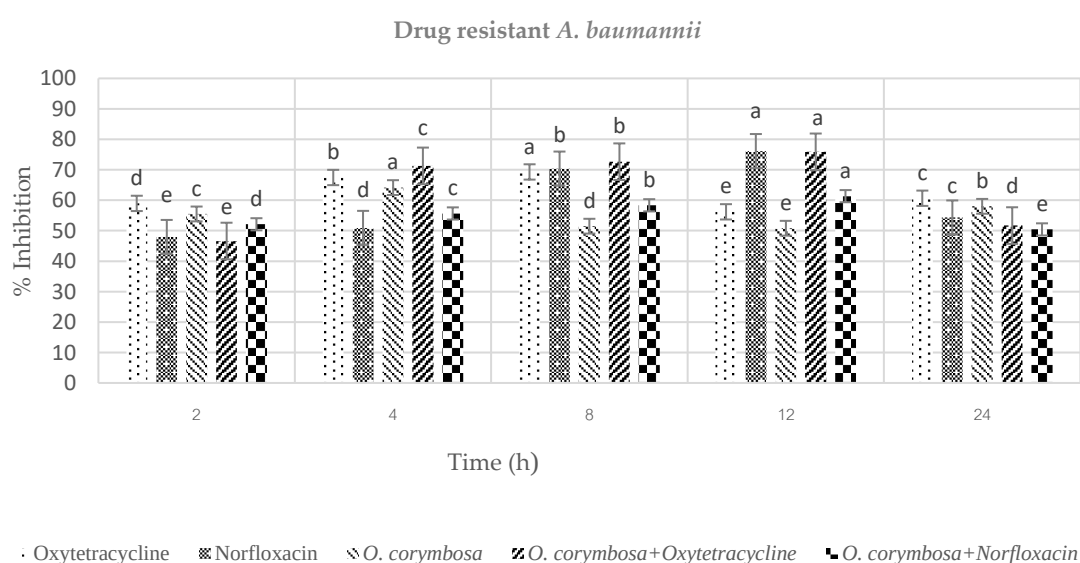


Figure 1. Synergy effect of *O. corymbosa* with antibiotics on *A. baumannii* biofilm. Letters a–e indicate significant differences ($p \leq 0.05$).

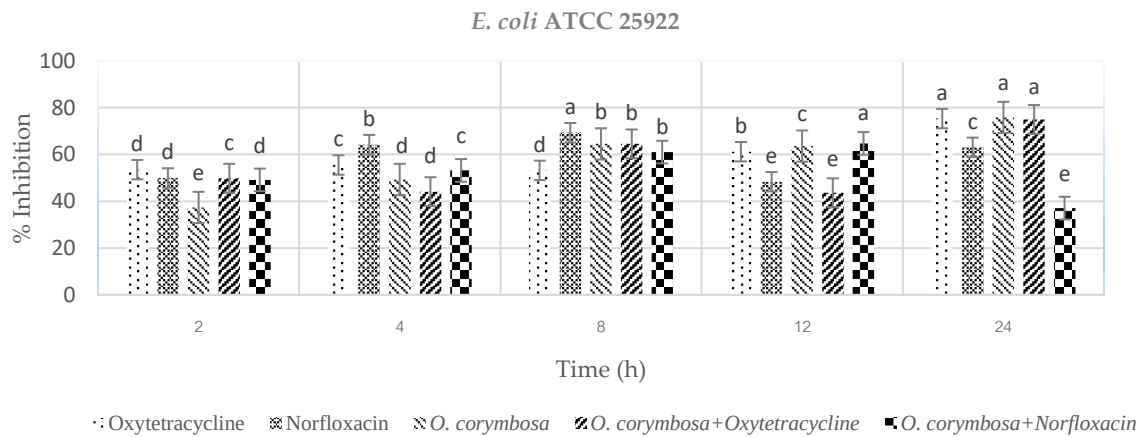


Figure 2. Synergy effect of *O. corymbosa* with antibiotics on *E. coli* ATCC 25922 biofilm. Letters a–e indicate significant differences ($p \leq 0.05$).

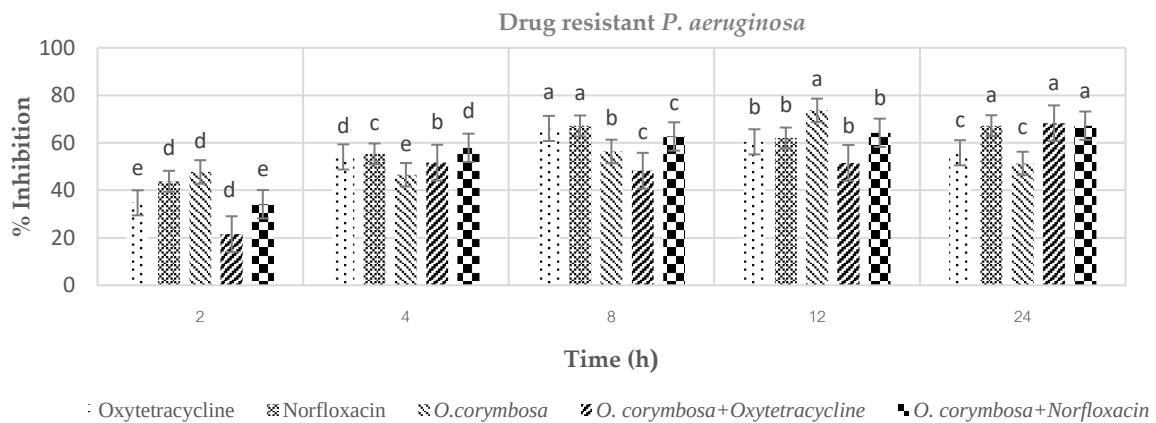


Figure 3. Synergy effect of *O. corymbosa* with antibiotics on *P. aeruginosa* biofilm. Letters a–e indicate significant differences ($p \leq 0.05$).

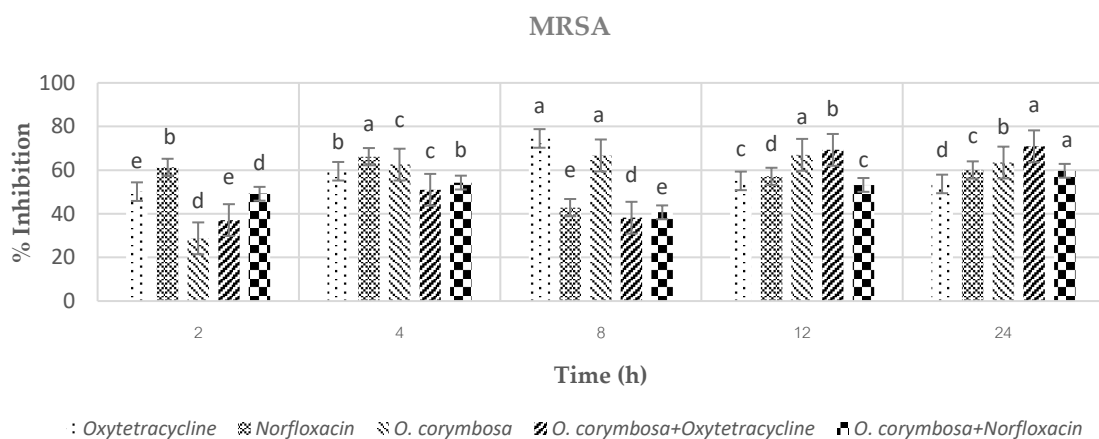


Figure 4. Synergy effect of *O. corymbosa* with antibiotics on *S. aureus* biofilm. Letters a–e indicate significant differences ($p \leq 0.05$).

Our study demonstrated that *O. corymbosa* extract exhibits strong antioxidant activity and antibacterial effects against both drug-resistant and non-drug-resistant opportunistic bacteria. Especially, combinations of

O. corymbosa extract with Oxytetracycline showed synergistic antibacterial activity against *S. aureus*, while combinations with Oxytetracycline and Norfloxacin effectively inhibited biofilm formation against some drug-resistant bacteria. These findings emphasized the potential of *O. corymbosa* as a complementary medicinal plant to conventional antibiotics, enhancing both antimicrobial and antibiofilm efficacy. Our results highlighted the therapeutic potential of combining crude plant extracts with conventional antibiotics to combat biofilm-associated, drug-resistant infections. Such combinations could provide a foundation for the development of novel antimicrobial agents or synergistic formulations, particularly targeting biofilm-related infections on medical devices. They may be applicable for managing nosocomial infections in patients undergoing cancer treatment or with immunodeficiency syndromes.

4. Conclusions

The ethanol extract of *O. corymbosa* demonstrated notable antioxidant, antibacterial, and antibiofilm activities, as well as selective synergistic effects when combined with certain antibiotics. The extract showed strong antioxidant capacity and broad-spectrum antibacterial activity, although relatively high MIC values were observed. Importantly, significant synergy with Oxytetracycline against *Staphylococcus aureus* and enhanced antibiofilm activity in both standard and drug-resistant strains highlight its potential as an antibiotic adjuvant. Overall, *O. corymbosa* represents a promising candidate for developing alternative strategies to combat biofilm-associated and multidrug-resistant bacterial infections.

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Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Effects of Cu and Nb Addition on Microstructure and Mechanical Properties of Ultra-low Carbon Steel under Different Annealing Temperatures

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Abstract: This paper investigated the beneficial effect of copper (Cu) and niobium (Nb) on grain size and mechanical properties of the ultra-low carbon (ULC) steel annealed at temperatures between 700 and 900 °C. The steel samples were prepared by melting input materials in an induction furnace, followed by hot forging, cold rolling into a thin plate, and annealing under an argon atmosphere. Mechanical testing and microstructural observations showed that the addition of Cu and Nb had a positive effect on the steel's properties. The grain sizes and the tensile strengths of the steel without Cu and Nb varied in 50-98 μm and 254-204 MPa, respectively, while those of the steel alloyed with Cu and Nb decreased to 40-83 μm and increased to 286-242 MPa at the same annealing temperatures. SEM analysis did not find Cu-enriched zones at the grain boundaries, consistent with the predicted Cu content in this steel. It can be concluded that Nb contributed to grain-size refinement and Cu hardened the ferrite matrix, leading to improved mechanical properties of ULC steel at the same annealing temperatures.

Keywords: Copper in steel; microalloyed by niobium; annealing process

1. Introduction

Current steelmaking processes can remove almost all harmful inclusions from steel products, except for tramp elements such as copper (Cu), which do not undergo any metallurgical reactions with others. As scrap is remelted multiple times, Cu accumulates in the steel. This leads to adverse effects on the mechanical properties of constructional steel, increased risk of hot tearing, and surface cracking as the Cu content rises [1, 2]. According to the iron (Fe) and Cu diagram, the solubility of Cu in Fe gradually decreases with lowering temperature. Because liquid steel solidifies slowly, saturated Cu tends to precipitate and concentrate near grain boundaries, deteriorating the mechanical properties of steel after hot rolling at 1050-1200 °C. Thus, it was acknowledged that the presence of Cu should be lower than 0.2 wt.% in steel; otherwise, it produces a particular characteristic, such as hot shortness when heated at elevated temperatures [2]. This is attributed to partial liquefaction in Cu-rich zones, as Cu melts at about 1083 °C. However, Cu in steel also has a positive effect, such as improving steel's corrosion resistance [3-6]. Zhou et al. noted that Cu precipitation enhanced the stability of retained austenite and the work-hardening rate, leading to increased elongation and strength after post-heat treatment [3]. In some cases, the strength of steel with a proper Cu content can

be increased because of ferrite strengthening by precipitation; however, this strengthening effect was thought to decrease with the increased C content [7-9]. Sellamuthu et al. found that Cu existed as a solid solution in as-cast low-carbon steel and precipitated during annealing; both strength and hardness increased with Cu addition [8]. According to Salvetti et al. [9], Cu precipitated out of a solid solution when the steel contained more than 0.5 wt.% Cu was reheated because the solubility of Cu was very low in the ferrite.

Ultra-low carbon (ULC) steel, containing less than 0.010 wt.% carbon, is widely used in the automotive and other industrial sectors. Due to its high ductility, this steel is used to produce cold-stamped components that require excellent surface quality and adequate strength. Manganese (Mn) and silicon (Si) are added to ULC steel to achieve a certain level of strength; however, they reduce ductility and toughness by dissolving into the steel matrix and distorting the crystalline network [10-12]. With these common alloying elements, a small amount of niobium (Nb) can be added to ULC steel to reduce grain size and harden the matrix phase through NbC formation, enhancing strength and ductility [13-15]. Unlike Cu, precipitated Nb compounds were found in annealed C steel, even when the Nb content was less than 0.03 wt.%; this precipitation was more pronounced in steels with higher C content [10]. Additionally, Nb can improve steel corrosion resistance. However, Nb content should be controlled at the micro-level (below 0.1 wt.%); otherwise, large grains will appear in the steel's matrix, causing stress concentration and deteriorating its mechanical properties [16]. With proper content, both Cu and Nb are expected to have a positive influence on steel's grain size and mechanical properties. For example, Kobayashi et al. proved that Nb and Cu existed independently in the steel's matrix; the effective hardening of Nb in the steel was 5 times larger than that of Cu [17]. The simultaneous alloying addition of Cu and Nb in steel is thought to lower the optimal heat-treatment temperature, balancing the steel's strength and toughness.

In practice, low Cu-containing scrap is prioritized for use in steel production to avoid harmful effects on the product. Although many studies have been conducted on ULC steel, the beneficial effects of Cu (a tramp element) and micro-alloying elements on this steel have not been well considered. Thus, this paper investigated the effect of Cu and Nb on the grain size and mechanical properties of ULC steel.

2. Materials and Methods

Two steel samples (M1 and M2) were prepared by melting the predetermined weight of pure metals, including iron (Fe), silicon (Si), manganese (Mn), copper (Cu), and niobium (Nb), in an induction furnace under an argon atmosphere. Amounts of the raw materials were calculated to achieve a normal ULC steel grade (0.01 wt.% C; 0.5 wt.% Mn; and 0.25 wt.% Si) with a content of Cu and Nb of about 0.1 wt.% for each element. Amounts of Cu and Nb were predetermined based on the above review of their impact (negative and positive) on the mechanical properties of steel. Chemical compositions of the round as-cast steel plates with 10 mm of thickness were analyzed by optical emission spectrometry (Spectromaxx LMF08), as given in Table 1. The main difference between these two steel samples was the Cu and Nb content: steel M2 had no Cu or Nb, while steel M1 contained 0.123 wt.% Cu and 0.108 wt.% Nb. A small deviation in the steel's chemical composition occurred; however, this was unavoidable due to loss during remelting.

Table 1. Compositions of the steel samples (wt.%).

Steel sample	C	Mn	Si	Cu	Nb	Fe
M1	0.010	0.490	0.244	0.123	0.108	Balance
M2	0.010	0.491	0.254	-	-	Balance

In practice, ULC steel slab is hot-rolled through several passes to obtain a desired thickness, at which its temperatures are in the range of 700 - 900 °C, and then slowly cooled to room temperature. This study used initial hot forging instead of hot rolling because a hot-rolling machine was unavailable. The as-cast steels were hot-forged to a thickness of 3 mm at 900 °C, cooled to room temperature, then cold-rolled into a 2 mm sheet through 2 passes, and annealed at various temperatures from 700 to 900 °C under an argon atmosphere. The annealing condition was fixed at 30 minutes of holding time, with slow cooling in the furnace. The specimens for the tensile test (MTS E45.105) and microstructural observation were cut along the rolling direction, as illustrated in Figure 1. Some steel specimens were ground, polished, 2% nital-etched, and observed using an

optical microscope (Olympus, GX53). Grain size was measured by the linear intercept approach, in which a line was superimposed over the optical microstructure. The true line length was divided by the number of grains intercepted by the line. This gave the average line length within the intercepted grains. The average grain size of the steel was obtained from five measurements. The micro-hardness was measured using Wolpert Wilson Instruments 401/402 MVD with a load of 1 kgf for 5 seconds. Scanning electron microscopy (SEM, JEOL 7600F) was used to observe the precipitation in the annealed steel.

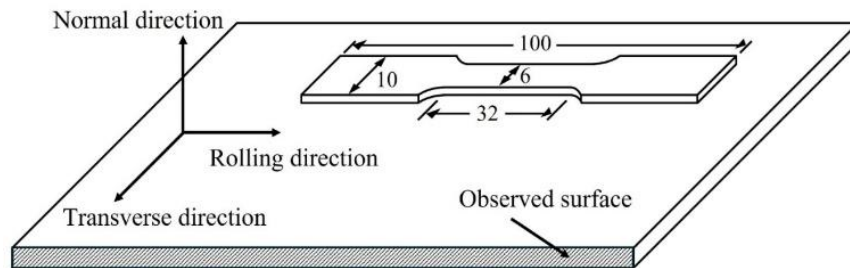
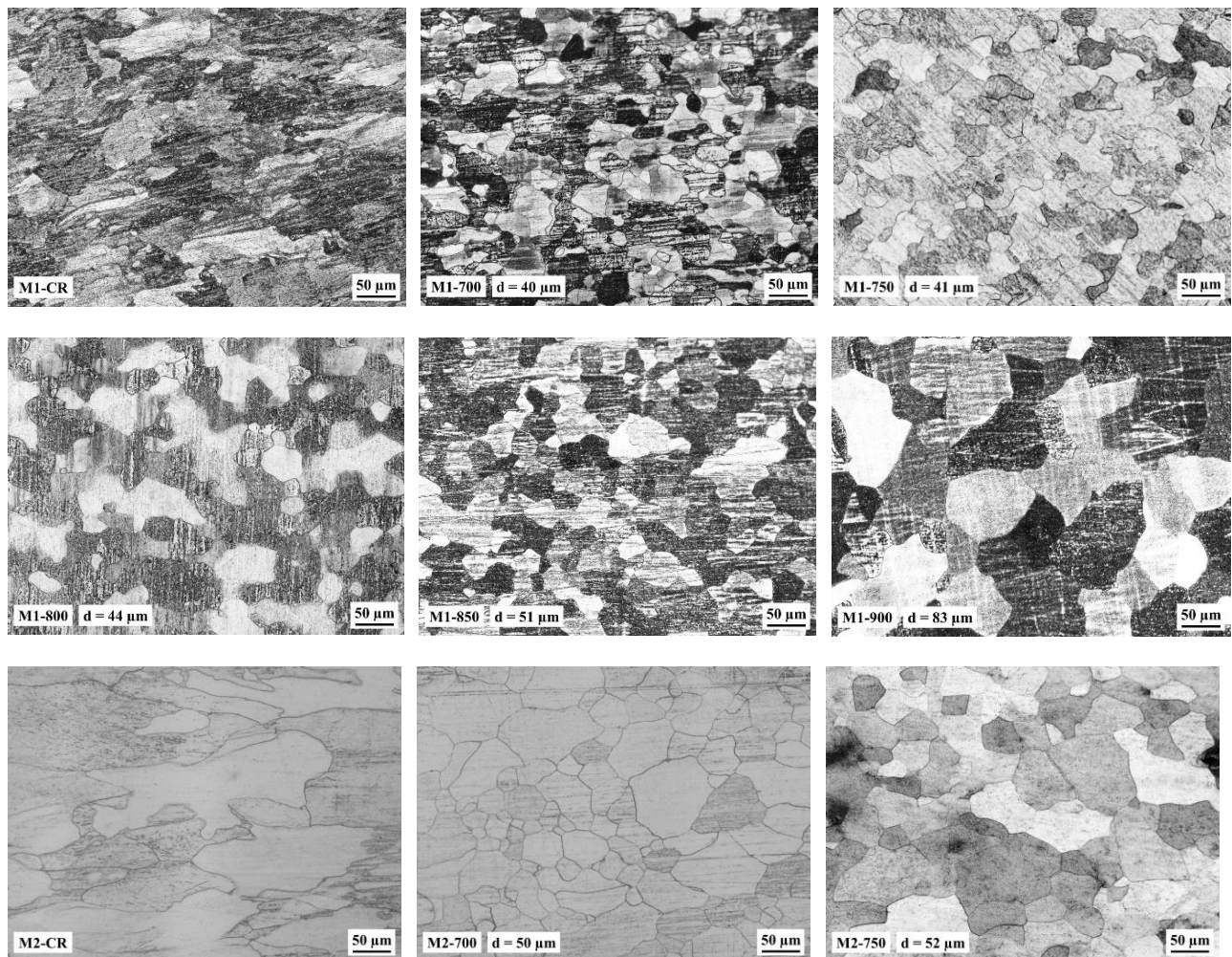


Figure 1. Cutting position of specimens for tensile test and microstructural observation.

3. Results and Discussion

3.1 Microstructure



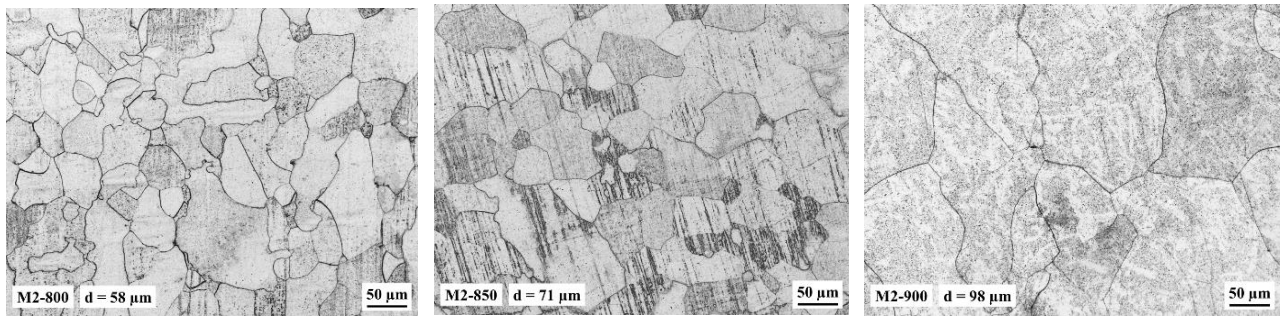


Figure 2. Microstructure of the cold-rolled and annealed steels ($\times 200$).

Microstructure is essential to the mechanical properties of steel. Figure 2 shows the optical images of the cold-rolled and annealed steels, in which ferrite grains were seen for both ULC steels (M1 and M2) with a C content of 0.01 wt.%. For the cold-rolled steels, the ferritic grains tended to lengthen along the rolling direction. However, a transformation from the microstructure of the long ferrite grains to a homogeneous microstructure occurs after annealing the steels at the given temperatures of 700–900 °C. Reducing cold rolling decreased the recrystallization temperature of steel and shortened the time required to complete the process [18]. Although the recrystallization temperature was considered to depend on the content of alloying elements [17], the temperatures of steel M1 and M2 were estimated not to be significantly different because steel M1 contained a small amount of Cu and Nb. Recrystallization was thought to occur completely at these annealing temperatures. In steel M2 annealed at 700 °C, the grain sizes were different. At higher annealing temperatures, the homogeneously coarsened microstructure was observed.

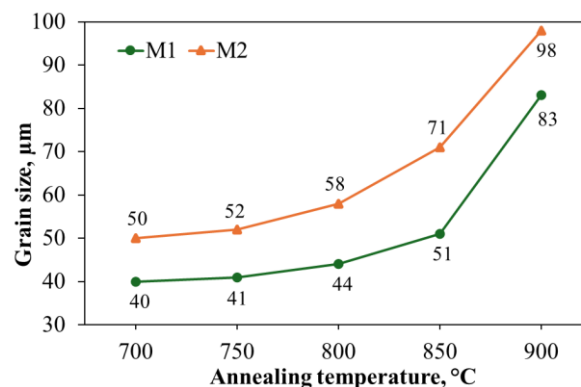


Figure 3. Grain size of steel M1 and M2 versus the annealing temperature.

In steel M1 with Cu and Nb, the microstructures were more homogeneous, with a finer grain size at all annealing temperatures. As plotted in Figure 3, the grain size annealed at 700 °C was 40 μm for steel M1 compared to 50 μm for steel M2 with no Cu and Nb. Notably, the grain size of steel M1 annealed at 850 °C was almost the same as that of steel M2 annealed at 700 °C. Consistent with other publications [13–15], this result was attributed to the grain-refining effect of Nb in the steel, due to grain-boundary pinning at the annealing temperatures. Thus, the mechanical properties of steel M1 were expected to improve. At higher annealing temperatures (800–900 °C), the grain size of both steel M1 and M2 tended to increase. However, the grain size of steel M1 with Nb-Cu was always smaller than that of steel M2 without these elements at the same annealing temperatures. In particular, the grain size of both steel samples increased significantly at 850 and 900 °C due to strong recrystallization. Once the grain boundaries became more flexible at these high temperatures, it was easy for smaller grains to merge and form abnormally large ones, even in the Nb-containing steel M1 annealed at 900 °C.

Additionally, SEM observations revealed no Cu precipitation at the grain boundaries or inside the ferrite grains for all steel samples, even in the steel M1 annealed at 900 °C, as shown in Figure 4. This can be

explained by the fact that the Cu content in steel M1 was not high enough for Cu to precipitate out from the ferrite [9]. It can be concluded that the presence of Nb has hindered the coarsening phenomenon, and dissolved Cu strengthened the ferrite grains of the annealed steel M1, which is expected to cause good mechanical properties in the steel.

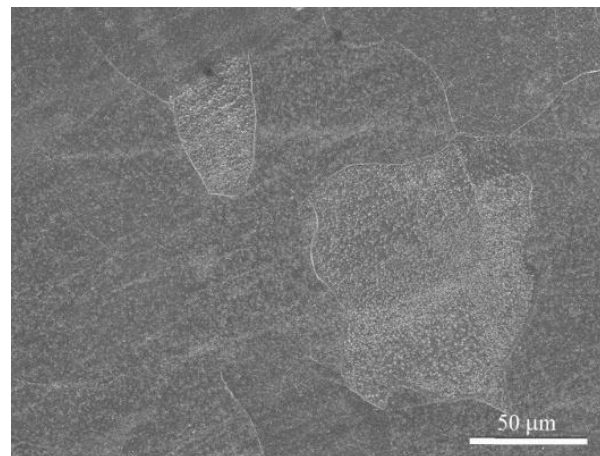


Figure 4. SEM image of the steel M1 annealed at 900 °C.

3.2 Mechanical properties

It is acknowledged that the distortion of the crystalline structure by cold deformation also contributed to hindering dislocation movement, thereby affecting the steel's deformation behavior. Once the annealing process effectively removes work hardening, dislocation density decreases significantly, leading to decreased strength and increased plasticity. Figures 5 and 6 show the stress-strain curves and the change in the strength of the steel processed under different conditions. The relatively large cold reduction (33%) increased the strength of the steel while reducing its ductility, consistent with published results [8, 19]. This can be explained by cold deformation increasing dislocation density and steel defects, resulting in increased residual energy within the steel. The change in the steel's mechanical properties with increasing annealing temperature can be predicted from microstructural images. For example, changes in grain size and homogeneity affect mechanical properties. Typically, steel strengthening mechanisms include grain refinement and precipitation of a hard phase. To explain the strength of steels M1 and M2 in this study, the large grain size decreased strength, while inhomogeneity reduced the elongation of the present steel. Besides the pinning grain boundary effect of Nb, the presence of Cu in the steel also contributed to the hardening of the steel's matrix phase, resulting in higher hardness of the steel M1 compared to the steel M2 under all experimental conditions.

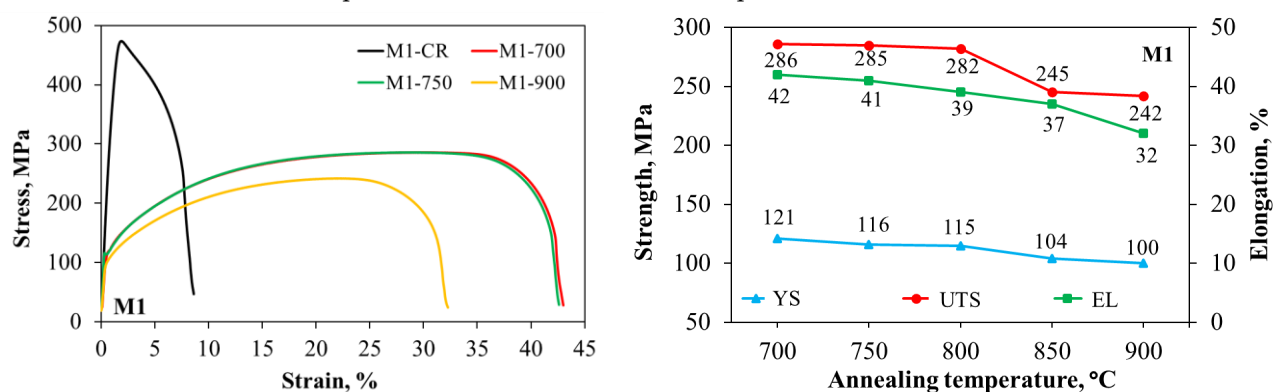


Figure 5. Typical stress-strain curves and the change in the strength of the annealed steel M1.

As shown in the calculated grain size (Figure 3) and tensile results (Figures 5 and 6), a higher annealing temperature yielded a larger grain size and decreased the strength of the steels. In general, a heterogeneous microstructure affected the mechanical properties of the steel; for example, coarsened grain zones deformed more easily than finer grain zones because fewer grain boundaries hindered dislocation movement. This was

attributed to concentrated partial stress, which resulted in earlier failure in the steel and reduced total elongation. The acknowledged trend for steel M1 and M2 was higher plasticity and lower strength at higher annealing temperatures. Both steels showed good ductility; the highest elongation was achieved at 700 °C for steel M1 (42%) and at 900 °C for steel M2 (41%). This indicated that the mostly ferritic soft matrix ensured sufficient plasticity for both steels at different annealing temperatures. For steel M1 annealed at 700 °C, a homogeneous microstructure with the smallest grain size was attributed to the highest strength and elongation. With a low content of Cu and Nb, steel M1 still maintained a balance between strengthening and softening effects and had good mechanical properties. However, this Nb content could not keep this balance at an annealing temperature of 900 °C, resulting in a drastic decrease in hardness. For steel M2 annealed at 900 °C, the homogeneously coarsened microstructure caused better ductility and a slight decrease in strength.

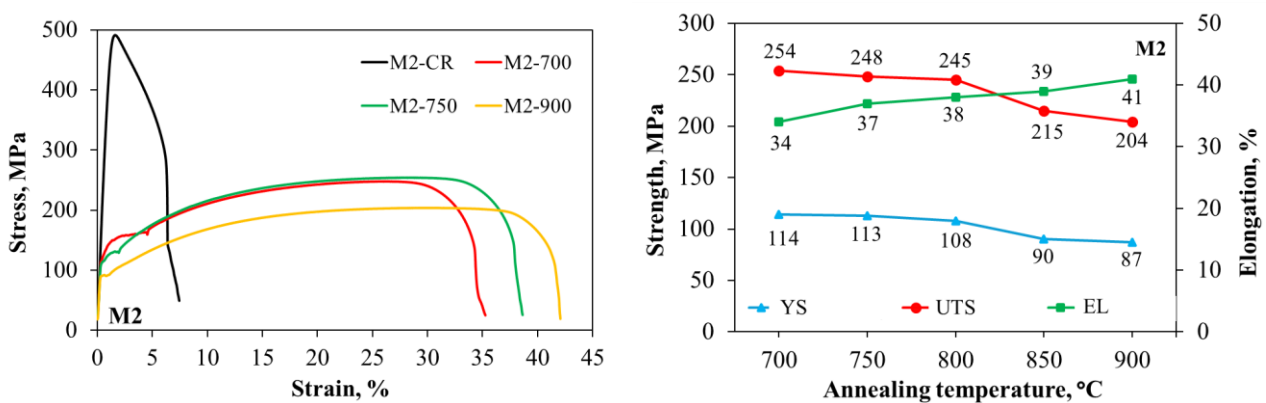


Figure 6. Typical stress-strain curves and the change in the strength of the annealed steel M2.

3.3 Hardness

The hardness and strength of steel are influenced by alloyed elements, grain size, and dislocation density [20-23]. As shown in Figure 7, the hardness of both steels decreased significantly after being annealed at 700-900 °C. Hardness was highest in the cold-rolled steel and decreased in the annealed steel. This reduction was attributed to a decrease in dislocation density and the release of stored energy accumulated in the cold-rolling process. When the annealing temperature increased from 700 to 900 °C, the hardness of both steel M1 and M2 exhibited a gradual decrease, and steel M1 had higher hardness than that of steel M2. Theoretically, the variation in strength and hardness with annealing temperature can be attributed to ferrite softening or strengthening and to matrix homogeneity. A decrease in hardness with the annealing temperature was found in both steel M1 and M2, caused by the coarsened grains and heterogeneity of the steel's matrix (as seen in Figure 2). Grain coarsening could explain the decrease in hardness as the annealing temperature increased. However, a higher hardness of cold-rolled steel M2 (without Cu and Nb), compared to that of the cold-rolled steel M1 (with Cu and Nb), was obtained. This phenomenon can be explained, as Syarif et al. confirmed, by the Cu strengthening effect on the ferrite matrix, which occurred only at low dislocation densities [24]. Thus, the presence of Cu in the cold-rolled steel M1 harmed its hardness.

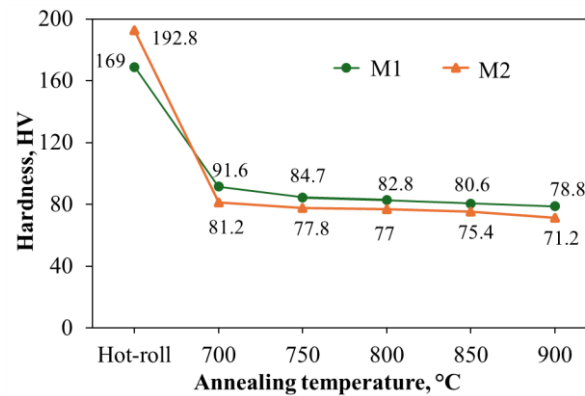


Figure 7. Hardness of steel M1 and M2 versus the annealing temperature.

4. Conclusions

This study investigated the beneficial effects of adding 0.123 wt.% Cu and 0.108 wt.% Nb on the grain size and mechanical properties of ULC steel containing 0.010 wt.% C. Adding Cu and Nb slightly reduced the strength and hardness of the cold-rolled ULC steel but significantly improved the strength of the annealed steel. The grain size of both steel samples increased with higher annealing temperatures; however, the presence of Cu and Nb effectively refined the grain size. Namely, the grain size ranged from 40–83 μm for steel M1 with both Cu and Nb, compared to 50–98 μm for steel M2 without these elements, corresponding to annealing temperatures from 700 to 900 °C. This refinement contributed to high strength and hardness in steel M1 annealed at 700–800 °C, but to lower values at 850–900 °C. This finding is relevant to the practical production of ULC hot-rolled coil (HRC), which is typically stored and cooled slowly within this temperature range to achieve the desired mechanical properties. At an annealing temperature of 700 °C, the steel M1 exhibited the highest UTS of 286 MPa and elongation of 42 %, while steel M2 achieved a maximum UTS of 254 MPa and the lowest elongation of 34 %. These results will help steelmakers apply appropriate processing for different applications of ULC steel.

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A Review of Adaptive Multi-Sensor Grids in IoT-Enabled Smart City Development

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Abstract: Rapid urbanization and continuous technological growth have increased the demand for sustainable and intelligent city infrastructures. Smart cities use the Internet of Things (IoT) and adaptive multi-sensor grids to improve resource management and real-time monitoring. This study examines how IoT-based adaptive sensor grids can improve the sustainability, resilience, and intelligence of future cities. It also highlights major innovations, current applications, and the challenges involved in implementing these systems. The authors conducted a systematic literature review using academic databases. The study analyzed research papers published between 2020 and 2025 using keywords such as “smart city,” “IoT,” and “multi-sensor grid.” The findings show that adaptive sensor grids are central to smart city infrastructure. These grids continuously monitor traffic flow, energy consumption, air quality, and public health conditions. When combined with Artificial Intelligence (AI), they support real-time decision-making. This enables predictive energy management, dynamic traffic control, and efficient waste handling. Despite these benefits, several challenges remain. Major concerns include cybersecurity risks, data privacy issues, and a lack of interoperability between systems. Overall, adaptive multi-sensor grids play a crucial role in shaping sustainable and human-centered smart cities. To achieve this vision, it is essential to develop open standards, secure data frameworks, and strong governance policies. These steps ensure that IoT-driven urban systems remain safe, resilient, and fair for all citizens. Unlike conventional IoT sensor networks that mainly focus on data acquisition from isolated devices, adaptive multi-sensor grids integrate heterogeneous sensing systems with dynamic decision-making, context-aware sensing, AI-driven data fusion, and scalable communication architectures. The “adaptive” nature refers to the system’s ability to modify sensing frequency, resource allocation, routing, and processing strategies based on environmental conditions, traffic load, energy availability, and application demands.

Keywords: Adaptive multi-sensor grids; smart cities; Internet of Things (IoT); sensor fusion; edge computing

1. Introduction

The concept of smart cities has emerged as a transformative framework for addressing urbanization challenges, optimizing resources, and promoting sustainability. A smart city is characterized by its ability to leverage advanced

technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to improve service delivery, enhance citizen's quality of life, and foster sustainable urban growth [1]. Unlike conventional urban systems, which are reactive and often fragmented, smart cities are proactive, data-driven, and adaptive [2]. Adaptive systems lie at the heart of this transformation, enabling urban infrastructure to respond dynamically to evolving conditions such as population surges, traffic congestion, or energy demand fluctuations [3]. When embedded in urban planning and operations, adaptive systems integrate real-time data streams from diverse sources, including transportation networks, energy grids, water systems, healthcare facilities, and public safety institutions, to support responsive and predictive governance. For instance, adaptive traffic systems can modify signal timings in real time based on traffic density, while adaptive energy systems can dynamically balance grid loads and promote renewable energy use [4]. By moving from static planning models to adaptive frameworks, cities can enhance resilience, sustainability, and efficiency [5].

The Internet of Things plays a pivotal role in the smart city vision. As the nervous system of a smart city, IoT encompasses a network of devices and sensors that collect, transmit, and interpret data in real time [6]. It enables real-time monitoring, decision-making, and optimization across the full range of urban management sectors, such as mobility, energy, the environment, and security [7]. Smart city applications demonstrate IoT's transformative potential across multiple urban domains. In smart mobility, sensors embedded in vehicles, roadways, and traffic infrastructure generate continuous data streams that help optimize traffic flow, reduce congestion, and lower overall emissions, contributing to more sustainable urban transport [8]. Smart energy systems rely on IoT-enabled grids and smart meters to balance supply and demand, facilitate the integration of renewable energy sources, and provide consumers with real-time feedback to manage energy use more efficiently [9]. In intelligent waste management, sensor-enabled bins identify fill levels and report collection requirements, enabling optimized routes that reduce fuel use, costs, and environmental footprints [10]. Intelligent health harnesses wearable technologies and Internet of Things monitoring platforms to enhance remote patient care, reduce hospital workloads, and shift toward preventive health management [11]. Finally, IoT applications fortify intelligent administration and security by facilitating transparent decision-making and active citizen engagement. These systems also enhance civic security through surveillance networks and instantaneous warning mechanisms [12]. In aggregate, applications show how Internet of Things-based solutions drive efficiency, sustainability, and a higher urban quality of life [13]. By connecting citizens, infrastructure, and administration platforms, the Internet of Things enables sustainable and equitable cities. As depicted in Figure 1, intelligent urban multi-sensor platforms integrate intelligent street lighting, intelligent transportation, waste-monitoring bins, water management platforms, fire alarms, charging stations, and other systems as intertwined networks that support sustainable urban administration [14].

Urbanization continues at an unprecedented pace, with estimates suggesting that nearly 70% of the global population will reside in cities by 2050 [15]. This rapid expansion strains existing infrastructure and creates significant challenges related to traffic, energy, the environment, waste disposal, and public safety [16]. Contemporary urbanization also presents an array of urgent challenges for smart city development. Traffic congestion is the most evident issue, as increasing vehicle numbers lead to longer journey times, higher fuel use, more pollution, and, consequently, decreased economic productivity [17]. In addition to mobility challenges, energy requirements present another important issue, as cities alone consume almost two-thirds of the planet's energy supply, placing enormous stress on the grid and driving greenhouse emissions [18]. Environmental imperatives add further complexity, as urban mobility and industrial development reduce atmospheric and aquatic quality, threatening public health and ecological balance [19]. Moreover, waste management grows more complex as larger urbanized communities produce higher volumes of waste, requiring more efficient recycling, collection, and disposal mechanisms, not only to reduce environmental degradation but also to manage rising costs [20]. Lastly, safety and security issues increase exponentially as cities continue to expand, as denser groups of people within urban areas become increasingly susceptible to crime, accidents, and disruptions from artificial and natural disasters [21]. Taken together, these challenges underscore the need for flexible, technology-based systems that facilitate sustainable and resilient urban life [22].

Adaptive multi-sensory grids constitute an integrated solution by combining different sensing technologies: air quality sensors, cameras for surveillance, RFID (Radio Frequency Identification) tags, GPS (Global Positioning System) devices, and mobile platforms under a single paradigm [23]. Such grids gather disparate data streams and convert them into actionable intelligence. In the context of smart city infrastructure, combining IoT and multi-sensor management enables responsive and efficient urban management. For example, transportation hubs use vehicle GPS data combined with feeds from CCTV cameras to monitor current traffic conditions and execute dynamic rerouting measures [24]. Similarly, environmental sensors distributed throughout urban areas continuously monitor air quality and pollutant levels and automatically trigger actions by authorities when hazardous situations occur, facilitating timely intervention and protecting public health [25]. Utility systems also use IoT-enabled smart meters to monitor energy consumption patterns, identify potential overload, and optimize resources. Beyond reducing energy waste, this also enables the development of more sustainable and resilient power infrastructure [26].

The motivation for studying adaptive IoT-enabled smart city systems stems from the urgent need to address mounting urban challenges while advancing sustainable development goals [27]. However, despite rapid progress, significant gaps persist. Smart city development is guided by objectives that go beyond technological advancement, focusing instead on building sustainable and inclusive urban ecosystems. A key goal is to promote urban resilience, ensuring cities are better equipped to withstand and recover from shocks such as natural disasters, infrastructure failures, or cyber-attacks [28]. By embedding adaptive systems and secure digital networks, cities can minimize disruptions and protect critical services. Equally important is the drive to advance sustainability, which involves reducing greenhouse gas emissions, conserving natural resources, and accelerating the adoption of renewable energy sources [29]. Through smart grids, intelligent transportation, and efficient waste management, cities can significantly lower their environmental footprint[30]. At the same time, smart city initiatives aim to enhance citizen well-being by improving access to services, strengthening safety measures, and fostering inclusivity in urban development[31]. Collectively, these goals highlight how adaptive, IoT-driven systems can create cities that are not only technologically advanced but also resilient, sustainable, and people-centered.

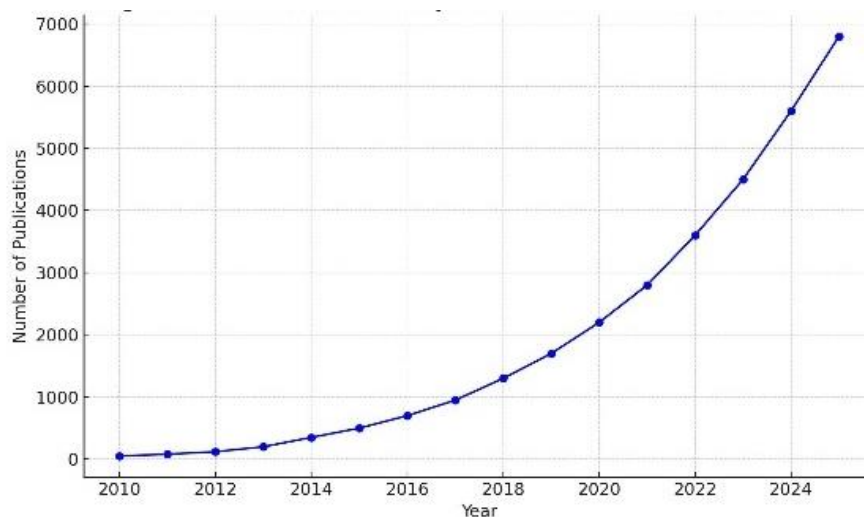


Figure 1. Growth of Smart City Research Publications (2010–2025)

Figure 1 illustrates the exponential rise in smart city research, underscoring the growing global focus on sustainable, technology-driven urban solutions. This growth reflects the growing need for adaptive, IoT-based systems. The deployment of IoT-enabled smart city systems faces several challenges that hinder their large-scale adoption and effectiveness. One major issue is integration, as many IoT platforms and devices function in isolated silos, preventing seamless communication and reducing overall efficiency [32]. Closely linked is scalability, since solutions that perform well in small pilot projects often encounter technical and operational difficulties when expanded to cover entire cities [33]. Another critical concern is security and

privacy, as the vast amount of personal and sensitive data collected by IoT devices raises risks of cyberattacks, data breaches, and misuse that can erode public trust [34]. Cost barriers also play a significant role, as the infrastructure, deployment, and ongoing maintenance of advanced IoT systems require substantial financial investments, making them difficult to implement in resource-constrained regions or developing nations [35]. Finally, the lack of standardization across devices, protocols, and platforms creates interoperability issues, preventing smooth integration of different technologies and limiting the scalability of smart city ecosystems [36]. Overcoming these gaps requires interdisciplinary approaches that merge technological, social, and governance perspectives [37]. Unlike conventional review studies that primarily summarize IoT applications in domains such as transportation, energy, waste management, and healthcare, this review critically synthesizes adaptive multi-sensor grid architectures for smart cities. The review focuses not only on application-level implementations but also on the evolution of intelligent urban sensing infrastructures through the integration of Artificial Intelligence (AI), edge and fog computing, sensor fusion, blockchain, federated learning, and adaptive communication frameworks. Furthermore, this study critically examines unresolved challenges related to interoperability, scalability, low-latency processing, cybersecurity, privacy preservation, and socio-technical integration within city-scale adaptive systems. By synthesizing architectural paradigms, adaptation mechanisms, and emerging research directions, this review aims to identify current limitations, research gaps, and future opportunities necessary for developing resilient, scalable, and context-aware smart city ecosystems.

Case studies from cities globally show the transformational ability of adaptive multi-sensor IoT technology. Barcelona's intelligent traffic management minimizes congestion using predictive analytics, Singapore's smart energy grid balances solar, wind, and storage loads, and Amsterdam's IoT-based waste management optimizes collection [38]. These examples show concrete gains in resilience, performance, and sustainability. The readings also highlight the potential of newer technologies such as AIoT (Artificial Intelligence + IoT), blockchain-based governance, and the use of digital twins in building transparent and inclusive urban ecosystems [39]. However, the same readings identify privacy, cybersecurity, and governance as important barriers that must be tackled on an ongoing basis [40].

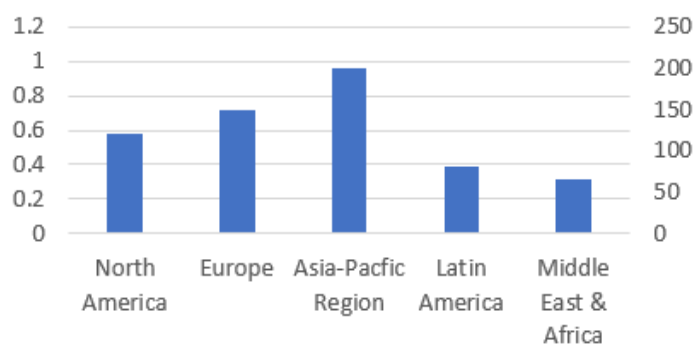


Figure 2. Global Smart City Initiatives Using IoT

Figure 2 highlights global adoption of IoT-enabled smart city initiatives, showing Asia-Pacific, Europe, and North America as leaders. The figure emphasizes adoption disparities, revealing gaps in technological readiness across regions.

In Summary, Smart cities are an innovative urban vision intended to address the challenges of rapid urbanization, sustainability, and inclusivity. IoT and flexible multi-sensor grids provide the cornerstone for the vision in linking heterogeneous data sources into reactive and predictive systems. While international programs show measurable advances, ongoing gaps in the literature document the requirements for scalable, secure, and standardized platforms. In this review, existing literature and case studies synthesize the current state of knowledge, define the opportunities and challenges ahead, and outline paths toward realizing future-ready, resilient, sustainable cities [41].

2. Method of Review

This study uses a systematic literature review to synthesize existing research on adaptive multi-sensor Internet of Things (IoT) systems for smart cities. The review process was structured to be rigorous, transparent, and reproducible. The process involved identifying relevant databases, developing search strategies, applying inclusion and exclusion criteria, and combining results from selected studies [1]. The process is described in detail below:

Using current, high-quality literature, this study relied on the world's foremost digital libraries and databases of scientific and peer-reviewed computer science, engineering, and urban studies journal articles. The following databases underwent a systematic search:

IEEE Xplore: for conference papers, periodicals, and standards on IoT, wireless sensor networks, and smart city infrastructures[2].

Elsevier (ScienceDirect, Scopus): for interdisciplinary papers on city sustainability, use of IoT, and flexible systems[3].

SpringerLink: for book chapters and articles with technology developments and conceptual uses of IoT-smart cities[4].

ACM Digital Library: database of computing-related works, covering IoT protocols, edge/fog computing, and city applications based on AI[5].

MDPI Journals (e.g., Sensors, Sustainability, Smart Cities): open-access journals that publish up-to-date results and global insights on systems of things[6].

This multi-database approach reduced publication bias and maximized coverage across technical, environmental, and governance aspects [7].

Literature searching was supplemented with a combination of pre-specified keywords and Boolean operators to ensure relevant, focused retrieval of studies. The following key search terms were used:

"smart city" AND "Internet of Things (IoT)".

"multi-sensory grid".

"IoT infrastructure" AND "urban sustainability".

"edge computing" OR "fog computing" AND "smart cities".

"adaptive IoT" AND "real-time decision-making"

Searches were performed across all fields (keyword, title, abstract, and full-text where available). Truncation and wildcard characters were used to capture keyword variations (e.g., sensor, sensing, sensors).

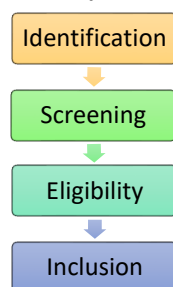


Figure 3. PRISMA-style review selection process.

The process of review can be explained with the help of Figure 3. The process of review can be explained with the help of Figure. 3. Initially,150 articles were identified across IEEE Xplore, Scopus, SpringerLink, ACM Digital Library, and MDPI databases. After duplicate removal,100 records remained. After title and abstract screening, 95 studies were retained for full-text assessment. Finally,80 articles satisfying all inclusion criteria were selected for qualitative synthesis. Duplicate and non-relevant articles at the screening level were eliminated from the pool of initially retrieved records. The dataset was further reduced through full-text review to ensure the final pool of studies directly addressed IoT-based adaptive systems and smart city infrastructure.

Inclusion and exclusion criteria were used to maintain the review's stringency.

Inclusion criteria:

Inclusion criteria for this review were structured to select high-quality, relevant research. The articles used were from 2020 to 2025, a timeframe selected to encompass the most current advances in IoT and smart city technologies [8]. The aim was to focus on peer-reviewed journals, conference papers, and book chapters to ensure academic quality and credibility. Attention was given to studies on IoT-based solutions for smart cities, multi-sensor grids, or flexible decision support systems, as these studies directly fall within the study's prime targets [9]. The literature also included studies that proposed ideas for merging IoT with city systems via frameworks, models, or architectures, as these studies provide explicit information on system design and deployment [10]. Lastly, a mix of empirical studies, case studies, and systematic reviews was included to understand both intellectual views and implementation practice within smart city development [11]. This multi-method approach allowed for a balanced and diversified synthesis of the literature.

Exclusion criteria:

To maintain the quality and direction of the review, a few exclusion criteria were used in the selection process. Non-English papers were excluded for purposes of clarity and consistency in interpretation [12]. Similarly, papers published before 2020 were excluded to focus on current developments in IoT and smart cities [13]. Papers containing merely abstracts and not providing full-text access were also excluded, as they did not contain enough detail for intensive analysis [14]. Moreover, studies beyond the scope of IoT in smart cities were also excluded to keep the review confined to its core objectives. Duplicate or identical records found through multiple databases were excluded to avoid duplication and bias. Lastly, studies without empirical support or theoretical depth were excluded to ensure the synthesis drew on only worthy and robust contributions. This screening ensured that only high-quality, contextually relevant studies were synthesized.

The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The review process began with identification, where relevant literature was downloaded from major academic databases such as IEEE, Elsevier, Springer, ACM, and MDPI [15]. This stage relied on strategically chosen keywords to achieve comprehensive coverage of smart city literature, IoT, adaptive systems, and multi-sensory networks. After downloading the first set of records, the screening process was carried out. Duplicate entries were eliminated, and titles and abstracts were screened to exclude non-relevant studies [16]. The eligibility stage followed, in which full-text articles were carefully examined to determine whether they adhered to the previously set inclusion and exclusion criteria, as well as their relevance and quality [17]. Finally, the inclusion stage comprised a review and consolidation of the shortlisted studies that had passed all the above stages. The studies were then systematically examined and synthesized to form the basis of the review [18]. The shortlisted studies were also examined for the extraction of key aspects of data, i.e.:

Author(s) and publication year.

Objectives and scope of the study.

Emphasis on technology (communications protocols, edge computing, fog computing, AI).

Field of applications (mobility, energy, waste).

Proposed challenges that have been identified. A qualitative synthesis was then performed to integrate results into thematic categories such as infrastructure design, adaptive multi-sensor grids, privacy/security issues, and future technologies (e.g., AIoT, blockchain, digital twins) [19].

The review's methodology places special stress on a few crucial traits to increase its reliability and rigor. The first is transparency, maintained by keeping an accurate account of all stages of the process from initial database search to final synthesis of results [20]. This allows readers to follow the process and enables other users to track the same trail. The second is reproducibility, whereby other users can replicate the approach to confirm results or update the review with additional studies uncovered. To avoid leaving out significant research, the process was exhaustive, with searches conducted across databases using broad, clearly defined keywords. This minimizes bias and provides maximum coverage of available literature. Relevance was also ensured through stringent inclusion and exclusion criteria, whereby unimportant works and less influential studies were weeded out, and the remaining studies had corresponding contexts and aligned with the purposes of the study. This critical framework strengthens the study by providing a

comprehensive, evidence-based synthesis of how multi-sensor adaptive IoT systems can enable the development of smart, sustainable cities.

3. IOT Foundation and Intelligent City Infrastructure

Developing smart cities relies on deploying robust IoT infrastructures. These infrastructures act as the virtual nervous systems of cities, enabling real-time sensing, communication, computation, and decision-making. Unlike fixed, systems-based traditional cities, smart cities use dynamic IoT architectures that integrate heterogeneous sensors, smart networks, distributed computing, and secure data platforms to address complex urban issues [20]. The value of IoT infrastructure is paramount.” or “IoT infrastructure is of critical importance. Without trustworthy sensing, communication, and computational foundations, the dream of a fully adaptable and sustainable smart city cannot come to fruition. A smart traffic control system, for instance, relies on vehicle sensors, high-speed networks, edge computing nodes for real-time processing, and cloud platforms for predictive insights. Energy grids also need IoT infrastructure for distributed renewable energy sources, demand prediction, and avoiding collapses [21]. The following sections discuss IoT infrastructure, including devices, communication protocols, sensor networks, computing paradigms, and adaptive decision-making. This is subsequently accompanied by an exhaustive discussion on the layer-based architecture of smart cities, with each layer perception, communication, processing, data management, applications, and security discussed extensively [22]. IoT devices provide the infrastructure foundations for a smart city. They act as the first interface between the physical and virtual worlds, extracting raw information and moving it up the stack for interpretation. They can be classified across different domains [23]:

Environmental Devices: Air quality sensors, temperature monitors, and pollution trackers provide real-time insights into environmental health. For instance, New Delhi’s pollution-monitoring IoT grids enable predictive air-quality management [24]. **Infrastructure Devices:** Intelligent streetlights and smart meters track usage patterns and optimize resource distribution. The Barban court’s smart streetlight system in Barcelona reduces energy usage by up to 30% [25]. **Mobility Devices:** GPS tracking-enabled buses, smart parking sensors, and traffic cameras enable predictive congestion and dynamic routing. The Singapore Connected Vehicle Grid is an example[26]. **Medical Devices:** Portable devices like heart rate monitors and intelligent emergency bands communicate with health systems to provide remote patient care [27]. Protocol communication is essential for interconnecting heterogeneous devices. No two protocols share the same strengths and weaknesses; each optimizes for specific applications. Table. 1 reflects their suitability, but it is essential for infrastructure design [28]: **MQTT (Message Queuing Telemetry Transport):** lightweight, highly efficient, and for constrained devices. Actively used for traffic control and energy metering [29]. **CoAP (Constrained Application Protocol):** Implements a request/response model tailored for constrained devices. In practice, it is used for environmental sensing and smart lighting [30]. **HTTP:** Popular but bandwidth-hungry, and best used with web services [31]. **AMQP (Advanced Message Queuing Protocol):** Offers reliable message transfer in enterprise applications such as financial and governmental systems [32]. **LoRaWAN:** Low-power, long-range, which is appropriate for long-distance infrastructure monitoring like smart meters [33]. **Zigbee:** The most suitable mesh network protocol for extremely dense local networks like smart homes [34].

Protocol selection influences scalability, energy efficiency, and inter-operability of smart city infrastructures [35].

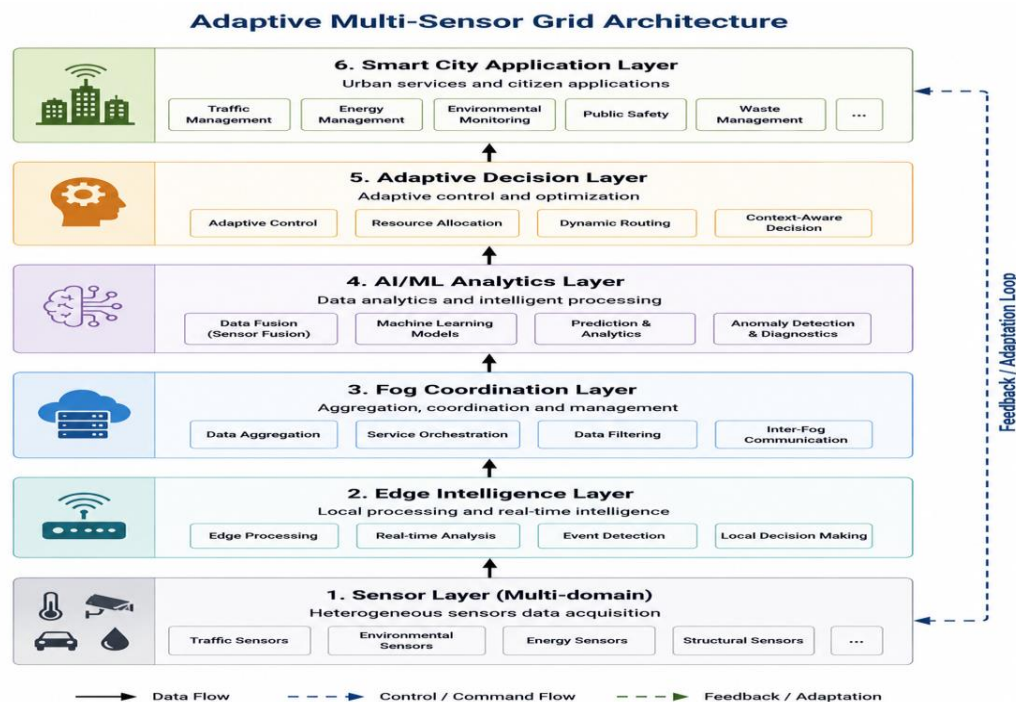


Figure 4. IOT architecture layer

Figure 4. The image illustrates a layered architecture of a smart city data ecosystem, consisting of four layers—Business, Application, Data Management, and Network. Each layer connects technologies like IoT sensors, mobile devices, data analytics, and machine learning to enable smart services such as smart transport, agriculture, and homes. Smart cities also require massive-scale sensing networks that connect numerous IoT devices. These networks also act as the central nervous system and convey environmental, infrastructure, and social-related information throughout the city. In smart city infrastructure, various network architectures are important for connectivity and efficiency [36]. Centralized networks also have wide applications in large city surveillance systems, where the huge amount of data received from sensors is routed to a centralized cloud hub for storage, processing, and decision-making purposes. While this method can support massive computation and large-scale joining, it also imposes latency and dependency on cloud availability. On the other hand, distributed mesh networks operate in a decentralized environment, where devices communicate directly with each other without relying on a central point. This topology is extremely robust and applies in smart grids and disaster scenarios, where redundancy and resilience are critical. Hybrid networks combine distributed and centralized elements. Both architectures exist within hybrid systems, combining the scalability and computing power of centralized architectures with the reliability and fault tolerance of distributed designs, and they are extremely useful for large-scale smart city applications [37]. Cloud infrastructure supports advanced storage, processing, and analytics. The advantages are scalability, compatibility with AI, and support for digital twins. However, bandwidth and latency costs can hinder real-time responsiveness [38].

The edge and fog computing lower latency by processing information closer to the source. Edge computing has proven indispensable for smart city deployments by enabling processing closer to the source, reducing latency and increasing responsiveness. In traffic control, for example, edge nodes near traffic lights can process real-time information from local cameras and sensors, identify congestion, and automatically optimize traffic-light intervals. This edge processing enables faster decision-making with minimal reliance on distant cloud servers, leading to smoother traffic and reduced waiting time. In health, wearable devices with edge processing can track vital signs continuously, such as oxygen levels, body temperature, or heart rate. Instead of streaming all raw information directly to the cloud, the wearable processes data at the edge to identify anomalies and stream immediate alerts to the user or health specialists. Only summarized or critical information is then uploaded subsequently to cloud systems for long-term storage and advanced analytics. This technique not only reduces network traffic but also increases the efficiency and reliability of health monitoring systems [39]. By harmonizing cloud and edge computing, cities gain responsiveness and long-term intelligence [40].

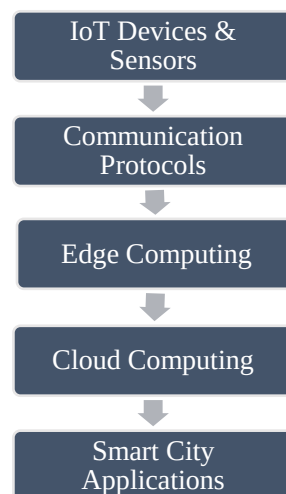


Figure 5. IoT Infrastructure Architecture

Figure 5 illustrates that IoT infrastructure is nonlinear, interconnected, and layered, with each layer depending on the integrity of the prior layer. End-to-end success for smart city applications relies on seamless connectivity from sensors → protocols → edge → cloud → applications. Adaptive decision-making distinguishes smart cities from traditional urban systems. It ensures that data is not only collected but also translated into meaningful actions. Smart city applications demonstrate how IoT and adaptive multi-sensor systems can significantly improve efficiency and responsiveness in urban services. For instance, smart lighting systems use sensors to monitor pedestrian or vehicle density, allowing streetlights to adjust brightness levels automatically. This not only enhances public safety but also reduces unnecessary energy consumption. In waste collection, sensor-equipped bins provide real-time fill-level data, enabling collection trucks to be dispatched only when needed. This approach minimizes operational costs, lowers fuel consumption, and contributes to a cleaner environment. Similarly, emergency response systems use edge-based video analysis to detect accidents or hazardous events immediately, ensuring that nearby hospitals and authorities are alerted without delay. Such rapid detection and communication can save lives and improve the overall resilience of urban safety systems. Collectively, these examples highlight how adaptive IoT-driven solutions make urban infrastructure smarter, more sustainable, and citizen-centric. This adaptability requires integrating AI algorithms, predictive analytics, and IoT data fusion into decision-making frameworks [41].

Table 1. IoT Protocols and Their Suitability

Protocol	Latency	Range	Best Use Case
MQTT	Low	Medium	Traffic monitoring
CoAP	Very Low	Short	Environmental sensing
LoRaWAN	High	Long	Waste management
ZigBee	Low	Short	Smart lighting
NB-IoT	Moderate	Long	Smart metering
5G	Ultra-Low	Wide	Autonomous vehicles

Table 1 shows that no single protocol can cover all smart city applications. Smart cities need a hybrid ecosystem of protocols, carefully chosen for specific applications, such as long-range tracking (LoRaWAN), local area mesh networks (Zigbee), or minimalist real-time communication with MQTT and CoAP. Integrating infrastructure and multi-layered design enables responsive, data-driven city systems. Theoretical implementations from Dubai, Barcelona, Singapore, and Songdo illustrate how such systems can optimize city mobility, resource use, sustainability, and citizen quality of life. But immediate challenges remain: interoperability, privacy, governance, and scalability. Resolution will demand open standards, secure protocols, inter-sector coordination, and citizen participation [50]. To manage the complexity of smart cities, IoT infrastructure is structured into six interconnected layers with distinct functions and seamless interaction [42]. Perception (Sensing) Layer – Multimodal information is provided by environment, infrastructure, mobility, and healthcare sensors. For instance, South Korea's city of Songdo utilizes building-integrated sensors for the real-time detection of energy usage [43]. Network (Communication) Layer – Transmits data using 5G, 6G, LPWAN (LoRaWAN, NB-IoT), Wi-Fi 6, Zigbee, and UAV-assisted systems. The rollout of 5G in Dubai supports autonomous vehicle deployment [44]. Edge/Fog Processing Layer – Processes local data with AI-enhanced fusion techniques. In Singapore, edge nodes process traffic congestion by adjusting traffic light intervals at interchanges on the fly [45]. Cloud and Data Management Layer – Offers centralized analytics, storage, and interoperability. Virtual twin models replicate city infrastructure, and federated learning enables privacy-preserving AI training [46].

Application Layer – Intelligent, IoT-enabled infrastructure within smart cities is designed to deliver an unprecedented set of integrated services that increase efficiency, sustainability, and citizen engagement. In smart mobility, such systems support adaptive use of traffic lanes and dynamic parking services, addressing traffic congestion, travel time, and emissions. Intelligent energy services employ real-time tracking and smart grids for demand balancing, integrating green energy sources, and reliable power distribution. In smart governance, IoT enables e-governance services and transparency platforms that increase accountability, support better decisions, and encourage active citizen participation. Finally, smart environment services use sensor networks to track pollution and optimize waste management, supporting healthier city ecosystems and sustainable natural resource use. Together, these services illustrate how multi-sensor adaptable grids transform conventional city operations into smart, responsive, and citizen-centric systems [47]. Security and Privacy Layer (Cross-Cutting) – One of the significant considerations in smart city planning is the ability to be resilient against cyber threats since IoT-equipped infrastructures process massive amounts of operational and sensitive information. One method is implementing blockchain-based authentication, securing sensors and devices' identities so it is extremely hard for rogue entities to alter or impersonate them. Moreover, federated learning offers a privacy-preserving mechanism by allowing machine learning models to be trained on distributed, decentralized data sources without exchanging raw citizen information, thereby mitigating breach risks while still enabling sophisticated analytics. In addition, intrusion detection systems keep IoT networks under constant surveillance, detecting and defeating potential cyberattacks before they become large-scale disruptions. Together, these form a multi-layer defense approach that reinforces the overall cybersecurity stance of smart cities and ensures reliability, trust, and safety for infrastructure and citizens alike [48, 49].

4. Multisensor Grid Concept

A conventional IoT sensor network generally consists of interconnected sensing devices that collect and transmit data from isolated urban environments. In contrast, an adaptive multi-sensor grid is a more advanced, intelligent architectural paradigm in which heterogeneous sensors, communication networks, edge/fog computing nodes, and AI-driven analytics operate collaboratively as an integrated urban intelligence system. The term “grid” refers not only to the physical interconnection topology of distributed sensing devices but also to a coordinated framework for data exchange, adaptive decision-making, and resource management across multiple city domains. Unlike static sensor deployments, adaptive multi-sensor grids dynamically modify sensing behavior, communication priorities, and computational workloads based on contextual conditions such as traffic density, environmental variations, energy demand, or emergency events. These systems employ distributed intelligence through edge and fog computing architectures, allowing localized processing and rapid response without relying entirely on centralized cloud infrastructure. Furthermore, sensor fusion mechanisms combine data from multiple heterogeneous sources at data, feature, and decision levels to improve situational awareness, reliability, and operational efficiency in smart city environments. A multi-sensory grid is an integrated, interconnected system that serves as the nervous system of an intelligent city. It is characterized by the large-scale deployment of heterogeneous, numerous Internet of Things (IoT) sensors that provide a unified network that captures, processes, and acts on real-time information from throughout the cityscape. The grid goes beyond single-shot data-collection systems and interlaces different sensor modalities to create a comprehensive, dynamic, and multi-faceted understanding of city operations. The overall aim is to use this combined intelligence to manage assets, services, and resources with unprecedented efficiency, and to improve sustainability and quality of life for the citizenry [51].

The strength of the multi-sensory grid lies not in individual sensors but in their interactions. By correlating information from multiple domains, the grid enables sophisticated analytics and predictive capabilities that would not be feasible with separate, siloed information. This hybrid approach underlies building smart urban solutions, from traffic control to public health tracking [52]. The multi-sensory grid's performance is characterized by the depth and width of its constituent sensor modalities. Its architecture is based on four major domains [53]. **Environmental Monitoring:** This layer focuses on the health of the city environment. Sensors are set up to track air quality (such as concentrations of pollutants like PM_{2.5} and NO_x), noise, temperature, and humidity. This information serves as an essential input for formulating sustainable policies, issuing public health alerts, and identifying the environmental consequences of city activities such as traffic jams. **Sharing environmental information on an IoT-based platform** is a central feature of this modality [54]. **Traffic and Mobility Sensing:** The mobility layer is one of the best-developed domains in smart cities. This includes a vast array of sensors, including inductive loops, cameras, GPS, and radar, that can detect traffic volume, vehicle occupancy, speed, and parking space availability. Intelligent traffic control systems interpret the data and can dynamically adjust traffic light intervals, redirect cars from jammed roads, and guide drivers to available parking spaces, reducing travel time and emissions [55].

Sensing Energy (The Smart Grid): The energy grid is an infrastructure component that is tracked by its own network of dense sensors. In a smart city scenario, this “smart grid” uses sensors to track real-time electricity consumption, detect faults, and manage the injection of renewable energy sources such as solar power. This modality is important for managing grid resilience, optimizing energy distribution, and enhancing environmental sustainability through effective energy management. Latest systems incorporate AI and blockchain for distributed energy trading and management [56]. **Healthcare and Public Safety Sensing:** This new modality leverages sensors for a whole range of public health applications. Applications range from wearable devices for remote patient tracking, environmental sensors that can serve as inputs for epidemiological studies, and smart cameras for public safety augmentation. The goal is a responsive, proactive healthcare and emergency services infrastructure that can predict public health patterns and respond swiftly in emergencies [57]. The multi-sensory grid provides a copious and diverse amount of raw data. To derive useful information from this data, intelligent cities use advanced sensor data fusion mechanisms. Data fusion combines and integrates information and data from multiple sources to achieve greater precision,

completeness, and reliability than a single source could provide. In a multi-sensor grid, fusion enables the city to derive an overall operational scenario, identify complex patterns, and make better decisions [58].

Adaptive Mechanisms in Multi-Sensor Grids: Adaptability is a defining characteristic that differentiates adaptive multi-sensor grids from conventional wireless sensor networks and static IoT infrastructures. While traditional sensor networks primarily rely on fixed sensing schedules and predefined communication patterns, adaptive multi-sensor grids dynamically modify their sensing, computation, and communication behavior according to changing environmental, operational, and user-driven conditions. This adaptive capability enables smart city systems to respond intelligently to real-time urban dynamics while improving energy efficiency, scalability, and service reliability. One major adaptation technique is context-aware sensing, where sensor nodes adjust their sensing frequency, transmission intervals, or operational modes based on contextual information such as traffic congestion, weather conditions, pollution levels, pedestrian density, or emergencies. For example, environmental sensors may increase their sampling rates during abnormal pollution spikes while remaining in low-power mode during stable conditions. Such context-sensitive operation minimizes unnecessary data generation and conserves network resources.

Predictive activation mechanisms further enhance adaptability by using Artificial Intelligence (AI) and Machine Learning (ML) models. Instead of continuously activating all sensing devices, predictive models can forecast events such as traffic congestion, energy demand fluctuations, or abnormal environmental conditions and selectively activate only the required sensors and computational resources. This predictive strategy reduces communication overhead, lowers energy consumption, and improves operational efficiency in large-scale smart city deployments. Adaptive multi-sensor grids also employ resource-aware task allocation techniques to optimize the distribution of sensing and processing tasks across heterogeneous devices. In highly dynamic smart city environments, edge devices, gateways, fog nodes, and cloud platforms collaboratively share workloads according to resource availability, latency constraints, and network conditions. This distributed intelligence improves scalability and reduces the dependence on centralized cloud processing. Dynamic routing mechanisms are another important adaptive feature in smart city sensor grids. Unlike static routing protocols used in conventional sensor networks, adaptive routing continuously modifies communication paths based on congestion levels, link quality, node failures, and mobility conditions. Such intelligent routing improves network reliability, fault tolerance, and real-time responsiveness in urban infrastructures.

Furthermore, edge intelligence plays a crucial role in enabling rapid local decision-making within adaptive grids. By integrating edge and fog computing with AI-enabled analytics, data processing can occur closer to the source of data generation, thereby reducing latency, bandwidth consumption, and cloud dependency. Edge intelligence allows adaptive grids to support real-time applications such as traffic optimization, emergency response systems, smart energy management, and autonomous urban monitoring. Overall, adaptive mechanisms transform traditional IoT sensing infrastructures into intelligent, self-optimizing urban systems capable of learning from environmental changes and dynamically adjusting their operations to meet evolving smart city requirements. An important feature of an effective multi-sensory grid is adaptive sensing. In place of acquiring data at a fixed, predetermined rate, an adaptive system continuously changes the sensing approach in ways such as the rate at which the data is collected or which sensors are active, following real-time activity and situational inputs. This technique optimizes resource usage, such as network bandwidth and energy, while ensuring that high-quality, relevant information is obtained where it is needed most. For instance, an adaptive street lighting system activates bright lighting when pedestrians or traffic are present and dims it when none are, saving considerable energy. Correspondingly, after mobility sensors detect a traffic accident, surrounding environmental sensors might automatically increase their sampling rate to detect possible air contamination from a toxic spill [59]. Data fusion can also be categorized at different levels and involves multiple techniques, mostly driven by machine learning and artificial intelligence (AI/ML) [60].

Levels of Data Fusion:

Data-Level Fusion: This involves merging raw data streams from multiple identical sensors to derive a reading superior to any single sensor reading. For instance, averaging temperature readings from a few co-

located sensors. **Feature-Level Fusion:** In this approach, specific features or attributes from each sensor's information are first derived. These derived features are subsequently amalgamated. Video feed features (car shape) and radar sensor features (car speed) can be combined to obtain a more accurate vehicle classification. **Decision-Level Fusion:** Here, at the final stage, each sensor system gives an initial, independent decision. The separate decisions are then gathered and combined using a voting technique or probability-based approach to produce a final, robust decision. **Artificial Intelligence (AI) and Machine Learning (ML):** Current data fusion is driven by AI, and its ML models can discover complex correlations and patterns in distributed data that would be beyond human analyst bandwidth to find. For example, traffic management and intelligent parking systems use deep learning models to fuse camera and IoT sensor data. **Probabilistic Models:** Kalman filters and Bayesian inference are also widely used to handle the natural uncertainty of sensor data. They have particular success with predictive applications, for example, estimating traffic congestion or energy demand.

Low-latency fusion can be carried out close to the sensors with edge computing, which is essential for real-time applications such as automated vehicle control. Powerful cloud computing infrastructures handle computationally heavy, city-wide perspective-based large-scale fusion tasks [61]. Although adaptive multi-sensor grids offer substantial improvements over conventional IoT infrastructures, the reviewed literature reveals several unresolved architectural and operational trade-offs. Data-level fusion provides high sensing accuracy but significantly increases communication overhead and bandwidth requirements in large-scale deployments. Feature-level and decision-level fusion reduce transmission loads but may sacrifice contextual richness and introduce computational complexity at edge nodes. Similarly, while edge computing enables low-latency adaptive responses for real-time urban services, resource-constrained edge devices often face limitations related to processing capability, memory availability, and energy consumption when executing AI-driven analytics. Cloud-centric architectures provide superior scalability and computational power but introduce latency and privacy concerns for delay-sensitive applications. Furthermore, integrating heterogeneous communication protocols and sensing platforms continues to create interoperability challenges that restrict seamless city-wide coordination. These observations indicate that future adaptive multi-sensor grid architectures must balance scalability, responsiveness, computational efficiency, interoperability, and privacy preservation to support sustainable smart city ecosystems.

The Challenges of Creating a Seamless Data Fabric: Ingesting vast, diverse streams of information from a multi-sensor grid in real time is a daunting process. The success of a smart city depends on its ability to overcome crucial technical challenges related to data handling, interoperability, and network performance. It is a challenge to integrate massive, highly variable streams of data from a multi-sensor grid in real time. The sustainability of a smart city depends on its ability to solve fundamental technical issues related to data management, interoperability, and network performance [62].

Data Heterogeneity and Volumes (Big Data):

The Challenge:

The grid integrates myriad sensors that provide data in an enormous collection of types and formats (e.g., numbers, words, images, video), at varying rates, and at different quality levels. The quantity and variety of this information create a major challenge for storage, manipulation, and analysis. Smart city infrastructure must handle and process this "big data" tsunami efficiently.

The Effect:

Systems may become overwhelmed, lose detail, take longer to process, and fail to provide timely insights [63].

Lack of Interoperability and Standardization:

The Issue:

IoT devices from various manufacturers use non-standard communication protocols and data structures. This lack of standardization creates "data silos," preventing systems from communicating or exchanging information effectively.

The Effect:

This greatly restricts the multi-sensory grid's functionality by hindering full analysis that results from integrating various sources of information. The ability of systems to share and comprehend the meaning of

information through semantic interoperability is a crucial but still unaddressed concern. Evolving common system architectures would dismantle these silos [64].

Scalability:

The Problem:

The smart city isn't fixed; it's dynamic, growing, and adapting. The multi-sensory grid's infrastructure must be scalable from the ground up and support continually growing numbers of sensors and data streams without performance degradation.

The Effect:

A non-scaling system will rapidly fall out of date and need expensive overhauls. Architectures must scale and often use cloud-native design and distributed computing patterns such as edge computing [65].

Latency and Real-Time Processing:

The Problem: Critical smart city applications, such as self-driving car coordination, smart grid protection, and public safety notification systems, cannot tolerate dead time. They must transport data, run analytics, and take action within millisecond time frames (low latency).

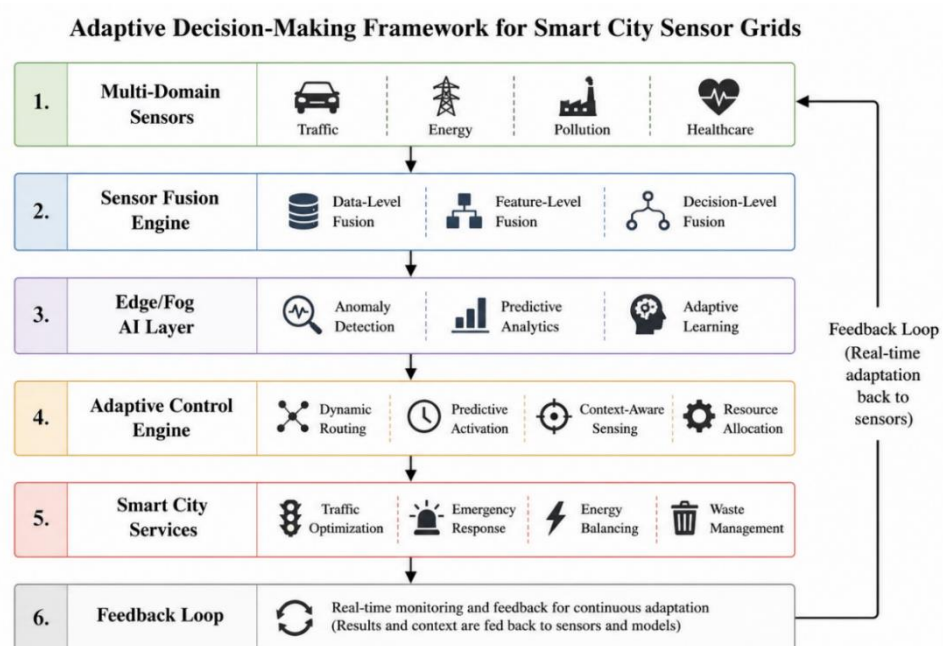


Figure 6. Framework of an adaptive multi-sensory grid for smart cities

Figure 6 illustrates the framework of a multi-sensory grid that is used for smart cities.

The Effect:

High latency can make applications inoperative or even harmful. Technologies such as 5G communication and edge computing are essential enablers, as they minimize the time it takes for the information to move from the sensor to the processing unit and from the processing unit to the sensor [66].

Data Quality, Reliability, and Trustworthiness

The Problem:

Sensor readings may be erroneous, unreliable, or incomplete due to hardware failure, improper calibration, environmental disturbances, or communication faults. Incorrect decisions based on faulty information can have severe adverse effects.

The Effect: The grid will need to incorporate robust mechanisms for validation, data cleaning, and error detection to work effectively. Data fusion can help by using redundant information to detect errors and faulty readings [67]. The immense power of a real-time, integrated multi-sensory grid comes with significant risks. As the city's central nervous system, the grid is a high-value target for cyberattacks, and its data-collection

capabilities raise profound privacy concerns. Building and maintaining public trust requires that security and privacy are not afterthoughts but are foundational principles of the system's design [68].

Cybersecurity Risks:

The grid's highly interconnected nature and the often weak security of individual IoT devices create an extremely large attack surface. Attackers might cripple essential services by, for instance, controlling traffic lights, subverting the power grid, or leaking sensitive citizen information. The ethical ramifications of each such security failure on public safety are staggering [69].

Mass Surveillance and Privacy Erosion:

The same sensors that improve efficiency can also enable pervasive surveillance, tracking citizens' movements and behaviors. This raises serious ethical dilemmas about balancing urban sustainability, security, and the individual's right to privacy. Clear governance is needed to prevent misuse of this powerful technology [70]. Overcoming these problems requires advanced technology and effective policy [71].

Blockchain for Trust and Security:

Blockchain consists of a distributed, unalterable ledger that can secure communication and transactions between IoT devices. By creating an immutable event history, blockchain can increase information integrity and prevent unauthorized modifications, building a safer and more reliable system [72].

Split and Federated Learning for Privacy:

In response to concerns over centralizing potentially sensitive data for training AI models, such as for facial identification, approaches such as federated learning have emerged [73]. This enables AI models to be trained locally on edge devices without the raw data leaving its origin, thereby upholding user privacy.

Public Participation and Ethical Governance:

Technology alone cannot provide a single solution. Cities must lay out comprehensive, transparent data-governance policies that clearly outline what data is collected, for what purpose, and who can access it. Public participation in governance is also important for building trust and ensuring the smart city evolves in a way that is fair and works in everyone's interest [74].

Communication Layer: This information is interpreted and read by an AI/ML engine from the Data Processing Layer to derive insights and make future predictions. The Application Layer then utilizes this information to drive city dashboards and transmit automated control signals back to actuators, closing the adaptive feedback loop [75].

The four-tiered architecture of an adaptive multi-sensory grid for smart cities is presented in Figure 6. This encompasses the Sensory Layer, which receives raw inputs from multi-domain heterogeneous sensors and conveys them over the communication layer. The raw inputs are interpreted by an AI/ML engine within the Data Processing Layer, producing insights and predictive information. The Application Layer then consumes this information, drives it to city dashboards, and automatically pushes control signals to actuators, forming the adaptive feedback loop. However, its success would depend on overcoming the vast technical challenge of merging real-time data and, no less significantly, addressing the basic security and privacy issues at the core of such a system. The long-term goal must be to leverage this dynamic technology as much for operational efficiency as for socially inclusive development, environmental sustainability in consonance with the SDGs, and ensuring that the smart city does not widen the urban digital divide [76].

Table 2. Types of sensors in multi-sensory grid

Sensor	Parameter	Application	Accuracy
Air Quality Sensor	Carbon dioxide, Particulate matter 2.5, Nitrogen dioxide	Environmental monitoring, pollution alerts	±2% for gas concentration
Temperature & Humidity Sensor	Temperature, Relative Humidity	Climate monitoring, HVAC control	±0.5 °C, ±2% RH (Relative humidity)
Smart Meter (Energy)	Electricity consumption, load data	Smart grids, energy optimization	±1% of reading

Table 2. Types of sensors in multi-sensory grid (continue)

Sensor	Parameter	Application	Accuracy
Water Quality Sensor	pH, Turbidity, Contaminants	Drinking water safety, wastewater monitoring	± 0.2 pH units, $\pm 5\%$ turbidity
Traffic Camera	Vehicle count, speed, congestion	Traffic flow optimization, smart mobility	90–95% detection accuracy
GPS Sensor	Location, velocity, route tracking	Navigation, fleet management, logistics	± 3 meters (civilian GPS)
Waste Bin Sensor	Fill level, weight, waste type	Waste collection optimization	$\pm 5\%$ of volume
Wearable Health Sensor	Heart rate, body temperature	Healthcare monitoring, emergency response	± 2 beats per minute, $\pm 2\%$ SpO ₂ (peripheral oxygen saturation)

Table 2 illustrates the wide variety of sensors used in adaptive multi-sensory grids, detailing their monitored parameters, applications, and accuracy levels. These sensors, ranging from air quality and water sensors to GPS and wearable health devices, collect real-time data that supports smart city functions such as mobility, healthcare, waste management, and environmental monitoring. Together, they form the foundation for data-driven decision-making and sustainable urban development.

5. Applications of Multisensor Grids

An integrated smart city platform is transforming urban mobility by creating a seamless, efficient, and sustainable transportation system. IoT is the foundation for such applications, enabling real-time data sensing, analytics, and evidence-based decision-making across various city domains. Applications in this segment increased tremendously from 2020 to 2025 and have focused on city resilience, sustainability, and citizen-centric services [1]. By ingesting data from various transportation and mobility streams into a centralized data platform, the system enables a wide range of cross-domain applications that redefine how goods and people move across the city [2]. The system enables an adaptive, responsive traffic control system that goes beyond fixed, pre-set timings at static traffic lights. Road sensors and GPS feed live data onto the shared platform. This provides a total city-wide view of traffic flows and congestion. This supports adaptive traffic control, where AI and multi-sensor inputs trigger IoT-based signals that dynamically change in response to real-time conditions, a technique that can reduce delays and emissions in cities like Singapore [3]. A major cause of urban congestion is the search for parking. To address this, IoT-enabled parking systems use embedded sensors to detect real-time space availability, which reduces congestion, fuel wastage, and driver frustration. Efficiency in urban parking management is further improved through AI-based allocation [4]. In the event of a breakdown or accident, the overall system can automatically call emergency services, alert digital signage, and divert other traffic to minimize secondary accidents and maintain traffic flow[5].

An integrated and harmonized public mobility infrastructure is the centerpiece of modern smart city development, aiming to break silos across different modes of transit. This development is based on the philosophy of Mobility as a Service (MaaS), in which public transportation such as bus services, rail networks, shared cycling systems, and other modes of transportation can be accessed via a single digital interface[6]. By incorporating common journey planning, the infrastructure brings together schedule and real-time location data from different transit services and enables passengers to set up the best possible routes that incorporate multiple travel modes seamlessly[7]. This not only makes travel more convenient but also promotes public and shared transportation over private cars, reducing traffic and emissions. A critical extension of this infrastructure is the inclusion of electric vehicles (EVs), where IoT sensors are used to track and manage charging infrastructure[8]. These sensors enable predictive energy allocation, optimize load balancing through

coordination with smart power grids, and ensure that power is harvested sustainably for charging EVs without stressing the grid [9].

To support mobility solutions, the energy and smart grids area also plays a critical role in powering the city sustainably and reliably. In a single data platform, energy usage patterns can be integrated with other city systems, so an intelligent grid can handle renewables, minimize energy wastage, and remain resilient to perturbations [10]. Together, these systems form an ecosystem in which transportation and energy infrastructures work in concert to advance sustainability, efficiency, and quality of life for city inhabitants [11]. A smart grid modernizes conventional power infrastructure by accommodating two-way communication between utilities and consumers, making it an intelligent network that increases efficiency, control, and sustainability [12]. One of its primary functions is incorporating IoT-based smart grids, where smart meters and networked devices gather real-time information to balance energy supply and demand effectively [13]. This infrastructure enables easy integration of renewable energy sources like solar panels and windmills so that green energy can be efficiently distributed across the grid without compromising stability [14]. Smart street lighting is another critical use case, using adaptive IoT-based systems that can automatically dim or brighten based on vehicle presence or pedestrian activity [15]. Furthermore, predictive maintenance makes energy systems' reliability and resilience even stronger. By analyzing data recorded by sensors on the network's transformers, power cables, and other infrastructure, AI applications can identify early signs of wear and tear, faults, or eventual collapses [16]. This predictive approach enables timely maintenance and intervention, reducing the frequency and duration of power outages and lowering repair costs. Together, these applications indicate that smart networks supported by IoT and advanced analytics form the foundation for sustainable, efficient, and future-proofed city energy systems [17].

The conceived framework is central to directing cities toward a sustainable and resilient energy mix, ensuring city development remains consistent with environmental and resource protection objectives [18]. One core component of this framework is managing renewable energy integration, where generation information from wind and solar sources is coupled with weather forecasts and current consumption patterns [19]. This allows grid managers to accurately forecast fluctuations in generation-based energy and adjust supply accordingly, keeping the system stable and optimizing green-energy use [20]. To further improve reliability, the framework uses IoT-supplemented microgrids that act as semi-autonomous energy systems and can identify faults and restructure in real time [21]. The microgrids add fundamental resilience by ensuring power availability during blackouts, natural disasters, or grid failures, thereby protecting vital services [22]. Another key area is supporting electric vehicle charging infrastructure, where the framework offsets the increased energy demand from electric vehicles within total grid capacity [23]. Through predictive analytics and incentive mechanisms, it promotes off-peak charging, avoiding system overloads and optimizing efficiency^[24]. Beyond energy, the system spans the broader arenas of environmental sustainability and resource efficiency, using interrelated data streams to reduce the city's ecological impact [25]. Through measures such as waste reduction, resource conservation, and support for a circular economy, the system ensures that city operations not only use the latest technologies but also operate in an environmentally conscious manner [26].

Table 3. Applications of multi-sensory grid

Domain	Sensor Type	IoT Role	Benefits
Smart traffic management & mobility	Multi-sensor systems including cameras, infrared sensors, and GPS in vehicles	IoT connects vehicles, sensors, and traffic signals into a cohesive network. It enables real-time monitoring and data collection to manage urban transport systems.	This leads to optimized traffic flow, reduced congestion, and improved urban mobility. It can also include advanced adaptive street lighting to save energy.

Table 3. Applications of multi-sensory grid (continue)

Domain	Sensor Type	IoT Role	Benefits
Smart parking	Ultrasonic or magnetic sensors in parking spaces	The IoT framework connects parking sensors to provide real-time data on parking availability.	This revolutionizes urban mobility by guiding drivers to available spots, saving time and fuel. It is a key component of an intelligent city's transportation infrastructure.
Smart energy grids	Smart meters and sensors integrated into the grid	IoT facilitates intelligent energy management across grids, often using AI and blockchain. It allows for the monitoring of smart home energy systems, including renewable energy sources and electric vehicles.	Benefits include enhanced environmental sustainability, increased energy efficiency, more resilient power grids, and decentralized energy trading.
Smart waste management	Ultrasonic sensors to detect fill levels in bins	IoT-enabled environments use multi-agent simulations to compare and optimize waste management models.	This optimizes waste collection routes, saving fuel and reducing operational costs.
Environmental monitoring	Air quality, temperature, and humidity sensors	IoT provides a platform for collecting and sharing environmental data across the city from various sensors.	Facilitates better urban planning and policy-making based on real-time environmental data, contributing to a more sustainable and healthier city.
Smart healthcare	Wearable devices, remote monitoring equipment	IoT connects various technologies to innovate healthcare delivery in smart cities.	Improves the accessibility and efficiency of healthcare services for residents in developing nations.

Table 3 highlights key smart city domains such as traffic management, parking, energy, waste, environment, and healthcare along with the sensor types, IoT roles, and benefits associated with each. It demonstrates how IoT-enabled sensor networks enhance efficiency, sustainability, and quality of life by enabling real-time monitoring, optimized resource use, and improved urban services. This proactive CCTV tracking boosts security, prevents incidents, and builds citywide robustness [44]. Environmental monitoring for smart cities uses IoT-enhanced infrastructure to generate real-time insights that support sustainability and public health [27]. Networks of air quality stations with IoT sensors track harmful gases such as CO₂, NO₂, and PM_{2.5}, and this information contributes to health programs and city-level policymaking [28]. The systems can also provide real-time warnings when smoke and other pollutants exceed safe levels, allowing authorities to take special measures and protect at-risk communities [29]. In addition to air quality, IoT is also important for noise and carbon footprint tracking [30]. Sensors in densely populated or densely trafficked locations measure noise pollution, guiding city planning and quality-of-life improvements [31]. Sensor information also comes together in carbon dashboards to track emissions, enabling cities to monitor performance against sustainability targets and climate actions [32]. At the same time, this use enables cities to take anticipatory action on environmental issues and support healthier, more sustainably livable cities [33]. In contemporary smart cities, AI and IoT technologies are being integrated to enhance waste and water management systems, making them more efficient and sustainable [34]. Intelligent waste collection relies on bins with fill-level sensors that provide real-time information, enabling collection services to use predictive routing for trucks [35]. This minimizes unnecessary travel, reduces fuel consumption, saves on operational expenses, and reduces environmental degradation.

To supplement this, automated waste segregation uses AI-based robotic systems that separate recyclable contents from mixed waste streams [36]. These greatly minimize the amount of waste that ends up in landfills but encourage circular economy practices by reusing valuable materials. In water management, similar devices with IoT continuously monitor leaks, assess water quality, and track distribution efficiency [37]. This supports the preservation of water sources, reduces losses, and ensures safe distribution, leading to long-term urban sustainability [38]. IOT technologies are having a transformative impact on healthcare and public safety in smart cities [39]. Wearable devices with integrated IOT sensors enable tracking of patient vital signs over a prolonged period, such as heart rate, oxygen levels, and body temperature [40]. These devices enable real-time transfer of information to healthcare professionals, which facilitates early detection of deviations, timely corrections, and enhanced long-term patient tracking [40]. In hospitals, IoT systems streamline operations through improved patient flow, optimized inventory tracking, and enhanced coordination of emergency responses [41]. Public safety, beyond healthcare, also benefits substantially from IoT-based CCTV systems with integrated AI analytics [42]. These systems track city spaces in real time to identify deviations from normalcy or suspicious activity and alert authorities promptly [43].

In smart cities, IoT-based platforms greatly enhance participatory governance by giving citizens real-time access to city data [45]. Real-time traffic flow, air and water quality, and energy consumption dashboards allow residents to engage directly with city operations and foster shared responsibility and inclusivity in decision-making [46]. This transparency not only strengthens civic engagement but also ensures that policies are conceptualized with high public input [47]. In addition, blockchain-based governance platforms enhance transparency and accountability by creating tamper-proof records of data transactions [48]. These networks safeguard the integrity of city information, reduce the chances of manipulation, and build increased trust between the government and citizens [49]. Together with blockchain and IoT technologies, they form a governance system that is transparent, accountable, participatory, and aligned with the citizen-centered smart city vision [50].

6. AI/ML Integration

The integration of Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL), transforms static, sensor-based smart cities into dynamic and truly intelligent systems [30]. While the Internet of Things (IoT) provides the city's sensory nervous system by collecting massive streams of real-time data, it is AI that acts as the brain, making sense of this information so that dynamic decisions can be taken, predictive insights can be obtained, and constant optimization of city services can take place [31]. This convergence, also known as the Artificial Intelligence of Things (AIoT), allows urban infrastructure not only to react quickly to immediate conditions but also to learn, adapt, and predict future requirements [32]. The goal is a responsive city fabric that increases efficiency, sustainability, and quality of life by embedding intelligence at the operational core of the city [33]. Machine Learning and Deep Learning models form the core of making adaptive decisions in smart cities [34]. They allow systems to discern patterns from data, predict outcomes, and make complex decisions programmatically without explicit human coding [35]. In a city environment, this means city services can dynamically adapt to the shifting needs of the citizen base and the environment [36]. For example, a smart traffic control system can use ML models on real-time traffic data streams from IoT sensors to programmatically tune traffic light timings to reduce congestion [37].

This shifts from hard-coded, time-based static signals to a dynamic, adaptable system that can intelligently react to real-time conditions [38]. Deep learning, a more advanced subset of ML, uses complex neural networks to discern subtle patterns in large datasets and is especially suitable for highly complex city problems [39]. A refined ensemble deep learning model, for example, can be used to develop smart parking systems that direct drivers to available spots, reducing traffic and pollution [40]. Likewise, multi-agent reinforcement learning systems may optimize recommendations for charging electric vehicles and, through experience and error, determine the optimal approach for balancing grid load and driver convenience [41]. This adaptability and learning ability are vital for long-term city administration [42]. In the long run, as cities grow and need to respond to new demands, AI-enabled systems can grow with the city [43].

The unification of neuro-symbolic AI, which brings together the strengths of symbolic reasoning and neural networks, offers the promise of a new-generation platform for city intelligence that can handle increasingly complex and nuanced decision-making scenarios [44]. Ultimately, the goal of both ML and DL is to move beyond limited automation and create systems that possess genuine adaptivity, steadily improving performance and efficiency over time [45].

ML Paradigms for Adaptive Multi-Sensor Grids:

Different Machine Learning (ML) paradigms suit different adaptive smart city tasks, depending on sensor data characteristics, computational constraints, and operational requirements. Supervised learning approaches are widely used in applications where labeled historical data is available, such as traffic flow prediction, energy demand forecasting, pollution estimation, and infrastructure fault detection. Algorithms such as Support Vector Machines (SVM), Random Forests, and Deep Neural Networks (DNNs) can achieve high prediction accuracy in structured urban environments. However, supervised models require large annotated datasets and frequent retraining to remain effective in dynamic city conditions. Unsupervised learning techniques are particularly useful for anomaly detection, clustering, and pattern discovery in large-scale sensor networks where labeled data may be unavailable or incomplete. These models can identify abnormal traffic behavior, unusual energy consumption, cyberattacks, or environmental irregularities without predefined training labels. Nevertheless, unsupervised approaches may suffer from reduced interpretability and sensitivity to noisy sensor data.

Reinforcement Learning (RL) has emerged as a promising paradigm for adaptive decision-making and autonomous optimization in smart city environments. RL models continuously learn optimal actions through interactions with dynamic urban systems and are well suited to adaptive traffic signal control, autonomous energy balancing, smart parking optimization, and resource-aware network management. Multi-agent reinforcement learning systems are particularly beneficial in distributed sensor grid architectures where multiple agents cooperate to optimize city-wide operations. However, RL models often require extensive training time, high computational resources, and stable simulation environments. Despite their advantages, deploying ML models within adaptive sensor grids introduces several practical challenges. Resource-constrained edge devices often have limited processing power, memory, and energy, making it difficult to deploy large AI models. Techniques such as model compression, pruning, quantization, and lightweight neural architectures are therefore essential for enabling efficient edge intelligence. Furthermore, adaptive smart city environments continuously evolve, causing concept drift in sensor data distributions. Consequently, AI systems must support online learning and continuous model adaptation to maintain long-term prediction accuracy and operational reliability.

The working deployment of AI in smart cities happens via a few basic abilities, namely predictive analytics, anomaly detection, and optimization [46]. These capabilities allow city managers to act proactively rather than reactively, resolving issues in advance and allocating resources as optimally as possible [47]. Predictive analytics leverages historical and real-time data to forecast future trends and events [48]. By analyzing data from IoT platforms, cities can optimize urban infrastructure and resource management [49]. This could involve predicting energy demand to prevent blackouts in a smart grid, forecasting traffic congestion to reroute vehicles in advance, or anticipating infrastructure maintenance needs before a failure occurs [50]. Anomaly detection is an important function for securing and making smart city infrastructure highly resilient [51]. In a city with thousands of web-connected devices, the risks of a cyberattack loom large [52]. AI models, especially those using federated and split learning technologies, can monitor network traffic within an IoT network and identify unfamiliar patterns that may indicate a cyberattack, enabling swift action and threat mitigation [53].

Optimization is perhaps the most widespread application of AI in making cities smarter [54]. AI algorithms are used to find the best possible solution to complex problems with multiple variables [55]. This includes optimizing waste management models through multi-agent simulations to determine the most efficient collection routes [56], enhancing urban sustainability through AI-driven energy efficiency strategies [57], and optimizing the performance and cost of big data processing with regional computing [58]. From street lighting systems that adapt to real-time conditions to the complex management of power grids, optimization ensures

that urban services are delivered with maximum efficiency and minimal waste [59]. The real strength of a smart city that can adapt lies in the seamless, hybrid combination of AI and IoT [60]. This mutually dependent relationship, where IoT sensors produce a continual flow of information, and AI programs take that information and make it into smart action, is the bedrock of the current smart city scenario. This combined model, referred to as AIoT, is transforming how cities are run and experienced. Hybrid systems appear in many smart city applications. In smart mobility, the combination of IoT, multi-sensor data fusion, and AI is central to conceptualizing smart traffic monitoring systems for roads. IoT devices on the roads and on vehicles gather information, which AI interprets for traffic control, accident detection, and real-time feedback for drivers. Smart energy systems also use a hybrid of 6G IoT, AI, and even blockchain to design sustainable and robust energy systems.

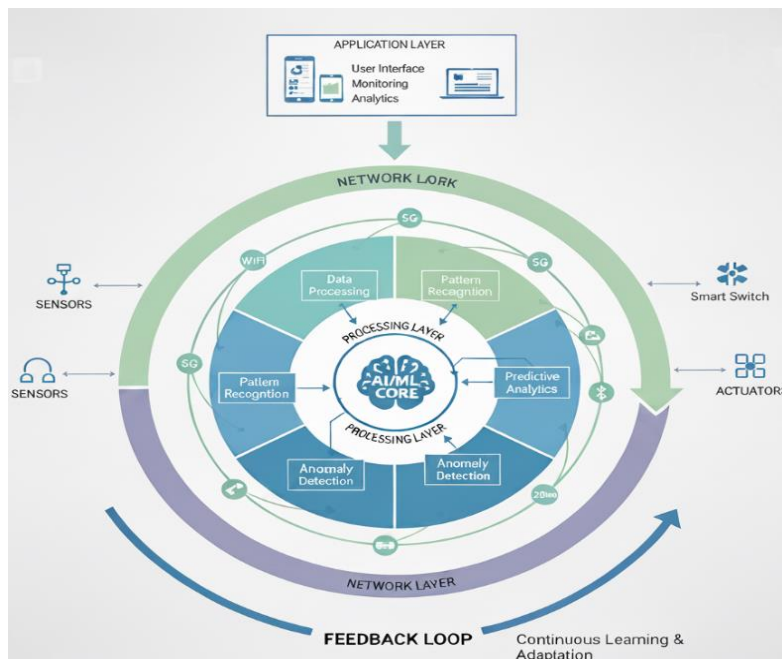


Figure 7. AI-enabled adaptive IoT framework

Figure 7 illustrates an AI-enabled adaptive IoT framework through a circular flow. It shows data moving from Sensors (Perception Layer) through a Network Layer to a central Processing Layer where an AI/ML Core performs data analysis, pattern recognition, and anomaly detection. The AI then sends decisions back through the Network Layer to Actuators, completing a Feedback Loop that enables continuous learning and adaptation, all managed and monitored through an Application Layer.

7. Challenges and Constraints

Establishing smart cities, although promising, faces numerous challenges that hinder success and proper execution. Challenges range across technological, financial, and ethical areas, all of which require careful attention and planning to overcome [61]. These include the system's ability to scale and integrate properly, safeguard large quantities of sensitive data while addressing privacy and ethical concerns, and manage the high costs and hardware constraints of installing sophisticated technologies in cities [62]. One of the main issues in developing smart cities is making deployed systems both scalable and interoperable [63]. Scalability involves a system's capacity to handle increasing workloads or expand to support growth. With increasing urban populations, smart-city infrastructure must support an ever-increasing number of devices and data volumes without performance degradation [64]. The large number of sensors and IoT devices needed for an extensive smart city network provides an incredible volume of data for processing, storage, and management [65]. Interoperability, the capacity of diverse systems and devices to communicate and share data without hindrances, is also an issue [66]. Intelligent cities may also depend on an assortment of technologies supplied by different makers, some of which may employ different standards and protocols. The absence of

standardization creates "information silos," where data from one system (say, traffic management) may not integrate straightforwardly with another (say, public safety), hindering the promise of holistic urban management[67]. To work effectively as an integrated whole, the disparate components of a smart city — from traffic sensors and smart grids to public safety networks—must also be able to communicate coherently. Making this possible requires defining common standards and open platforms that enable seamless integration among diverse technologies and functions [68].

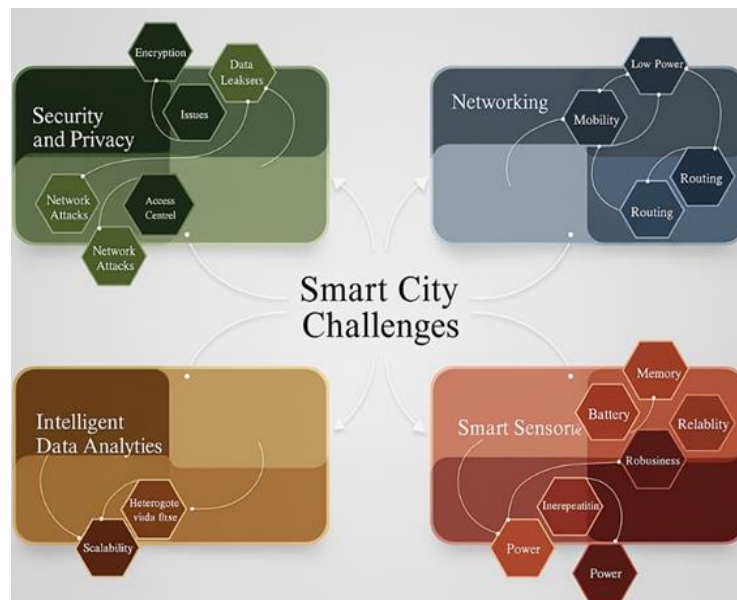


Figure 8. Challenges in Smart City

Figure 8 presents the key challenges in smart city development, categorized into four areas: Security and Privacy, Networking, Intelligent Data Analytics, and Smart Sensors. Each category highlights specific issues such as data leaks, network attacks, scalability, interoperability, power, and reliability, reflecting the complex technological and infrastructural hurdles in building smart urban environments. The wide collection of data inherent in the smart city raises deep security, privacy, and ethical issues [69]. Because IoT devices are highly interconnected, the attack surface for the entire smart city infrastructure is large, making it susceptible to cyberattacks. Adversaries may compromise critical urban infrastructure such as traffic management, power supply, or emergency response, thereby threatening public safety [70]. Guaranteeing the security of the interconnected infrastructure presents an ongoing challenge. Emerging technologies such as blockchain are being researched to develop more secure and transparent data management frameworks for smart cities[71]. Beyond security, ongoing data collection on citizens' movement, behavior, and activities also poses serious privacy issues. Data can be abused for surveillance or commercial exploitation by corporations or government entities without citizens' approval. This creates an important ethical tightrope: balancing the use of data for the common good with safeguarding individual privacy. Smart city development must therefore be guided by strong ethical considerations and sound data protection laws to build trust among people and ensure the technologies work for all people[72]. An ethical issue also arises: the potential for an "urban digital divide," where unequal access to technology may increase underlying social inequalities. Hardware limitations and high implementation costs also hinder implementation of smart city projects. Infrastructure installation required, i.e., sensors, communication infrastructure (e.g., 5G), data centers, as well as smart devices, is very costly. High capital expenditures might prove the biggest challenge for small cities or new economies with limited finances. For example, establishing an IoT sensor network for traffic and environmental monitoring for smart grid management requires enormous capital expenditure. Apart from the financial implications, there are also physical and hardware constraints. Most IoT devices also impose constraints on power consumption, data processing, and data storage. Installing sensors in the remote or hard-to-access parts of the city may also pose logistics challenges. Additionally, the fast-evolving nature of technology means hardware may become outdated quickly, requiring ongoing maintenance spending and infrastructure upgrades to keep

it running. Long-term fiscal sustainability also raises concerns, as cities need to establish sustainable business cases that cover both the start-up costs of deployment and the recurring costs of operation.

Open Research Challenges and Future Gaps

Despite substantial progress in adaptive smart city infrastructures, several unresolved research challenges continue to limit the large-scale deployment and operational efficiency of adaptive multi-sensor grids. One major open issue involves interoperability among heterogeneous IoT devices, communication protocols, and sensing platforms. Although multiple standardization efforts have been proposed, seamless integration across large-scale urban infrastructures remains difficult because of differences in data formats, communication standards, and vendor-specific architectures. Scalability also remains a critical concern in adaptive smart city environments. As sensor density and the volume of real-time urban data increase, centralized cloud-based systems often struggle to provide low-latency processing and efficient resource allocation. While edge and fog computing architectures reduce communication delays, optimal workload distribution between edge, fog, and cloud layers remains an open research problem. Artificial Intelligence (AI)-driven adaptation mechanisms introduce additional technical complexities. Although Machine Learning (ML) and Deep Learning (DL) models improve predictive analytics and automated decision-making, deploying such models on resource-constrained edge devices requires lightweight architectures, model compression, and energy-efficient inference mechanisms. Furthermore, AI models operating in highly dynamic urban environments must continuously address challenges related to concept drift, real-time adaptation, and changing environmental conditions.

Privacy-preserving techniques such as federated learning have emerged as promising solutions for decentralized AI training in smart city systems. However, federated learning performance in highly heterogeneous and non-independent and identically distributed (non-IID) sensor environments remains an unresolved challenge. Variations in sensor quality, communication latency, device capability, and local data distributions may negatively affect model convergence, stability, and prediction accuracy. Similarly, blockchain-based frameworks improve transparency and trust in distributed smart city infrastructures but introduce computational overhead, latency, and scalability limitations. Traditional blockchain architectures are often unsuitable for high-frequency real-time sensor data streams because of transaction throughput constraints and energy consumption requirements. Beyond technical limitations, socio-technical concerns such as unequal sensor deployment, digital inequality, mass surveillance risks, and ethical governance remain insufficiently explored in the literature. Future research must therefore focus not only on technological optimization but also on fairness, transparency, sustainability, and citizen-centric governance models for adaptive multi-sensor smart city ecosystems.

Table 4. Challenges vs solutions for adaptive multi-sensory grids

Challenge	Solution
Big data management	Regional computing can optimize the performance and cost of managing large volumes of data. Edge computing can also be utilized. Real-time data analytics helps in optimizing urban infrastructure and resource management.
Cybersecurity and privacy	A privacy-preserving and secure framework can be developed using blockchain and machine learning. Hybrid quantum architecture offers another solution for smart city security. Federated and split learning can enable anomaly detection of IoT cyberattacks. Blockchain and federated learning can be combined for enhanced cybersecurity in scalable smart city frameworks. Ethical dilemmas between sustainability and privacy require balancing and mitigation strategies.

Table 4. Challenges vs solutions for adaptive multi-sensory grids (continue)

Challenge	Solution
Interoperability	Smart cities need clear interoperability requirements. Semantic interoperability is a key research area that enables different systems to communicate effectively.
Scalability	Scalable smart city frameworks can be designed using technologies like blockchain and federated learning. For large-scale AIoT systems, multi-level split federated learning is a potential solution.
Energy consumption & sustainability	AI-driven energy efficiency strategies can enhance urban sustainability. Smart grids with sensors contribute to environmental sustainability. This includes intelligent energy management using 6G IoT, AI, and blockchain, as well as decentralized energy trading on blockchains.
Network connectivity	5G and LPWAN-IoT technologies can be used to improve connectivity for smart cities and remote areas.
Multi-sensor data fusion	Data fusion approaches are essential for IoT-based smart cities. Multi-sensor information fusion allows combining data from various IoT-enabled sources.
The digital divide	Smart city development should focus on being a social transition towards inclusive development to counter the urban digital divide.

Table 4 outlines major challenges in smart city development—including big data management, cybersecurity, interoperability, scalability, sustainability, and the digital divide—and pairs them with innovative IoT-driven solutions. It highlights how technologies such as edge computing, blockchain, AI, federated learning, and 5G can overcome these barriers to build resilient, secure, and inclusive smart cities.

8. Future Directions

The development of the smart city will see revolutionary breakthroughs through the interplay of different underlying technologies [60]. The long-term evolution is towards a highly integrated, smart, safe, and responsive city[61]. This will be achieved through next-generation wireless networks such as 5G and 6G, the decentralization of artificial intelligence via Edge AI and federated learning, the use of blockchain for increased security and transparency, and digital twin applications for high-end real-time simulation and governance of a city [62]. The convergence of 5G and future 6G networks will be a foundation for the next-generation smart city [63]. Next-generation wireless technologies will aim to transcend limitations of current networks by providing ultra-high bandwidth, ultra-low latency, and the ability to support a vast quantity of concurrent IoT devices [64]. 5G will act as the basis for communication infrastructure, which will support real-time communication of data for a plethora of applications such as smart traffic systems, automatic vehicles, and virtual public services [65]. The evolution of 5G and LPWAN-IoT architectures will be indispensable for optimizing smart city applications, primarily in rural locations[66]. As cities evolve and become increasingly data-intensive, seamless and expedient communication supported by 5G and 6G will be indispensable for managing the vast amount of information from an infinite number of sensors and connected objects [67]. This increased interconnectivity will enable increasingly complex and responsive cities, with systems ranging from dynamic energy grids that can intelligently manage power distribution to interlinked public safety networks that can respond quickly in emergencies [68]. The interface between these future networks and the IoT will facilitate an interconnected urban fabric, enabling cities that are leaner, greener, and more liveable [69]. To handle huge volumes of data from urban IoT networks, there is a distinct shift toward distributed data processing with Edge AI and federated learning [70]. Rather than pushing all data to a centralized cloud for processing, edge computing processes data in city, closer to the point of origin. This significantly reduces

latency, which is essential for real-time applications such as vehicle autonomy and citywide smart traffic management. This also reduces the expenses associated with pushing and storing vast volumes of data in the cloud. Federated learning also augments this setup [71]. This enables AI models to be trained from different data sources (e.g., different sensors or entities) without raw data ever leaving its point of origin. This approach is especially useful for smart-city applications, where data privacy and security concerns prevail. For example, one can apply federated learning to identify cyberattacks on IoT networks or improve traffic flow across the city by learning from distributed sources of information while keeping individual data points private [71]. Together, Edge AI and federated learning enable a decentralized, responsive, effective, and privacy-preserving architecture for urban intelligence that lets cities learn and adapt in a distributed fashion [71]. Blockchains are also an increasingly significant catalyst for addressing the security, privacy, and transparency concerns at the core of smart city infrastructures. In supply chain transactions and other interactions across various IoT devices and systems, blockchain can facilitate secure, transparent transactions and data management through a decentralized, immutable ledger. This is valuable for applications involving sensitive information or multi-party interactions, such as multi-party energy trading for smart energy grids, secure public governance, and multi-party supply chain transactions. In smart grid applications, blockchain can facilitate transparent and secure peer-to-peer energy transactions between consumers and support a decentralized, efficient energy platform [72]. In public governance, blockchain can facilitate tamper-proof records and enhanced public engagement and confidence. Further, when combined with machine learning and IoT, blockchain can provide a privacy-preserving, secure platform for smart city operations and protect against unauthorized use and manipulation of information. Integrating blockchain represents a significant step toward developing robust, trustworthy digital infrastructure so the information underlying smart city services remains reliable and secure [72].

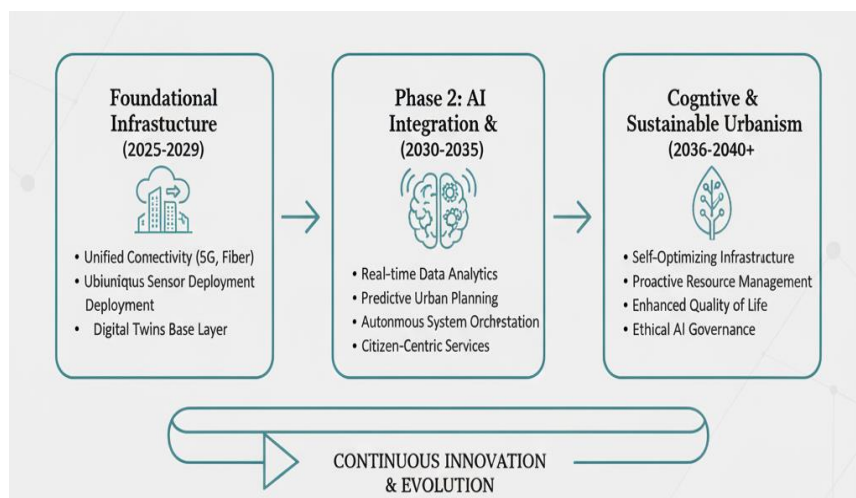


Figure 9. Future roadmap for adaptive multi-sensory smart cities.

Figure 9 outlines a three-phase roadmap for developing adaptive multi-sensory smart cities. It begins with Foundational Infrastructure, progresses to AI Integration & Adaptation for advanced data analytics and urban planning, and culminates in Cognitive & Sustainable Urbanism focusing on self-optimizing infrastructure and ethical AI governance, all driven by continuous innovation.

City planning and administration have a landmark innovation in the form of digital twin technologies [73]. A digital twin is a current, real-time replica of a city, including its structures, infrastructure, and operational systems [74]. The model is continuously updated with inputs from IoT sensors and enables city planners and managers to monitor city dynamics, simulate the impact of hypothetical changes, and optimize city operations virtually before changes take place in the physical world [75]. For instance, traffic flows can be simulated with a digital twin and tested for the impact of new traffic signal timings or layouts to alleviate congestion [76]. The environmental effects of new-building projects can also be simulated, waste collection routes optimized, or emergency response protocols planned for different scenarios [77]. A comprehensive

study of 4,200 papers highlights the growing importance and volume of studies on this topic through a thorough bibliometric analysis [78]. By providing a dynamic, citywide perspective, digital twins support better-informed, data-based decision-making [79]. This technology is central to the notion of urban intelligence, with powerful capabilities for designing greener, resilient, and effective cities [80].

9. Conclusions

Smart city development is propelled primarily by the Internet of Things (IoT), which can be described as the nervous system of cities. Multi-sensor grids enabled by IoT form the basis of modern urban ecosystems through the dynamic accumulation of transportation, energy, waste, and environment-related data. This constant flow of information informs urban intelligence and enables city managers to optimize public services, alleviate traffic congestion, optimize energy use, and improve residents' overall quality of life. When paired with Artificial Intelligence (AI), big data analytics, and other new digital technologies, IoT enables cities not just as networked infrastructures but as intelligent, responsive, and sustainable ecosystems. Despite rapid development, numerous problems remain unaddressed. One of the foremost is interoperability: the lack of global standards frequently hampers seamless communication between platforms and, as a result, creates disjointed "data silos." No less problematic is scalability, as fast-expanding populations and surging numbers of IoT devices create tremendous data flows that strain existing infrastructure. Cybersecurity is also another central issue. As city systems grow increasingly interconnected, they increasingly risk falling prey to cyberattacks that can harm critical services such as traffic control, public health, or electrical distribution. Though promising technologies such as blockchain, federated learning, and hybrid quantum architectures have been proposed as protections, further study is needed to develop scalable, robust security solutions. Financial sustainability is another vital barrier. Installing and operating the needed hardware—such as sensor networks, 5G and 6G connectivity, data centers, and advanced IoT-enabled devices—requires massive capital investments. Many cities, especially in developing nations, lack funds for such infrastructure, which is why innovative new models and funding mechanisms must be introduced that are both feasible and sustainable. One of the differentiating factors of successful smart cities is the merging of AI, particularly Machine Learning (ML) and Deep Learning (DL). While the sensory layer of the city consists of IoT, its cognitive layer consists of AI that interprets, analyses, and translates this data to enable predictive insights, adaptive decision-making, and dynamic system optimization. This amalgamation, sometimes described as the "Artificial Intelligence of Things (AIoT)," turns static infrastructures into dynamic systems that can respond quickly to current issues as they happen and predict future needs. ML and DL allow systems to learn from fluctuating urban data, automate sophisticated decision-making, and optimize service provision. For instance, AI-based traffic control systems can use real-time data to dynamically optimize signal patterns, minimizing congestion and emissions compared with fixed, pre-programmed systems. Similarly, deep models can identify complex patterns in urban datasets, supporting applications such as predictive maintenance, optimized parking allocation, and efficient energy distribution. Reinforcement learning mechanisms also extend flexibility by repeatedly optimizing strategies through trial and error and are particularly useful for applications such as electric vehicle charging infrastructure management. The evolution toward neuro-symbolic AI promises even more by combining data-driven learning with rational capabilities so that cities can address increasingly complex and nuanced issues. This way, AI does not merely automate routine tasks but creates genuinely adaptive systems that evolve with time and shifting city needs. The revolutionary role of AI in smart cities is most evident in three core functions: predictive analytics, anomaly detection, and optimization. Predictive analytics supports proactive administration by forecasting infrastructure needs, traffic patterns, and energy demand. Anomaly detection improves robustness by spotting abnormalities in IoT network traffic that might indicate cyber threats and enables immediate response. Optimization optimizes resource use across functional domains such as waste management, energy networks, and transportation infrastructure, eliminating waste and maximizing efficiency.

Hybrid AI-IoT solutions are breaking barriers of innovation with tightly coupled sensing technologies and smart analytics. In transportation, multi-sensor-based IoT with AI is used for real-time tracking and dynamic traffic control. In energy, smart grids with AI, blockchain, and advanced connectivity (5G/6G) enable

optimal integration of renewables, load balancing, and decentralized trading. Future paradigms like federated learning enhance privacy and scalability by training AI models in a distributed way without centralizing sensitive information. These hybrid systems represent a significant milestone toward increasingly automated and highly cognitive systems, making cities smart but also resilient, sustainable, and highly responsive to the needs of the populations they serve. The future smart city vision involves closing the distance between technological possibilities and socio-economic imperatives. Meeting interoperability standards, ensuring effective data protection, and creating sustainable financial models are critical prerequisites. Similarly, cities also need to put inclusivity first, so that city development and technological advances can be shared across communities and not used to exacerbate inequality. Looking ahead, new technologies such as digital twins for real-time simulation, 6G-based ubiquitous connectivity, and new-generation AI architectures will play a determining role in achieving the next generation of city intelligence. Overcoming current technical, ethical, and financial barriers will unlock the transformative value of smart cities, making them not only technology-intensive but also socially just and environmentally sustainable. Despite significant advancements in IoT-enabled smart city systems, the transition from conventional sensor networks to adaptive multi-sensor grid architectures remains an evolving research challenge. This review highlights that future smart cities will increasingly depend on distributed intelligence, adaptive sensing, AI-driven decision-making, and real-time sensor fusion for achieving resilient and scalable urban management. However, several unresolved issues persist, including interoperability among heterogeneous infrastructures, deployment of lightweight AI models on resource-constrained edge devices, privacy-preserving learning over non-IID sensor data, and low-latency coordination across large-scale urban environments. Emerging technologies such as 6G-enabled ultra-reliable low-latency communication (URLLC), federated learning, digital twins, and edge AI are expected to address many of these limitations by enabling real-time adaptation, predictive urban analytics, and decentralized intelligent control. Future research should therefore focus on developing self-optimizing, context-aware, secure, and socially inclusive adaptive multi-sensor grid frameworks that support sustainable and equitable smart city development.

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Experimental Performance of a Roof Solar Fibre-Cement Chimney and Thermoelectric Power Generation

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Abstract: Experimental performance of a roof solar fiber-cement chimney and thermoelectric power generation can enhance ventilation and mitigate heat gain in the attic. This paper presents initial experimental findings on the thermal performance of an advanced roof design using a recently introduced solar chimney configuration that incorporates ten thermoelectric modules. Specifically, one thermoelectric module (MT2-1, 6-127), measuring 40 x 40 mm, was placed in the roof solar fiber-cement chimney, which has a surface area of 0.24 m², and installed on the roof of a small south-facing room measuring 120 cm x 120 cm x 120 cm. Field test results demonstrated that this roof solar fiber-cement chimney, designed with thermoelectric modules, effectively fulfills its intended purposes of promoting ventilation and reducing heat gain through the roof envelope. Therefore, the proposed roof solar fiber-cement chimney with ten thermoelectric modules represents an innovative and viable alternative for various applications, including natural ventilation, indoor air circulation, and reduced roof heat gain. The roof solar fiber-cement chimney and thermoelectric power generation conserve energy and promote solar energy use.

Keywords: Roof solar fiber-cement chimney; heat gain reduction; thermoelectric power generation

1. Introduction

The roof is a vital component of a residential home, and heat beneath it can be used to generate electricity through thermoelectricity. This innovative approach not only harnesses renewable energy but also reduces dependency on fossil fuels. By optimizing design and materials, energy efficiency in buildings can be significantly enhanced (see Figure 1), providing protection against rain (moisture) and helping shield against sunlight, including intense solar radiation (shortwave radiation). During the day, when sunlight hits the roof surface, some rays are reflected while others are absorbed, transferring heat into the house. Consequently, the roof surface becomes hotter than both the outside air and the home's interior. This temperature difference causes heat to flow from the roof surface to the outside air. The accumulated heat in the roofing material conducts heat through the layers, moving from the exterior roof surface to the interior. This results in convection between the air beneath the roof and the interior roof surface, raising the temperature in that area. Following this, convection between the air under the roof and the ceiling leads to heat conduction through the ceiling material, transferring heat to the interior

ceiling. Lastly, convection between the indoor air and the ceiling further elevates the temperature inside the house. Because Thailand is in a hot, humid climate zone with hot, rainy weather year-round [1], temperatures range from 32 to 38°C, air humidity is 59-100%, and solar radiation intensity is approximately 17 MJ/m²/day. This radiation strikes the roof tiles, causing heat to accumulate and transfer through the roof structure into the building, resulting in heat and humidity buildup in the attic. This process raises indoor temperatures, leading to heat-accumulation problems in modern houses and buildings, which is a significant concern for residents' comfort. Therefore, the primary solution is to use mechanical air conditioners to reduce indoor temperatures and improve thermal comfort, which increases electricity consumption in residential houses or buildings. To combat this issue effectively, it is also crucial to consider energy-efficient alternatives, such as enhanced insulation and improved ventilation systems. By implementing these strategies alongside mechanical cooling, homeowners can maintain a comfortable indoor environment while minimizing energy consumption and associated costs.

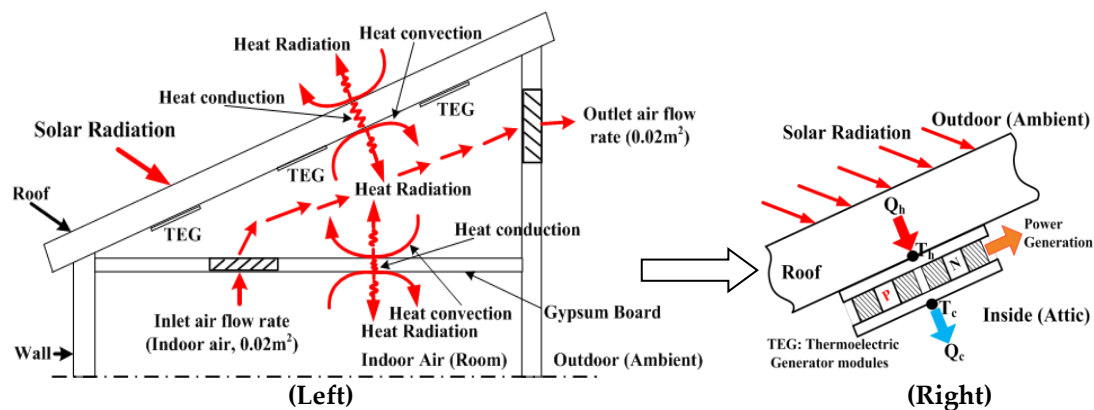


Figure 1. Schematic representation of heat transfer through roof solar fiber-cement chimney (left) and thermoelectric power generation (right).

In hot and humid climates, excessive solar heat gain and heat accumulation within building envelopes significantly affect indoor thermal comfort and increase cooling requirements [3]. In Thailand, as in many other tropical regions, residential buildings are increasingly featuring modern roof designs that are both visually appealing and cost-effective. Common roof types in housing estates include hip roofs, triangular gable roofs, and square or curved roofs. While these designs effectively protect against rain and shield against direct short-wave solar radiation during the day, they remain inadequate in mitigating long-wave radiation. Consequently, the roof surface absorbs solar heat and transfers it indoors through conduction, convection, and radiation. This process raises indoor temperatures above ambient levels, forcing air-conditioning systems to work harder and increasing electricity consumption and household energy costs [2–4].

Thailand's hot and humid climate, characterized by consistently high solar radiation and lengthy rainy seasons, worsens indoor heat buildup. [5]. To address these challenges, research efforts have focused on reducing heat gain through roofing materials and ventilation strategies. Levinson et al. [6] demonstrated that the color and reflectivity of roof tiles influence heat absorption, while Ogoli [7] investigated the benefits of attic insulation in minimizing heat transfer. Experimental studies have further confirmed that both cool roof designs and thermal insulation can lower indoor air temperatures. Building upon this, Chantawong, Khedari, Waewsak, and colleagues [8–12] explored naturally ventilated roofs and turbine-ventilated systems, showing that improved roof configurations significantly enhance airflow and reduce indoor thermal loads. Their findings highlight the critical role of roof design and orientation in improving ventilation efficiency and thermal regulation.

Against this backdrop, integrating passive cooling strategies with innovative energy-harvesting technologies offers a promising pathway toward sustainable building design. This study introduces and evaluates a roof solar fiber-cement chimney (RSFCT). This research employs carefully designed and controlled field tests to evaluate the effectiveness of hybrid passive-active roofing systems in reducing

household energy demand and improving thermal comfort. The study focuses on integrating a fiber-cement solar roof chimney with thermoelectric modules (RSFCT) and compares its performance against a conventional simple cement roof (SCR) under Thailand's hot and humid conditions. The originality of this work lies in developing and evaluating a dual-function roofing system that simultaneously enhances natural ventilation and harvests renewable energy. Unlike conventional roofing systems that focus solely on thermal regulation or ventilation improvement, the proposed Roof Solar Fibre-Cement Chimney integrated with thermoelectric modules (RSFCT) combines passive cooling and energy generation in a single system. This integrated approach improves indoor thermal comfort, reduces cooling energy demand, and provides supplementary electricity, supporting sustainable building design in tropical climates. The outcomes are expected to demonstrate how such systems can lower cooling requirements, enhance natural ventilation, and provide supplementary energy generation. Beyond Thailand, the findings have broader relevance for other tropical regions that face similar challenges in balancing indoor comfort with sustainable energy use.

2. Experimental Methodology

Building on the research framework outlined in the Introduction, the experiment compared two model houses: one equipped with a fiber-cement solar roof chimney with ten thermoelectric modules (RSFCT) and the other with a standard fiber-cement roof (SCR). Both houses were identical in size and materials, differing only in roofing design. Each had a volume of 2.016 m³, a south-facing orientation to maximize solar exposure, plaster walls (8 mm, painted white), a 6 mm plasterboard ceiling, and pearl-blue fiber-cement roof tiles set at a 30° slope with a roof area of about 2.04 m², consistent with international and domestic testing practices[13,14].

Figure 1- 2 illustrates the overall layout and configuration of the model houses. The walls were constructed from plaster sheets approximately 8 mm thick and finished with white paint to enhance reflectivity. The ceiling consisted of 6 mm plasterboard, while the roofs were covered with pearl-blue fiber-cement tiles inclined at 30°. Each house had a roof surface area of about 2.04 m². Home 1 (SCR) used a conventional roof configuration. For Home 2 (RSFCT), the roof was modified to include a solar chimney with a two-layer structure. The upper layer consisted of blue pearl-colored double-corrugated fiber-cement tiles designed to enhance ventilation, while the inner layer consisted of flat fiber-cement tiles approximately 8 mm thick. A thermoelectric module (MT2-1, 6-127, 40 × 40 mm) and the thermoelectric specifications in Table 1 were used; ten TEG modules were installed in the RSFCT channel (Figure 2). The gap between the upper and lower roof layers was approximately 0.01 m, creating a ventilation pathway. The 10 mm gap was selected primarily as a practical design constraint to facilitate integration with the existing fiber-cement roofing structure while maintaining a compact, low-profile configuration suitable for residential roof applications. Such a narrow channel may increase viscous resistance and influence airflow development within the chimney. The larger channel gaps are generally associated with lower flow resistance and may enhance buoyancy-driven ventilation performance. However, channel geometry, chimney height, solar heat gain, and temperature difference also play important roles in determining the overall airflow characteristics.

Openings of about 0.02 m² were provided at both the lower (indoor side) and upper (outdoor side) ends of the channel to promote buoyancy-driven airflow. Additional construction features included a 0.6 m² plastic door (7.5 cm thick) installed on the north wall and a 0.4 m² louver to allow additional air exchange; the thermal performance of these two houses is shown in Table 2. The overall construction followed previous studies on roof ventilation and thermal performance carried out by Chantawong, Khedari, Waewsak, and colleagues, but was extended here to incorporate thermoelectric energy harvesting [15, 16].

Table 1. Specifications of Thermoelectric MT2-1, 6-127 [17]-[19]

Leg height (mm)	1.5
Area of the thermoelement (mm ²)	1.96
Contact height (mm)	1.0
Insulator plate thickness (mm)	0.63
Module height (mm)	3.9
Area-to-length ratio	1.27
No. of couples (number)	127
Maximum operating hot side temperature (°C)	150
Thermal conductivity (W/m K)	1.647

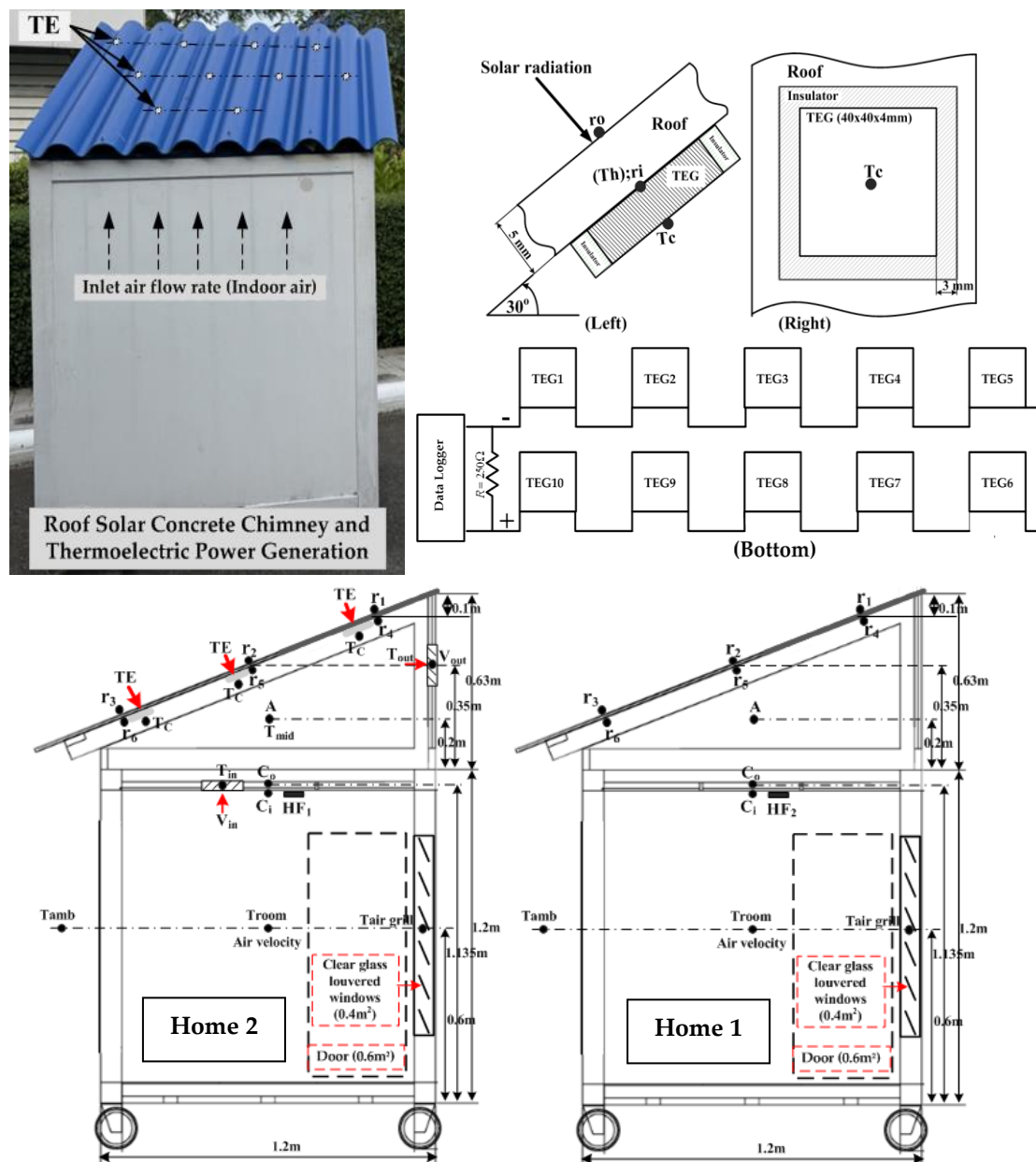
**Figure 2.** South-facing through-roof solar fiber-cement chimney view of the experimental houses (left), TEG modules (right), house dimensions and positions of measurement (Bottom).

Table 2. Materials thermal properties [14].

Type of material	Fiber-cement board	Thermal insulation
Thermal conductivity (W/m.K)	0.297	0.029
Density (kg/m ³)	775	120
Specific heat capacity (kJ/kg.K)	1.09	840
Emissivity	0.95	0.9

The experiments were carried out on 2 November 2025, with the air-conditioning system switched off to isolate natural ventilation and heat-transfer effects. Measurements focused on ambient conditions, indoor air performance, and roof thermal behavior. Solar radiation was measured using an MS 402 EKO pyranometer with an accuracy range of 0–1000 W/m². Temperature variations were captured using Type-K thermocouples (range: 0–1250°C; accuracy: $\pm 0.5^\circ\text{C}$), installed at multiple points, including indoor air, ceiling, roof surfaces, and the chimney interior. Wind speed was monitored using a TSI Model 8380 anemometer with a range of 0–50 m/s and an error margin of $\pm 5\%$, both inside and outside the houses. Airflow velocity was measured at the inlet (Vin) and outlet (Vout).

Roof heat flux was recorded using an EKO Heat Flow Meter MF-140, operating from -20°C to 120°C with an error margin of $\pm 5\%$. The thermoelectric module's voltage was monitored via 20 AWG UL1007 wiring (rated at 80°C and 300 V), connected to a 250 Ω matched load resistance, and power output was calculated using Ohm's law. Data from all instruments were logged at five-minute intervals between 8:00 AM and 6:00 PM using a Hioki 8422-52 data logger, which has a recording accuracy of $\pm 0.8\%$. Figure 2 shows the placement of the measuring instruments within the test houses for the SCR model, and Figure 3 shows it for the RSFCT model. Through this methodology, the study evaluated a wide range of performance indicators, including changes in environmental temperature, solar radiation intensity, indoor and ceiling temperature variations, roof surface temperature, and temperature fluctuations inside the RSFCT chimney. The analysis also included wind speed profiles inside and outside the model houses, heat flux through the roof surfaces, and the thermoelectric module's electrical performance. The comprehensive dataset ensured that the RSFCT system could be rigorously assessed for its capacity to reduce heat gain, promote ventilation, and generate supplementary power, thereby advancing sustainable building design for tropical climates.

3. Results and Discussion

The experimental investigation generated a comprehensive dataset on environmental conditions, indoor thermal performance, ventilation behavior, and thermoelectric output for the two model houses. Figure 4 illustrates the variations in indoor temperature, ambient temperature (T_{amb}), and solar radiation intensity (I_t) during the test period. The ambient temperature ranged between 27.5°C and 36.5°C , while solar radiation intensity varied between 0.59 and 1,298 W/m², peaking around 1:50 PM. A comparison of heat flux (HF1 and HF2) showed that the model house with the RSFCT (Home 2) experienced significantly lower heat transfer through the roof than the SCR house (Home 1). Specifically, the RSFCT reduced roof heat conduction by approximately 78.8% over the course of the day, highlighting the system's capacity to mitigate heat accumulation, and daytime air circulation measurements further confirmed the system's effectiveness. Internal airflow in the RSFCT house ranged from 0.013 to 0.75 m/s, which was markedly higher than that in the SCR house (0.01–0.015 m/s). The observed maximum velocity of 0.75 m/s occurred during periods of maximum solar radiation and temperature difference across the solar chimney, which enhanced buoyancy-driven airflow through the chimney channel.

External wind speeds were measured between 1.1 and 2.2 m/s, while the RSFCT's outlet ventilation reached 0.82–1.12 m/s, demonstrating the chimney's role in expelling indoor air and improving ventilation efficiency.

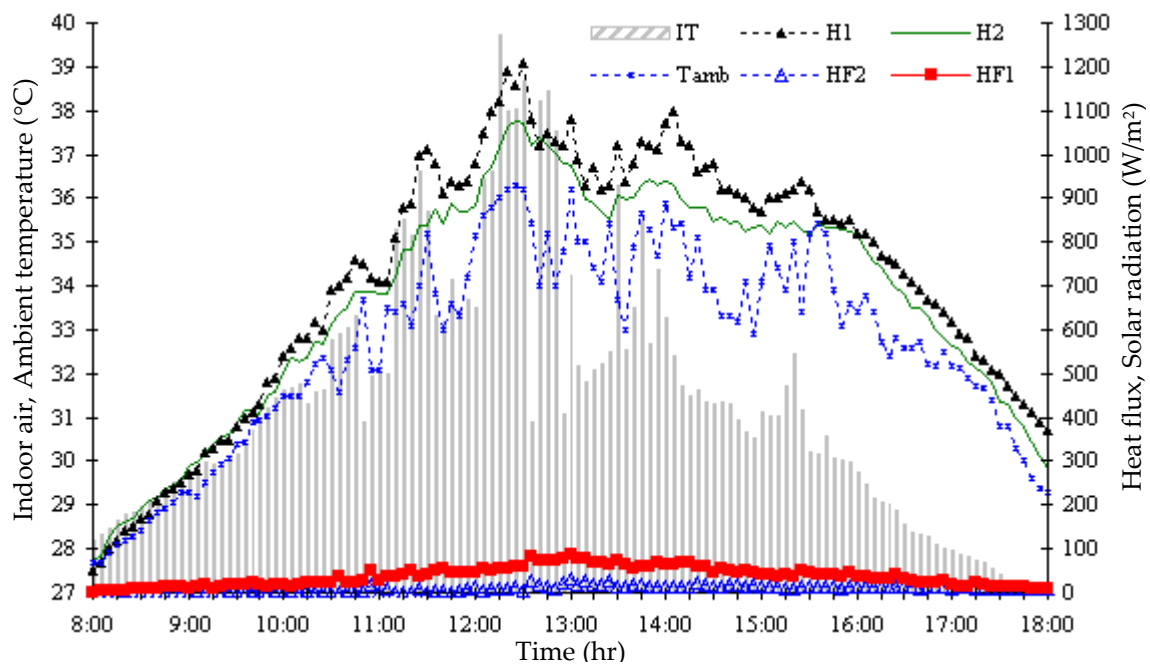


Figure 3. Changes in indoor temperature, ambient temperature, heat flux (HF1 and HF2), and solar radiation intensity.

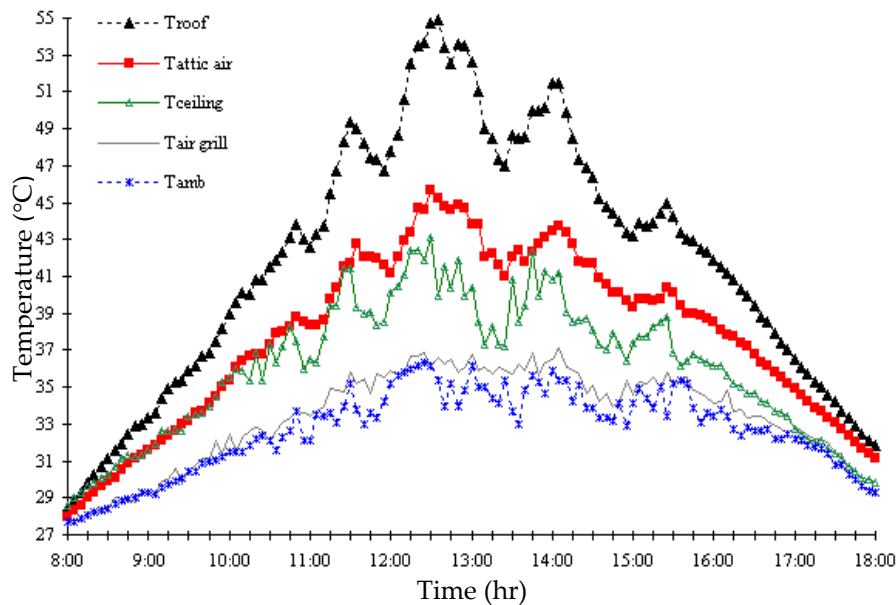


Figure 4. Results of temperature changes inside the installed test house with an SCR (Home 1).

Figures 4 to 6 show the temporal evolution of indoor temperatures in the two houses. Home 2, equipped with the RSFCT, maintained an indoor temperature approximately 0.2–2.8°C lower than Home 1 throughout the daytime. While the roof surface temperatures were similar for both houses—since they used identical materials and colors—the temperature inside the RSFCT chimney was consistently higher than both the indoor and ambient air. This thermal gradient generated buoyancy-driven airflow, enhancing natural ventilation. The 10 mm air gap used in the present RSFCT configuration is smaller than those commonly reported in solar chimney and ventilated roof studies, which typically range from 30 to 150 mm.

While a narrow channel may increase viscous resistance and potentially restrict airflow, it was selected in this study to enable practical integration with the fiber-cement roofing structure and to maintain a compact roof profile. The measured airflow enhancement suggests that buoyancy-driven ventilation was still successfully established under the tested conditions. Nevertheless, the influence of channel width on airflow resistance, thermal performance, and thermoelectric power generation warrants further investigation. Future studies should evaluate alternative gap dimensions to identify optimal design parameters for tropical building applications.

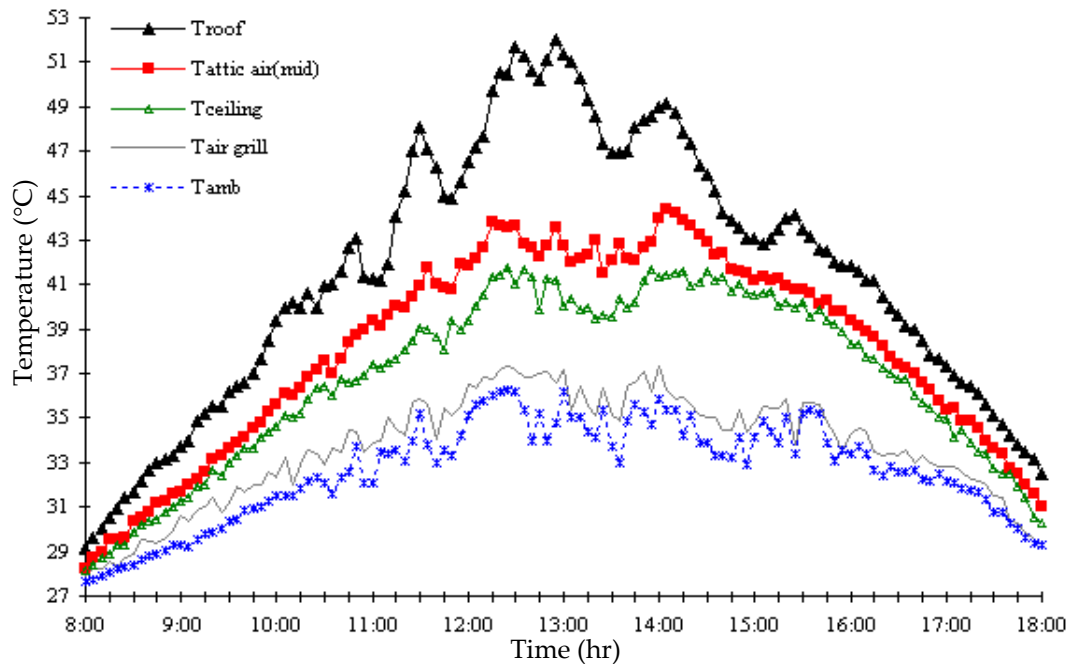


Figure 5. The results of temperature changes inside the installed test house with RSFCT (Home2).

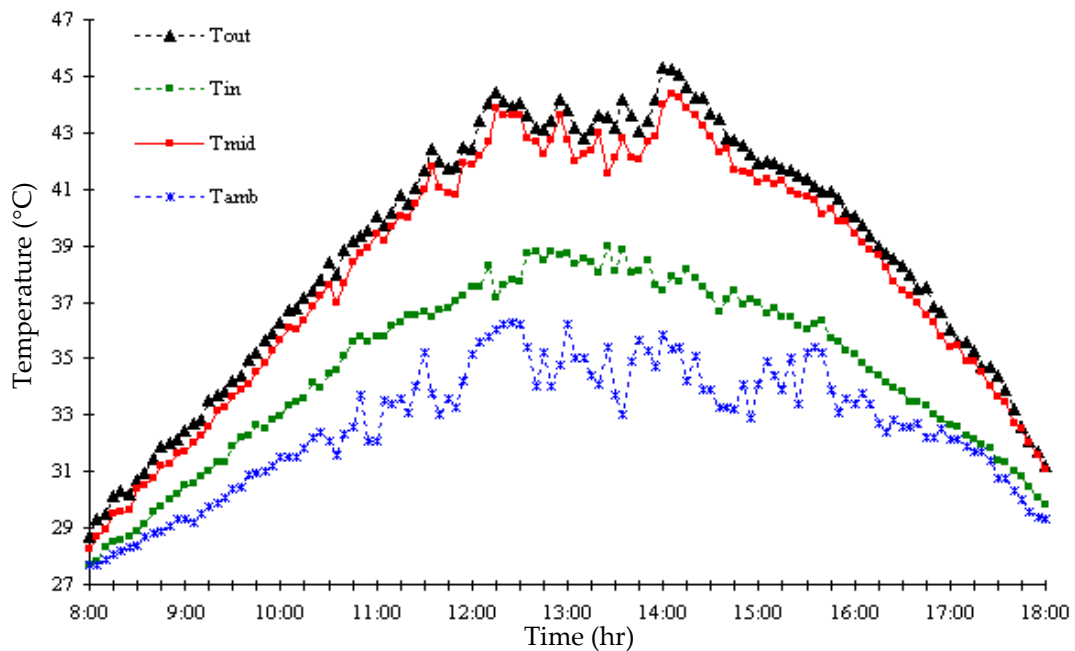


Figure 6. Results of temperature changes inside the RSFCT (Home 2).

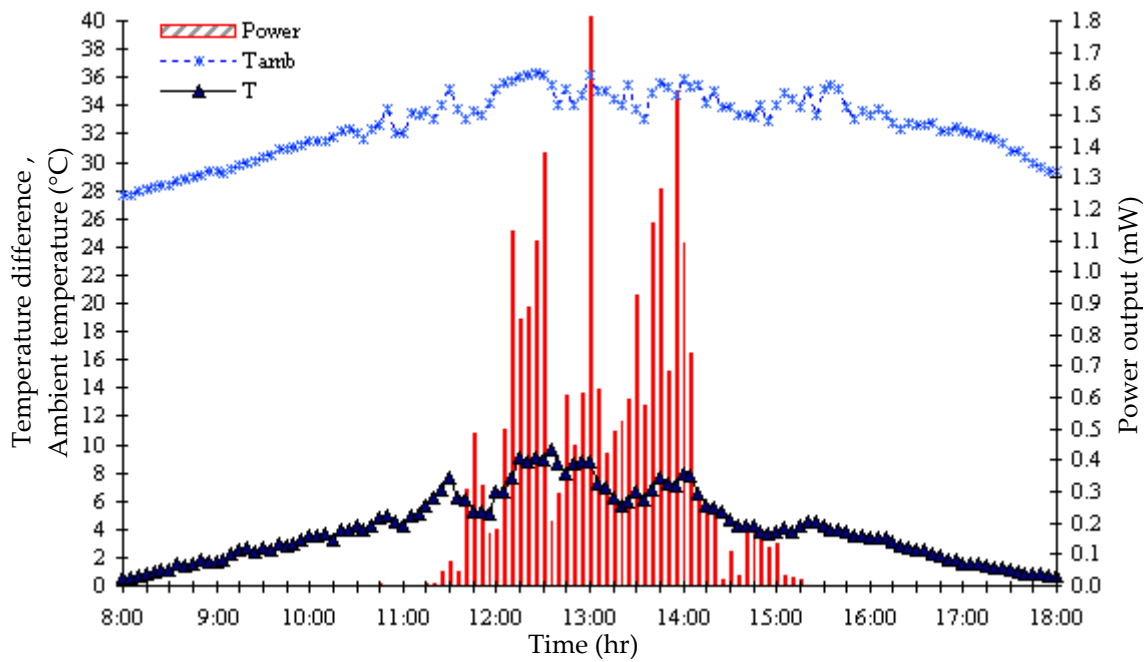


Figure 7. The results of the temperature change of the ambient, the temperature difference of the thermoelectric, and the power output (Home 2)

The electrical performance of the thermoelectric module is presented in Figure 7. Power generation ranged from 0.12 to 1.8 mW, depending on the temperature difference between the module's hot and cold sides. Although modest, this output demonstrates the potential of the RSFCT system to provide supplementary power alongside its primary function of improving indoor thermal comfort. Several limitations of this study should be acknowledged. First, the experimental evaluation was conducted over a single measurement day under specific climatic conditions. While the selected day was representative of typical hot and humid weather in Thailand, the results do not capture potential variations arising from seasonal changes, cloud cover fluctuations, rainfall events, or other meteorological factors. Consequently, the findings should be interpreted as an initial proof-of-concept assessment of the proposed Roof solar fiber-cement Chimney integrated with thermoelectric modules (RSFCT) rather than a comprehensive long-term performance evaluation. Second, the experiment was performed using a specific test-house configuration and roof geometry. The thermal and ventilation performance of the RSFCT system may vary depending on building characteristics, roof orientation, construction materials, occupancy patterns, and local climatic conditions. Therefore, exercise caution when generalizing the results to other building types or geographical regions. Third, the electrical power generation from the thermoelectric modules was evaluated under the temperature gradients achieved during the test period. Variations in solar radiation intensity and ambient conditions may influence the thermoelectric performance under different operating scenarios. T_h and T_c will be observed for a more complete assessment of TEG operating conditions. The optimization of chimney gap width was beyond the scope of the present study. Future investigations will evaluate a wider range of channel dimensions to determine the optimal balance between thermal performance, airflow enhancement, structural practicality, and thermoelectric energy generation. Moreover, future work will include detailed electrical characterization of the TEG array, including load-matching analysis and maximum-power-point determination, to optimize energy-harvesting performance. Future work will involve numerical modeling and full-scale experimental validation to investigate the scalability of the proposed system and quantify its performance under realistic residential operating conditions. Because the present study was based on a single experimental campaign, statistical uncertainty bands derived from repeated measurements were not available. Future studies involving repeated experimental trials will enable a more comprehensive

uncertainty analysis and statistical assessment of system performance. Finally, future studies should extend the monitoring period to encompass multiple days, seasons, and weather conditions to evaluate long-term performance, repeatability, and reliability. In addition, numerical simulations and economic assessments could be incorporated to investigate further the scalability and practical implementation potential of the proposed RSFCT system in tropical buildings.

4. Conclusion

This study presented a comparative evaluation of the thermal insulation performance between a fiber-cement solar roof chimney integrated with thermoelectric modules (RSFCT) and a conventional fiber-cement roof (SCR). The findings indicate that heat flow through the roof of the house with SFR was higher than that of the RSFCT-equipped house. Integrating RSFCT improved interior air circulation, reducing heat accumulation and enhancing natural ventilation. Such performance demonstrates the potential of FSRC as an energy-saving approach for building applications. Unlike solar cell roof ventilation systems, which typically rely on forced ventilation through DC fans [8]-[9], the RSFCT system is a simple modification of conventional roofs and operates as an open, naturally ventilated design. In addition, the thermoelectric modules incorporated into the RSFCT enabled small-scale electricity generation in the range of approximately 0.12–3.8 mW, adding further value through energy co-benefits. Specifically, the observed results demonstrate the potential of the proposed system under the specific environmental conditions tested. We emphasize that additional experiments over multiple days, seasons, and weather conditions are needed to validate the long-term performance, reliability, and generalizability of the findings. Overall, the development and application of RSFCT technology highlights a promising pathway for utilizing solar energy as a free, sustainable source to improve building thermal comfort, reduce energy consumption, and generate supplementary electricity. Future advancements in such roof ventilation systems could play a significant role in promoting renewable energy utilization and sustainable housing practices.

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ClothBiz Manager: An Offline GST-Ready Inventory and Billing Automation System Using Rule-Based Domain-Specific OCR

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Abstract: Smaller cloth wholesalers in India continue to use manual methods and paper-based systems, leading to discrepancies in inventory and delayed billing, among other issues. This paper describes ClothBiz Manager, an offline inventory management and billing automation solution tailored for Indian wholesale textile businesses. The solution combines a rule-based, domain-specific optical character recognition (OCR) process chain with a normalized PostgreSQL database, implemented using Java Servlets, Java Server Pages (JSP), and the Tess4J library. Our custom-developed Domain-specific Invoice Parser (DIP) processes invoices by applying domain-specific contextual rules and extracts the relevant information, including structured fields such as bale number, LR code, HSN code, and taxes. We evaluated our solution on 150 invoices obtained from Indian textile markets in Tiruppur and Surat. Our method scored 89% on exact matching for structured fields and 78% for multi-line product description fields. Running exclusively on a local server, our application provides absolute data sovereignty and guarantees GST compliance at the database level. Our results clearly show that our system can significantly minimize manual data entry.

Keywords: Cloth wholesale automation; domain-specific invoice parsing; GST compliance; offline inventory management system; optical character recognition

1. Introduction

Cloth wholesalers in semi-urban areas of India still use manual processes, including paper-based invoicing, inventory monitoring, and accounting practices. These systems lead to billing problems, missing invoices, inventory discrepancies, and compliance issues with GST laws [1]. These constraints adversely impact performance and compliance with regulatory norms among MSMEs [3]. Several studies propose innovative inventory management techniques [9], while some offer generic OCR-based methods for invoice processing [6]. Nevertheless, existing systems suffer from major constraints because they are mostly cloud-centric, cater specifically to Western-style invoices, do not account for the peculiarities of Indian textile wholesaler bills, and cannot address the complexities associated with Indian invoices, including multiple columns of data, bale numbers, LR numbers, multiple line items with HSN numbers, and shipping information. Moreover, only a limited number of these systems can operate fully offline, with database schema-level enforcement of GST compliance rules, in areas lacking Internet access [4].

As a result, to fill the gaps described above, in this paper we introduce ClothBiz Manager – a fully offline, on-premises web-based solution for inventory management and invoicing automation targeted at cloth wholesaler MSMEs. In this work, we introduce an important innovation in invoice processing by proposing the rule-based OCR pipeline (Invoice Parser-DIP), developed specifically for Indian textile invoices. By incorporating this OCR pipeline into a normalized PostgreSQL database that requires mandatory GSTIN and HSN fields, we provide total data sovereignty along with guaranteed compliance. To implement this project, we followed an iterative process starting with requirement analysis, architectural design, implementation, integration, and validation of the OCR pipeline and error conditions with invoice upload [4]. Finally, in the last phase, we configured the environment and Tessdata [16].

2. Materials and Methods

This paper describes the development of ClothBiz Manager, an online and offline-enabled inventory management and billing software intended for the wholesale cloth industry in semi-urban areas of India. ClothBiz Manager was developed using Java Servlets and JavaServer Pages (JSP) for server-side coding, with PostgreSQL used as the relational database for storing structured data. OCR features have been incorporated using the Tess4J library, which acts as a Java wrapper for the Tesseract OCR tool. This allows the system to automatically scan any textual data in scanned invoices. The domain-specific OCR system was designed to process the invoices in the textile domain. Invoice images were scanned, and grayscale images were formed from them. Preprocessing steps included noise removal and resolution normalization. Using the Tess4J tool, the system extracted raw text. Further, rule-based parsing techniques were applied to extract invoice attributes such as GSTIN number, HSN codes, bale number, LR code, item description, and tax details. The system validated the information and entered it into a normalized PostgreSQL database, ensuring mandatory GSTIN and HSN compliance. The proposed system's performance was evaluated using a dataset of 150 invoices received from wholesalers in Tiruppur and Surat. For each invoice attribute, accuracy was computed against the manually annotated ground-truth value. Precision was used to evaluate the results for multi-line item descriptions on the invoice. Additionally, system performance was measured by the time saved in the manual data entry process.

2.1 Domain-specific OCR Pipeline

An OCR pipeline for textile wholesale invoices was constructed. Textual information on scanned invoices is preprocessed, including conversion to grayscale, denoising using a Gaussian filter, and adaptive thresholding. The Domain-specific Invoice Parser (DIP) resulted from several design iterations based on a corpus of over 200 textile invoices. These invoices were collected between January and June 2024 from textile trading hubs in Tiruppur (Tamil Nadu), Surat (Gujarat), and Chirala (Andhra Pradesh) through direct collaboration with local wholesalers and cluster associations. The corpus was gathered using convenience sampling to ensure diversity and was kept completely separate from the 150-invoice evaluation dataset.

The development corpus represents a wide variety of real-world conditions, including:

- Different invoice layouts (single-column, multi-column, and tabular formats)
- Varying print qualities (laser-printed, inkjet, thermal, and dot-matrix)
- Multiple languages (primarily English, with some English-Telugu and English-Tamil invoices)
- Different paper types and conditions (new, aged, slightly crumpled)
- Variations in font styles, sizes, and ink density

No additional preprocessing beyond standard image enhancement was applied to the development corpus during rule creation so that the DIP rules could generalize to typical field conditions encountered in actual business environments.

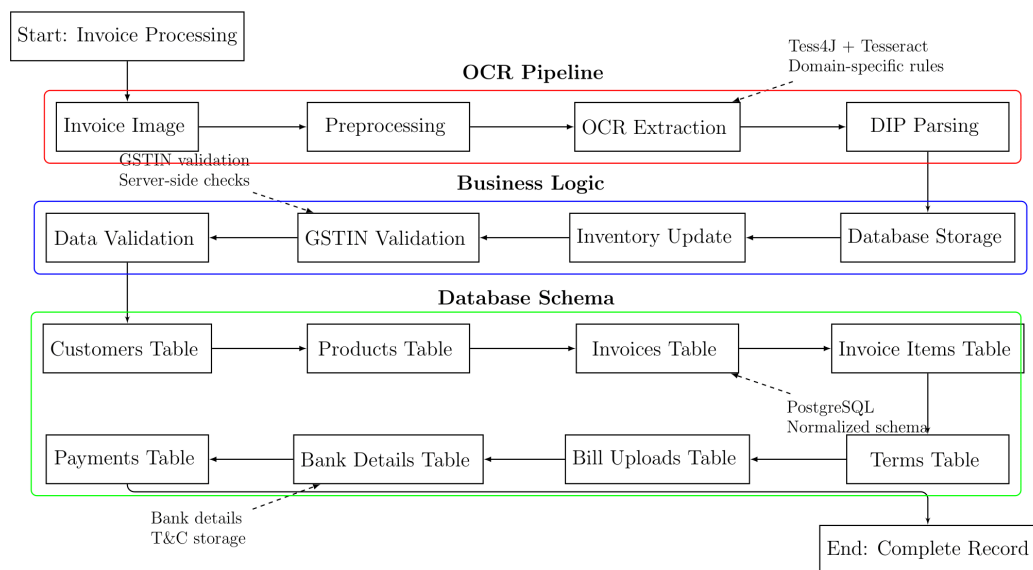


Figure 1. Manager System Architecture and Data Flow of ClothBiz.

This shows the end-to-end invoice processing pipeline of the ClothBiz Manager application. It starts with OCR extraction of invoice images and continues with domain-specific parsing and verification of GSTIN and inventory records. The business logic layer ensures data integrity before storing records in a normalized PostgreSQL schema consisting of customer, product, invoice, payment, and bank detail tables. The workflow produces a complete, audit-ready record of compliant business operations.

2.2 Requirement Analysis and Planning

Operational challenges were determined by interviewing stakeholders (textile cluster owners) in textile clusters like Tiruppur and Surat. According to stakeholders, lost invoices during power cuts were a repeatedly mentioned critical failure mode, which led to the offline-first design imperative. Other concerns included manual invoice processing, a high error rate in sales documentation, and a strict obligation to comply with Goods and Services Tax (GST). The functional requirements were obtained to support GSTIN-approved customer management, inventory with association of Harmonized System Nomenclature (HSN) code, and domain-specific invoice data extraction using optical character recognition (OCR). Non-functional requirements prioritized offline functionality, data sovereignty, and high extraction precision to fit on-premises IT limitations and data privacy expectations. The technology stack was chosen to meet the following constraints: backend and frontend development was based on Java Server Pages (JSP) and Java Servlets because they have a low external dependency footprint and compatibility with legacy Windows environments. For OCR, the Tess4J library, a Java implementation of the Tesseract engine, was selected to process invoice images client-side, so no data is sent to third-party servers. An experimental version of the Waterfall model was used, justified by the stability of the GST specification regulations; changes were lightweight feedback after OCR testing, which refined parsing rules based on user-reported extraction errors, allowing controlled adaptability without losing process traceability.

Waterfall model with limited iterative refinement was adopted for system development. This decision was justified by the nature of the core functional requirements, including GSTIN validation, HSN code handling, computation logic, and DB schema design, which have already been established and standardized under regulatory frameworks. Although the Indian GST framework has seen numerous changes since 2017, its basic features have not changed enough to warrant an iterative approach. The Waterfall model is characterized by sequential activities, making it easier to document and implement a specific solution. Rule-based DIP processing logic was implemented in a structured manner, except for rule refinement following initial tests of invoice processing results.

2.3 System Design

The following two aspects were maintained through the use of three-tier architecture design: modularity and separation of concerns. The presentation tier was developed using JSP files that validate all essential input parameters on both client and server sides. Java Servlets were used to manage customer, stock management, and OCR processes. The database follows normalization rules; there are tables for customers, inventory products, invoices, and OCR extraction logs. A development corpus containing over 200 authentic wholesale cloth invoices was collected to develop the Domain-Specific Invoice Parser (DIP). Invoices were sourced with the help of active participation from various textile wholesalers based predominantly in the Tiruppur and Surat wholesale textile networks, which constitute two prominent wholesale textile networks often utilized in the regional cloth market. Permission was sought from participating firms to use invoices for research purposes on an anonymous basis. Invoices were sourced in the field under practical conditions, such as using mobile phone cameras and flatbed scanners. Significant variance was observed in invoice structure, print quality, paper condition, font types, GST field location, bale number formatting, LR code presentation, and multiple line items in invoice descriptions. Both thermal-print and printed invoices (A4 size) were included in the corpus to increase the invoice parser's flexibility. To improve text-recognition accuracy in invoices, invoices were processed before OCR through image preprocessing tasks such as grayscale conversion, adaptive thresholding, noise removal, and skew correction. The development corpus was used exclusively for parser rule construction, contextual anchor refinement, and preprocessing optimization, and was kept separate from the final 150-invoice evaluation dataset used for performance assessment.

2.4 Implementation

The front end was deployed with JSP, and the GSTIN format was validated on both the client and server to ensure compliance with Indian tax laws. Java Servlets were written to provide backend logic that communicates with the PostgreSQL database via JDBC, using parameterized queries to avoid SQL injection vulnerabilities. The system integrates the OCR module through Tess4J, and image preprocessing routines precede text recognition to improve robustness against low-resolution scans and paper artifacts. The DIP engine maps unstructured invoice text to structured database fields with high fidelity by using patterns and contextual anchors, based on field-specific invoice structure, to interpret the resulting raw OCR output.

2.5 Testing and Debugging

System evaluation was conducted on a separate test set of 150 real-world wholesale cloth invoices that were not part of the DIP development corpus. The invoices were collected through convenience sampling from participating textile wholesalers in Tiruppur and Surat with prior permission for anonymized research use. The dataset consisted of 72 Tiruppur invoices and 78 Surat invoices. The evaluation dataset accounted for realistic scenarios and included thermal-printed invoices (46 invoices) and standard A4-printed invoices (104 invoices). Moreover, it included 38 invoices with poor scan quality, including blur, fading, distortion, or scanner artifacts. It included another set of 61 invoices with multi-line product descriptions. Invoices with substantial physical damage, handwritten notes that were difficult to interpret, and blurred parts were excluded because it was impossible to establish the ground truth. On average, 10 to 15 key fields per invoice were checked, including invoice number, GSTIN, customer information, HSN codes, bale number, LR code, product description, quantity, tax, and total amount. Two reviewers familiar with GST invoices and textile documents collected the ground truth independently. The reviewers reconciled differences through discussion. No blind testing approach was used, as this was an independent verification task.

Evaluation criteria included the following:

- Field-level exact match accuracy: The percentage of successfully extracted fields out of the total number of all analyzed fields, taking into account that the field is correct only if its content corresponds to the ground truth after normalization. This metric is used to evaluate structured fields like invoice number, GSTIN, bale numbers, and LR codes.
- Token-level accuracy (Jaccard similarity): Applied to multiple line descriptions to evaluate semantic similarity in case of minor differences in the text formatting.

In addition, precision, recall, and F1-score were calculated for the main fields' groups. Character Error Rate (CER) was evaluated for descriptive text fields. The system achieved 89% field-level exact-match accuracy and 78% token-level overlap accuracy in multi-line product description analysis. Overlapping print, handwritten notes, and low-resolution scanned copies were the most frequent types of errors due to the inherent limitations of rule-based OCR systems. Unit testing was carried out for GSTIN checking and inventory management, as well as for parser rules. Appropriate indexing of database fields frequently used in queries was performed (GSTIN, HSN code, invoice date). Field extraction performance was further evaluated using precision, recall, and F1-score metrics on major invoice fields to better assess the effectiveness of the OCR and information extraction process. Structured fields like GSTIN, invoice numbers, and HSN numbers performed well because of their standardized structure and context in the Domain-Specific Invoice Parser (DIP). The multi-line product description field performed poorly due to variations in layout structure, overlapping text fields, and deteriorating print quality in wholesale cloth invoices.

Table 2. Performance Metrics of the Domain-specific OCR Pipeline

Field Category	Precision	Recall	F1-score	Evaluation Basis
Invoice Number	0.89	0.87	0.88	Field-level exact match
GSTIN	0.92	0.90	0.91	Field-level exact match
HSN Code	0.88	0.86	0.87	Field-level exact match
Bale Number / LR Code	0.84	0.81	0.82	Field-level exact match
Multi-line Descriptions	0.78	0.74	0.76	Token-level overlap

2.6 Deployment and Maintenance

This was deployed as on-premises software based on the Apache Tomcat servlet engine, with a locally installed PostgreSQL database. Environment-related parameters, such as image locations and where the Tesseract engine's language data resided, were configured to provide portability in a mixed environment. This application was designed to be very low-maintenance. It relied on a stable base stack, and future enhancements would maintain modularity to add features like invoice scanning and role-based security.

3. Results and Discussion

The system has a lightweight, form-based web interface developed in JSP and CSS to support low-resource Windows-based machines prevalent in semi-urban textile centers. The main processes of customer onboarding, product directory, and invoice generation use coordinated input forms that enforce GSTIN validation, HSN code entry, and tax-compliant field requirements. Although this paper does not dwell on the UI, it provides operational accessibility for non-technical shop owners, bridging OCR automation and business use.

3.1 Bill Upload/OCR Processing Interface

The automation procedure starts at the upload interface depicted in Figure 2, where users enter scanned invoice images to be processed. This interface is the access point to the Domain-specific Invoice Parser (DIP) that is fully on-premises to guarantee data sovereignty. No invoice data flows outside at any level, meeting the stringent data privacy needs of cloth wholesale companies in semi-urban India. The design and testing protocols are based on quantitative assessment of 150 real-world invoice images, showing 89% accuracy on the invoice number and 78% accuracy on each multi-line item description. When multiple lines of description existed, adjacent text blocks having similar vertical alignment along with little horizontal spacing between them were combined to preserve semantic coherence. Post-segmentation validation rules were used to enforce uniformity in the extracted information, including the fixed number of digits for the GSTIN code, the numerical range for quantity and tax value, and alphanumeric characters for bale and LR codes. The segmented areas were then fed to the Tesseract OCR engine using the Tess4J library for text extraction. Figure 2 demonstrates DIP's performance results across the various fields found in invoices. Standardized invoice attributes such as GSTIN, invoice ID, and HSN code achieved higher precision, recall, and F1-scores due to validation constraints applied to the recognized data. Multi-line product descriptions

showed poor extraction results owing to variations in layout and spacing, along with degraded print quality usually seen in wholesale textile invoices.

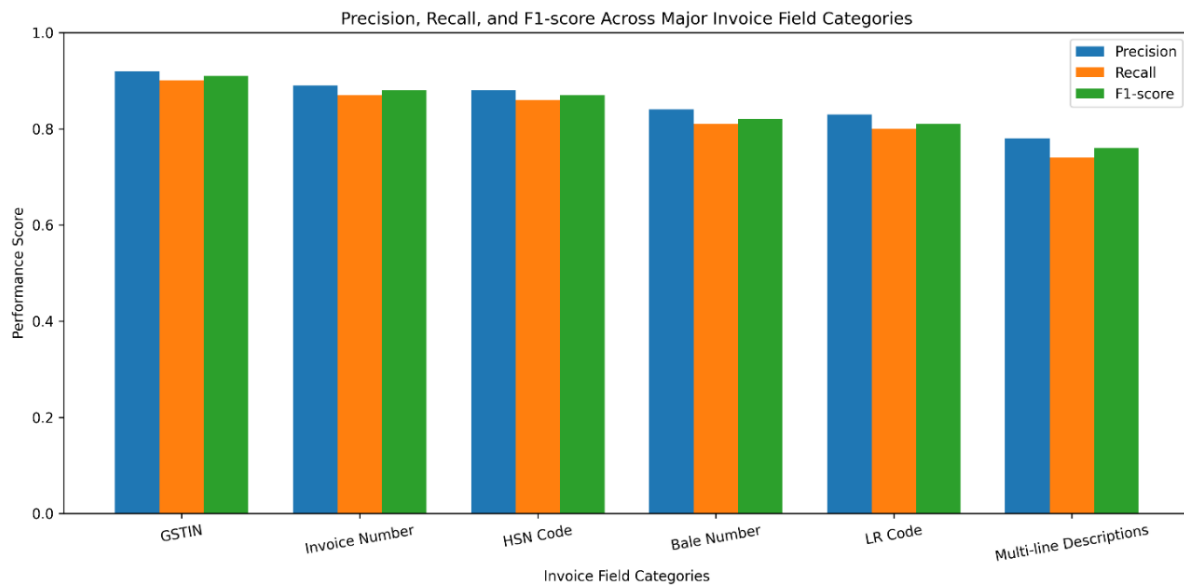


Figure 2. Precision, Recall, and F1-score Across Major Invoice Field Categories.

3.2 OCR Field Segmentation

To start, the invoice images were converted to grayscale, and adaptive thresholding was performed to address illumination issues and noise. Subsequent morphological image processing, such as dilation and erosion, would enhance text contours while removing non-textual objects from the invoices. Then the document structure would be broken down into regions through vertical/horizontal projections. For the tabular part of the invoices, line detection and word-level segmentation would be done through the connected components method and bounding box clustering. Column boundaries were determined based on whitespace distribution and the requirement that they align along the x-axis for each row. In addition, certain invoice-specific keywords such as “HSN”, “GSTIN”, “Qty”, “Rate”, and “Amount” were identified as reference points. Figure 3 visually represents the domain-specific competence of the parsing mechanism, where important fields such as bale numbers, lorry receipt (LR) codes, and HSN-carrying item descriptions can be segmented and extracted successfully from multi-column invoice layouts. Through layout-aware rules based on cloth trade conventions, DIP can perform reliable field isolation even in dense print settings, unlike generic OCR systems that treat invoices as unstructured text blobs.

Table 2. Customer Information Extraction.

Field Name	Extracted Value	Mapped To (DB Table)
customer_name	PARAMESWARI HANDLOOMS	Customers.customer_name
address	S.NO:74, NEAR GANDHI COLONY, GUNTUR – 583 655 BAPATLA (DIST)	Customers.address
Gstin	37BAINKJG7525ZZ	Customers.gstin
state_code	37	Customers.state_code
phone_number	7777788888	Customers.phone_number

This table renders all buyer fields extracted by the invoice header block. All fields have been normalized and mapped to the Customers table so that the same client can be identified in a given transaction.

0 **HANUMAN INDUSTRIES**

1 High Class Fancy Towels, Terrey Towels

2 72-E, Ramasamy Lane, Hanuman Complex, Chennai 638 001, (TN), INDIA

8 To: PARAMESWARI HANDLOOMS

9 S.NO:74, NEAR GANDHI COLONY

10 GUNTUR 583 655 BAPATLA (DIST)

11 GSTIN: 37BANKJG7525ZZ

12 State Code: 37

13 Ph: 7777788888

4 INVOICE No. 5 :317

6 INVOICE DATE 7 :25/07/2024

11 Order No

14 Transport

18 Place

22 Mode

13 SASI LORRY

17 CHIRALA

22 To Pay

25 S.No	Description of Goods	26 SIZE	27 HSN	30 PCS	28 Tax %	31 Rate	29 Amount
32	FANCY KRISHNA TOWELS	35 30X60	36 6304	37 540	5	39 66.00	38 35640.00
41	Gross Total						40 540

44 Rupees Thirty Seven Thousand Four Hundred And Twenty Two Only

49 BANK: PUNJAB NATIONAL BANK, RG STREET

50 AC NO: 0000 0000 0000

52 IFSC: PUNB 0361600

54 Terms & Conditions:

56 1. Interest will be charged @ 18% on bill, if payment not received within 15 days.

57 2. We are not responsible for any loss or damage in transit.

58 3. Goods once sold cannot be taken back under any circumstances.

59 4. All dispute subject to ERODE Jurisdiction.

60 For HANUMAN INDUSTRIES

Figure 3. OCR Field Segmentation and Bounding-Box Detection on a Sample Wholesale Textile Invoice. The image shows the DIP pipeline's domain-specific segmentation output. Red numbered bounding boxes highlight the automatically detected key fields such as seller information, customer details, GSTIN, invoice metadata, item descriptions with HSN codes, totals, bank information, and terms & conditions. Detailed mapping of each numbered region is provided in the accompanying legend.

Table 3. Extraction of Seller Information.

Field	Extracted Value
seller_name	HANUMAN INDUSTRIES
seller_address	72-E, Ramasamy Lane, Hanuman Complex, Chennai – 638 001
product_category	High Class Fancy Towels, Terrey Towels

This table captures the information about the issuing business that does not change with any invoice. These values support data provenance and ensure adherence to GST documentation requirements.

Table 4. Metadata Extraction Invoices.

Field Name	Extracted Value	Mapped To
invoice_id	317	Invoices.invoice_id
invoice_date	25/07/2024	Invoices.invoice_date
order_no	(missing, recorded as NULL)	Invoices.order_no
transport	SASI LORRY	Invoices.transport
place	CHIRALA	Invoices.place
mode	To Pay	Invoices.mode
gross_total	540	Invoices.total_amount
amount_in_words	Thirty Seven Thousand Four Hundred And Twenty Two Only	Invoices.amount_words

This table represents basic transactional metadata, including invoice number, date, transport, and total amount. These fields are mapped to the Invoices table and can serve as the main reference for accounting and audit processes.

Table 5. Line-Item Retrieval of Invoice Items.

S.No	Description	Size	HSN	Qty	Tax%	Rate	Amount	Mapped Table
1	FANCY KRISHNA TOWELS	30×60	6304	540	5%	66.00	35640.00	Invoice_Items

The table below is itemized product-level information retrieved from the invoice. Normalization supports accurate calculation of totals, tax payments, and inventory adjustments.

Table 6. Extraction of Bank Information.

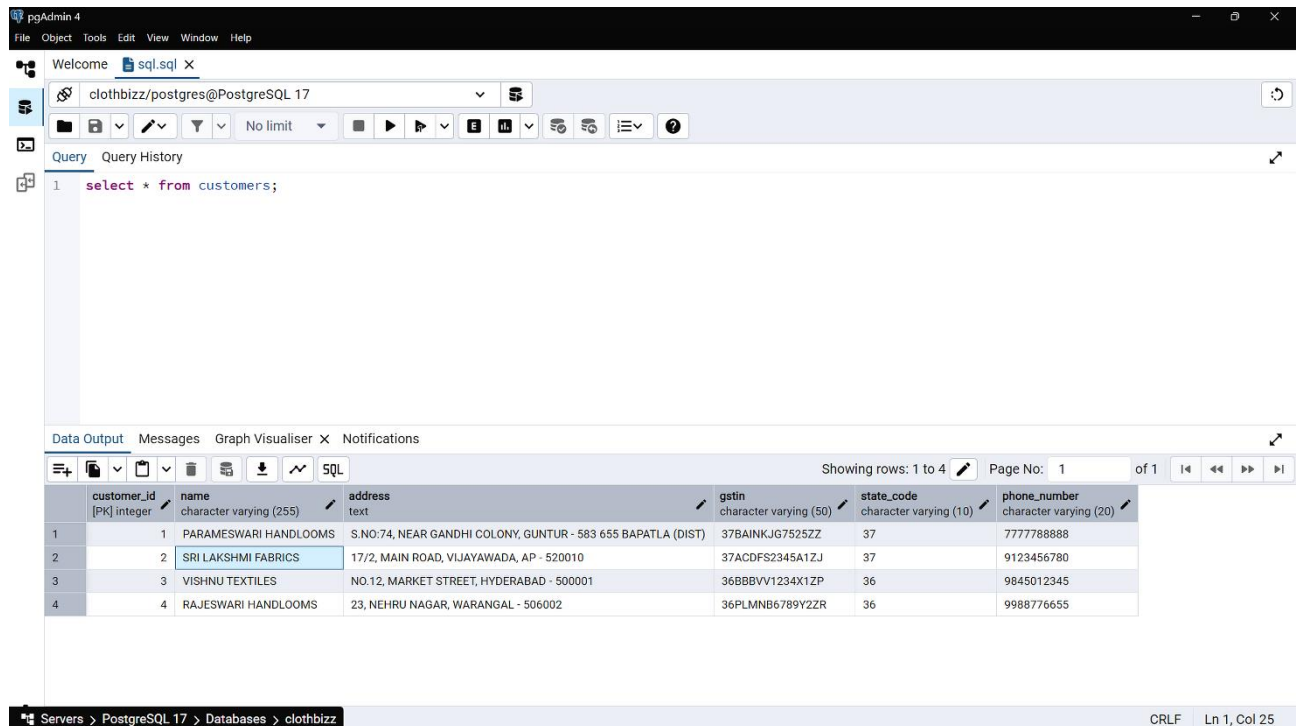
Field Name	Extracted Value	Mapped To
bank_name	PUNJAB NATIONAL BANK, RG STREET	Bank_Details.bank_name
account_number	0000 0000 0000	Bank_Details.account_number
ifsc_code	PUNB0361600	Bank_Details.ifsc_code

This table contains the bank characters of payment on the invoice. These values are associated with the Bank_Details table and automatically reconcile customer payments.

Table 7. Extraction of Terms and Conditions.

Term ID	Description	Mapped To
1	Interest @18% if payment is delayed beyond 15 days	Terms.term_text
2	No responsibility for loss/damage in transit	Terms.term_text
3	No returns after sale	Terms.term_text
4	Disputes subject to Erode jurisdiction	Terms.term_text

The following table lists the legal and transactional clauses removed from the invoice footer. The indices on each term are to be stored and tracked to create uniformity and traceability in the invoices generated by the system. The final end-to-end workflow will process unstructured invoice text into fully normalized, structured records compliant with GST. The system identifies and delineates all statutory fields, such as customer identity, seller details, invoice details, itemized HSN-coded line entries, tax percentages, logistics data (e.g., LR number, transport mode, place of supply), and banking details, as elaborated in Tables 1-6. These structured elements are stored in specific relational tables so the system can create GST-compliant invoices in real time from the database. The design ensures document consistency, enables auditing, and keeps all generated invoices compliant with regulatory requirements.



pgAdmin 4

Welcome | sql.sql

clothbizz/postgres@PostgreSQL 17

Query | Query History

1 select * from customers;

Data Output | Messages | Graph Visualiser | Notifications

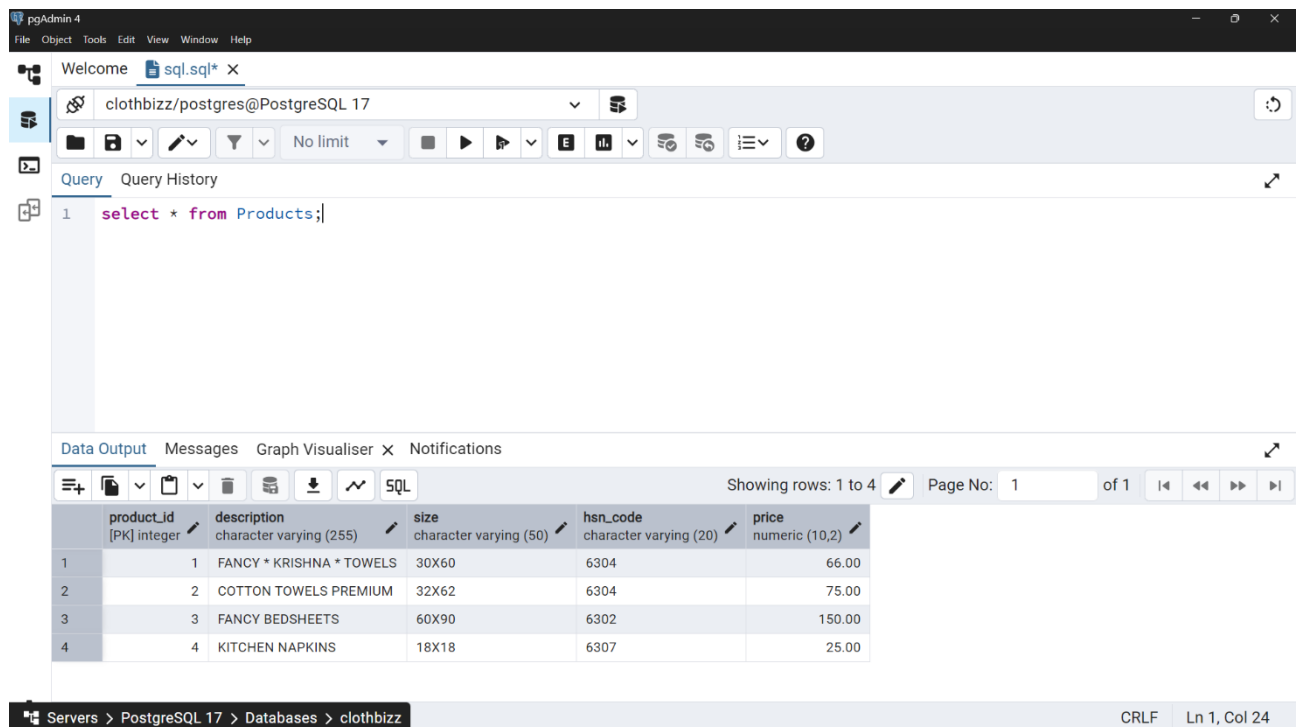
Showing rows: 1 to 4 | Page No: 1 of 1

	customer_id [PK] integer	name character varying (255)	address text	gstin character varying (50)	state_code character varying (10)	phone_number character varying (20)
1	1	PARAMESWARI HANDLOOMS	S.NO.74, NEAR GANDHI COLONY, GUNTUR - 583 655 BAPATLA (DIST)	37BAINKJG7525ZZ	37	7777788888
2	2	SRI LAKSHMI FABRICS	17/2, MAIN ROAD, VIJAYAWADA, AP - 520010	37ACDFS2345A1ZJ	37	9123456780
3	3	VISHNU TEXTILES	NO.12, MARKET STREET, HYDERABAD - 500001	36BBVV1234X1ZP	36	9845012345
4	4	RAJESWARI HANDLOOMS	23, NEHRU NAGAR, WARANGAL - 506002	36PLMNB6789YZZR	36	9988776655

Servers > PostgreSQL 17 > Databases > clothbizz

CRLF Ln 1, Col 25

Figure 4. Customer Database Table Structure.



pgAdmin 4

Welcome | sql.sql*

clothbizz/postgres@PostgreSQL 17

Query | Query History

1 select * from Products;

Data Output | Messages | Graph Visualiser | Notifications

Showing rows: 1 to 4 | Page No: 1 of 1

	product_id [PK] integer	description character varying (255)	size character varying (50)	hsn_code character varying (20)	price numeric (10,2)
1	1	FANCY * KRISHNA * TOWELS	30X60	6304	66.00
2	2	COTTON TOWELS PREMIUM	32X62	6304	75.00
3	3	FANCY BEDSHEETS	60X90	6302	150.00
4	4	KITCHEN NAPKINS	18X18	6307	25.00

Servers > PostgreSQL 17 > Databases > clothbizz

CRLF Ln 1, Col 24

Figure 5. Product Database Table Schema.

The PostgreSQL schema is normalized to support structured data persistence. Figure 4 shows the customer table, which enforces GSTIN format validation at the application and database levels. The product table shown in Figure 5 maps all products to their corresponding HSN code. The proposed system design will eliminate issues arising from erroneous entries during user data entry. Together, these factors indicate that the developed system can convert unorganized invoice documents into structured business records.

The synergy between domain-driven OCR and the system's data-driven management capabilities will directly address the operational inefficiencies evident in the requirements analysis phase, including minimizing manual entry errors and ensuring regulatory adherence. The system is very reliable with standard printed invoices. However, its behavior on documents with handwritten annotations or heavy print overlap indicates a known limit of rule-based parsing in this area and suggests a possible future direction toward hybrid symbolic-neural methods.

3.3 Aggregate OCR Extraction Performance

The representative invoice example presented in Tables 2–7 demonstrates the proposed system's operational workflow on a single real-world invoice. To evaluate the overall reliability and generalizability of the proposed Domain-Specific Invoice Parser (DIP), we conducted an aggregate experimental analysis using a separate dataset of 150 real-world wholesale textile invoices collected from Tiruppur and Surat textile trade networks. The validation data included heterogeneous invoice formats, thermal invoice formats, A4-sized invoice formats, poor-quality invoice scans, and invoices with multi-line product descriptions. Extraction performance was measured using accuracy, precision, recall, and F1-score for structured invoice fields at the field level. We assessed multi-line product descriptions using token overlap accuracy because line breaks could change formatting without affecting semantics.

Table 8. Aggregate OCR Extraction Performance Across Major Invoice Field Categories

Field Category	Accuracy	Precision	Recall	F1-score	Evaluation Basis
GSTIN	92%	0.92	0.90	0.91	Field-level exact match
Invoice Number	89%	0.89	0.87	0.88	Field-level exact match
HSN Code	88%	0.88	0.86	0.87	Field-level exact match
Bale Number	84%	0.84	0.81	0.82	Field-level exact match
LR Code	83%	0.83	0.80	0.81	Field-level exact match
Tax Values	86%	0.86	0.84	0.85	Field-level exact match
Bank Details	82%	0.82	0.79	0.80	Field-level exact match
Multi-line Product Descriptions	78%	0.78	0.74	0.7.	Token-level overlap

Table 8 illustrates the overall extraction efficiency for each invoice attribute category. Structured attributes like GSTIN, Invoice Nos., and HSN codes had better extraction efficiency because of their uniform formatting and the context-specific validation logic used in the Domain-Specific Invoice Parser. On the other hand, multi-line product descriptions showed comparatively low extraction efficiency due to non-uniform spacing, overlapping print areas, skews, and poor print quality that characterize wholesale textile invoices. In addition to the Character Error Rate (CER), OCR accuracy increased on invoice documents with faded thermal printing, low-quality image capture, handwritten notes, and strong scanning artifacts. Structured data had relatively low CER scores compared to semi-structured text due to stronger positional and context-based constraints during parsing. The comprehensive results indicate that the developed domain-specific OCR model performs accurately on invoice data extraction tasks for GST purposes.

3.3.1 GSTIN Validation Performance

The GSTIN was extracted using a contextual and structural validation method incorporated into the Domain-Specific Invoice Parsing (DIP) system. First, invoice images were processed via the OCR pipeline, where they were converted to grayscale, thresholded adaptively, noise-reduced, and deskewed. The OCR pipeline then extracted textual content from the invoice images.

For GSTIN identification, contextual cues used in wholesale textile invoices were considered, such as “GSTIN,” “GST No.,” and others. The parser used pattern-matching techniques with regular expressions to identify potential GSTIN values from the raw OCR output.

The GSTIN validation method made use of the standard 15-character GSTIN format as follows:

22ABCDE1234F1Z5

The validation technique determined the following criteria:

- The first two digits as valid Indian state or union territory codes,
- The next ten characters as PAN-format identifiers,
- The thirteenth character as the registration sequence code,
- The fourteenth character as the reserved “Z” field,
- And the fifteenth character as the checksum digit used for error detection.

Values that did not pass formatting check, length constraint, state code validation, and alphanumeric pattern check were discarded during the post-processing stage. This validation was highly effective in eliminating false positives caused by numerical patterns in documents, invoice totals, transport numbers, or fragmentation due to poor invoice quality.

3.4 Error Analysis

However, despite satisfactory OCR accuracy in extracting structured data from invoices, experimentation identified several OCR challenges.

Table 9. Common OCR Error Categories Observed During Evaluation

Error Category	Primary Cause
Misread characters	Blurred scans and faded printing
Missed invoice fields	Low-contrast text regions
Spurious extractions	Overlapping print artifacts
Incorrect line grouping	Multicolumn layout of an invoice
Partial identification of descriptions	Inconsistent alignment of text lines in multilines
Inaccurate identification of numbers	Degradation in thermal prints
Fragmentation of extracts	Image skew

The proposed system frequently failed during OCR operations on documents with fading thermal prints, overlapping characters, handwritten notes, and inconsistent multilines. The system achieved relatively accurate extraction of structured invoice elements like GSTIN and invoice number due to their consistent formatting. Several other errors were also caused by poor lighting and low-resolution mobile phone images. The proximity of characters in several other invoices caused segmentation errors due to inaccurate tokenization, especially where the invoice included dense product descriptions. Additionally, multi-column invoice formats sometimes interfered with line groupings during segmentation. However, despite these limitations, the Domain-Specific Invoice Parser performed consistently well across invoice types and greatly reduced repetitive manual data entry.

3.5 Comparative Analysis with Existing Studies

Implementing contextual parsing rules with a normalized PostgreSQL database helped capture customer information, invoice details, logistics details, inventory information, and bank-related details in an

integrated, GST-enabled document-processing pipeline. The design improved document traceability, minimized repetitive manual data entry, and supported record-keeping practices to facilitate auditing in contexts with limited digital infrastructure. In addition, the offline-first nature of the designed system allowed processing to continue without interruption, even under unstable Internet connections often seen in semi-urban business settings. Unlike cloud-enabled OCR platforms, our solution does not require access to remote servers, as the entire invoice parsing takes place in the local deployment environment. Moreover, in aggregate terms, it was found that structurally organized invoice details could be extracted reliably from invoices compared to semi-structured product description fields. However, the deterministic nature of the designed parsing rules proved fragile under poor invoice conditions, including handwritten details, overlapping print information, and non-standard invoice formats. Overall, the experiments suggest that domain-specific OCR solutions can help effectively address digitization needs of MSMEs in infrastructure-limited business environments. On the other hand, the OCR-only model made use of no context anchors, position-related constraints, invoice layout heuristics, or GST-specific field validations while extracting text directly from the invoice images. The model presented above used all such features, customized to the invoices' structure and nature.

Table 10. Comparative Evaluation of Baseline OCR and Proposed DIP Framework

System	Invoice Number Accuracy	GSTIN Accuracy	HSN Code Accuracy	Multi-line Description Accuracy
Tesseract OCR Without DIP	72%	79%	74%	58%
Proposed DIP Framework	89%	92%	88%	78%

The comparative analysis revealed that the proposed DIP method had much better reliability in data extraction than the benchmark OCR-based approach across all tested invoice-field categories. The biggest performance gain was in multi-line product descriptions, due to the application of line-grouping and layout rules. Structured invoice fields such as GSTIN, invoice numbers, and HSN codes also exhibited improved extraction performance because of the contextual validation constraints integrated into the parsing framework. GSTIN extraction particularly benefited from regular-expression-based validation and positional anchor detection mechanisms, which reduced false-positive extractions from unrelated numeric text regions. The baseline OCR-only workflow frequently produced fragmented outputs in invoices containing multi-column layouts, overlapping text regions, thermal-print degradation, and irregular spacing patterns. In contrast, the proposed framework showed improved resilience under heterogeneous invoice conditions by integrating domain-specific parsing logic and invoice-aware segmentation strategies.

3.6 Limitations and Future Directions

1. In the case of the rule-based engine, DIP is not robust in the face of handwritten or degenerated invoices; future research will investigate novel hybrid symbolic-neural models (e.g., CNN + regex) to meet the needs of this task.
2. Before and after parsing Static Template Assumption: Current parsing assumes that layout patterns are constant; adaptive template learning of new invoice formats is required.
3. Image inputs will only be processed; extraction of native PDF text layers will be introduced.
4. English and Telugu invoices are optimized, and other regional scripts (Tamil and Gujarati) will be supported.
5. It will be deployed as a desktop-only system; the field agent will have access through a lightweight PWA / Android application. systems.

The automation of semi-urban Indian MSIs indicates that the best way to digitize such enterprises is through domain-specific automation instead of generic AI, as shown by the ClothBiz Manager system. The Domain-specific Invoice Parser (DIP) was designed with cloth trade conventions (bale numbers, LR codes, and embedded item descriptions in the HSN) with an accuracy of 89 percent on invoice numbers and 78 percent on multi-line descriptions of items, compared to generic OCR tools, which consider an invoice to be

just plain text. Crucially, the system is completely offline, safeguarding data sovereignty, with GST compliance guaranteed by required schema-level checks: GSTIN, HSN, and state codes. In this version of the product, one can expect moderately stable invoice layout schemes. Adaptive learning of invoice templates and dynamic layout modeling may further enhance the parser's ability to generalize to novel invoice layouts. Currently, the system focuses exclusively on invoice layouts that come from scans. However, future versions could consider extracting native text layers from PDF files, alongside introducing support for OCR in other regional scripts, including Tamil and Gujarati. Other possible directions include developing lightweight mobile and PWA interfaces for collecting invoice fields, as well as maintaining inventory across distributed systems. On the other hand, the deterministic, rule-based nature of the parsing engine could be seen as a flaw, especially in handling illegible handwriting. It isn't a problem per se, since the focus here is on transparency and reliability rather than AI opacity or novelty. This solution delivers up to 70 percent more efficiency to the MSME users who employ standard printed invoices, without any cloud dependencies whatsoever.

3.6.1 Pilot Usability Evaluation

In practice, a pilot usability test was carried out in a wholesale cloth business environment to evaluate the usability of the processes involved, including uploading the invoice, OCR-based data extraction, generating the bill in accordance with GST requirements, and updating inventory.

Table 11. Pilot Usability Evaluation Results

Task	Task Completion Rate	Average Completion Time	Common Operational Issues
Invoice Upload	100	18	Incorrect image orientation
OCR Processing	92	24	Low-quality invoice scans
GST Bill Generation	95	31	Minor manual field correction
Inventory Update	90	27	Product-description mismatch

4. Conclusions

ClothBiz Manager solution has proved efficient in breaking down the conventional cloth wholesale business and its digitization compliance challenges. The synergy between the domain-specific OCR pipeline (DIP) and the fully normalized PostgreSQL database schema makes it possible to turn inefficient paper handling into efficient workflows that are also GST-compliant, while executing everything 100% offline. In a test conducted using the Domain-specific Invoice Parser (DIP) with 150 actual invoices, it achieved an accuracy rate of 89% for correct invoice numbers and 78% for correct descriptions in multi-line items, and the parser will always parse invoices better than any other generic OCR solution. The system ensures data integrity through its schema, including GSTIN, HSN, and logistics metadata; therefore, all invoices created will be statutory. The system built to handle semi-urban MSMEs will eliminate ledger errors and reduce data input by more than 70%.

Deployment Status:

Development of the system, ClothBiz Manager, is complete. It has been extensively tested using the invoices received from textile wholesalers. Although the system is ready to be piloted, it has not yet been put into use. Feedback from textile traders on the system's requirements and operation showed that they were pleased with its ability to work offline, its ease of use, and its potential to eliminate manual work. The next step will be pilot implementation of the system in selected cloth wholesale businesses in Tiruppur and Surat.

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Author Contributions: Penugonda Venkata Ayyappa contributed to the conceptualization of the research problem and the development of the methodology. He designed and implemented the ClothBiz Manager system, including the domain-specific OCR pipeline, invoice image preprocessing, OCR-based text extraction, contextual invoice parsing, and structured information extraction. He developed the GSTIN and HSN validation mechanisms and implemented the mapping of extracted invoice information into the normalized

PostgreSQL database. He conducted the experimental evaluation using real-world wholesale cloth invoices, analyzed the system performance, carried out testing and debugging, and prepared the tables, figures, workflow representations, and initial manuscript draft. He also analyzed the results, limitations, and potential future enhancements of the proposed system.

P S V S Sridhar provided expert supervision and strategic oversight throughout the research, contributing to methodological enhancements, validation of the system architecture and experimental results, and ensuring the technical rigor of the proposed inventory and billing automation system. He critically reviewed and substantively edited the manuscript to enhance its technical accuracy, clarity, and coherence. Furthermore, he provided guidance on the domain-specific OCR methodology, invoice information extraction, GSTIN and HSN validation, database design, and evaluation of the proposed system. His involvement was instrumental in maintaining the rigor, reproducibility, and integrity of the research, while also strengthening the discussion of system limitations and prospective future work, including hybrid OCR approaches, adaptive invoice template handling, native PDF processing, and mobile/PWA deployment.

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Development of Rubber Farmer Groups Towards Good Agricultural Practices for Rubber in the form of Cup Lump Rubber in the Northern Region of Thailand

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Abstract: This research aims to develop a group of rubber farmers in northern Thailand to adopt Good Agricultural Practices (GAP) for cup-lump rubber and to explore approaches to developing GAP for cup-lump rubber. The study focused on rubber farmers in Phrao District, Chiang Mai Province, using a participatory action research methodology. The research involved two steps. 1) assessing the farmers' capacity to manage rubber plantations according to Good Agricultural Practices (GAP) principles; and 2) proposing recommendations for developing Good Agricultural Practices (GAP) for cup-lump rubber farmers. The study found that in 2022, farmers had an average rubber plantation area of 3.31 Ha, generating an average income of 235,549.33 baht per year from rubber plantations, while incurring average plantation management expenses of 4,621.46 baht per year. Most farmers sold their products as dry cup lumps to their cooperative members, and most had a high potential for Good Agricultural Practices (GAP) in rubber (average 4.13). The development of rubber farmer groups in northern Thailand toward Good Agricultural Practices (GAP) for rubber in the form of cup lumps should involve promoting member participation, particularly in farmer group management, and establishing clear standards for rubber trading. This should be coupled with the development of knowledge and skills in rubber plantation management through training with the Rubber Authority of Thailand. Furthermore, product quality should be improved, participatory inspection systems implemented, fair marketing and profit-sharing plans promoted, and sustainability planning implemented. However, to successfully develop farmer potential, farmers must begin by shaping their attitudes toward the benefits of Good Agricultural Practices (GAP) and promoting knowledge and understanding of proper Good Agricultural Practices (GAP).

Keywords: Farmer group development; good agricultural practices for rubber; upper northern region; Thailand

1. Introduction

Thailand is a major global exporter of agricultural and food products. However, agricultural and food products have historically been unsafe for consumers due to chemical residues, pesticides, and microbial contamination. This has resulted in the quality and safety of these products not meeting international standards and those of importing countries. Therefore, the Thai government promotes and encourages farmers to produce safe agricultural

products in accordance with quality management systems, particularly Good Agricultural Practices (GAP), which prevent or mitigate risks associated with agricultural and food products [1]. Rubber (*Hevea brasiliensis*) is an important economic crop for Thailand and the ASEAN region. To produce clean, high-quality, fresh latex and cup-lump rubber cost-effectively, rubber plantations require sound management from planting through post-harvest [2].

In 2005, the 1 million Rai Rubber Plantation Project, initiated by the government, aimed to expand rubber plantations across 36 provinces, comprising 48,000 Ha in 17 northern provinces and 112,768 Ha in 19 northeastern provinces. The project, costing a total of 1.4 billion baht, aims to alleviate poverty and ensure rubber production meets global demand, which is growing at an estimated 2.6 percent per year [3]. At that time, the Cabinet approved the project and assigned the Department of Agriculture to study and define appropriate rubber plantation areas, monitor and control them, and procure suitable rubber varieties for cultivation in the northern region. Chiang Mai Province is the pilot area for the 1 million Rai Rubber Plantation Project in northern Thailand, initially implemented in Phrao, Fang, and Chai Prakan districts. According to 2023 statistics, Chiang Mai Province had 1,422 rubber farmers and a total rubber plantation area of 16,963 rai. This comprised 1,146.40 Ha of land with title deeds, comprising 694 farmers with title deeds, and 1,083.36 Ha of land without title deeds, comprising 728 farmers without title deeds [4]. In Chiang Mai, rubber farmers produce cup lump rubber due to its simple production process, long shelf life, and lower production costs compared to other types of rubber, such as fresh latex and smoked rubber sheets [5]. A report on the rubber production situation in the Northern Region found that rubber farmers sell their products at low prices due to trade barriers and the need for certified rubber production standards. Currently, rubber buyers require rubber to be produced to two main standards: the Forest Stewardship Council (FSC) and Good Agricultural Practices (GAP), which have led buyers to pressure farmers to lower their prices. Resolving trade barriers requires developing farmers' rubber production potential, both in terms of yield and quality, to meet international consumer demand [6]. Furthermore, import requirements for rubber products from the United States and European Union member countries require traceability, regulated under the Food Safety Modernization Act. Imported products must meet safe production standards [7]. Furthermore, a weakness for Thai rubber farmers is their reliance on exports alone. Under international trade regulations, agricultural products from exporting countries must undergo inspections to ensure compliance with agricultural product standards. Farmers lack the knowledge and understanding to standardize their own agricultural products, resulting in prices they receive that do not align with market prices and mechanisms [8].

For this reason, this study aims to develop rubber farmer groups towards good agricultural practices for cup lump rubber in the northern region of Thailand. The objectives are to develop rubber farmer groups towards good agricultural practices for rubber in the form of cup lump rubber in the northern region of Thailand and to seek guidelines for developing rubber farmer groups towards good agricultural practices for rubber in the form of cup lump rubber, which will lead to solutions to the problem of rubber prices for farmers that do not comply with market prices and mechanisms.

2. Materials and Methods

This research on the development of rubber farmer groups towards good agricultural practices for cup-lump rubber in the northern region of Thailand collected data from June 2023 to December 2023. The research process was divided into two stages.

In the first stage, assessing the potential of rubber plantation management according to good agricultural practices (GAP) in the northern region of Thailand, the researcher selected Chiang Mai Province as the data collection area because it is the pilot area for the 1 million rai rubber plantation project. The researchers used a quantitative research process, including an interview form with an incongruence value, to determine reliability (IOC) equal to 0.768 and a reliability value (Cronbach alpha) equal to 0.872. The researchers also used a qualitative research process, including non-participant observation, to study data from rubber farmers in Chiang Mai province. The population in this research was rubber farmers in Chiang Mai province. Which are farmers who are registered with the Rubber Authority of Thailand, Chiang Mai Province, in the year 2022, a total of 7 groups, These include: Chai Prakan Rubber Plantation Fund Cooperative Limited,

Phrao Rubber Farmers Group, Mae Chaem Agricultural Cooperative Limited, Fang-Mae Ai Rubber Plantation Cooperative Limited, Muang Na Subdistrict Rubber Growers Group, Mae Chaem Rubber Plantation Assistance Fund Cooperative Limited, and Mae Taeng Rubber Cooperative Limited. totaling 553 people (data as of April 30, 2022), by setting the sample size that sets the acceptable error of estimation of the total population at 0.05 using the formula for calculating the sample size of Taro Yamane [9], which calculated a total of 233 samples and performed simple random sampling by drawing lots of farmers' names to collect data using a semi-structured interview consisting of closed-ended questions and open-ended questions. The interview content is divided into 3 parts.

Part 1: Questions about some basic personal characteristics of farmers, some economic and social conditions of farmers, and the management conditions of rubber plantations of farmers.

Part 2: Questions to assess farmers' potential in managing rubber plantations according to Good Agricultural Practices (GAP) standards, according to the Good Practices Manual for Rubber Plantations, Field Latex Collection and Good Agricultural Practices (GAP) Standard Cup Lump Production of the Rubber Authority of Thailand, and according to the agricultural product standard TASK 5910-2020, Good Agricultural Practices for Rubber and Cup Lump Production, National Bureau of Agricultural Commodity and Food Standards, Ministry of Agriculture and Cooperatives, in 12 areas: 1) Rubber plantation management 2) Use of agricultural hazardous substances 3) Farmer production factor management 4) Pre-tapping management 5) Post-tapping management 6) GAP rubber tapping techniques 7) Rubber tree management (making cut marks) 8) Rubber lump production process 9) Harvesting 10) Post-harvest management 11) Plantation personnel management 12) Data recording and verification By using the practice scale adapted from the Likert Scale, a score of 5 is assigned as immediately actionable, a score of 4 as immediately actionable, a score of 3 as possible but takes time, a score of 2 as possibly actionable, a score of 1 as unlikely to action, and a score of 0 as impossible to action. The potential of Good Agricultural Practices (GAP) for rubber was divided into levels to interpret the results from the average stratification this is a 6 point application Likert scale by average values are calculated as follows: 5.00 – 4.16 points means the highest level of potential; 4.15 – 3.33 points means a high level of potential; 3.32 – 2.50 points means a medium level of potential; 2.49 – 1.67 points means a low level of potential; 1.66 – 0.84 points means the lowest level of potential; 0.83 – 0.00 points means no potential.

Part 3: Questions about problems, needs, and suggestions regarding Good Agricultural Practices (GAP) for rubber were asked. In addition, the researcher used Non-Participant Observation to observe farmers' management of their rubber plantations. The collected data will be analyzed using descriptive statistics, including mean and standard deviation, to describe basic personal characteristics, socio-economic conditions, and rubber plantation management conditions of farmers. Stepwise Multiple Regression Analysis will be used to identify relationships between independent variables and the potential for Good Agricultural Practices (GAP) among rubber farmers. Second stage: seeking ways to develop rubber farmer groups towards good agricultural practices for rubber using participatory development theory by conducting focus group discussions (FGD), in-depth discussions with specific target groups (group committee representatives and 5 farmer members per group, 7 groups) to plan operations and decision-making on the development process of rubber farmer groups towards good agricultural practices for rubber. Data analysis was conducted using the principles of farmer group potential development according to the 2022 Farmer and Farmer Institution Development Manual of the Rubber Authority of Thailand in 6 areas: 1) Farmer group management, 2) Knowledge and skills in rubber plantation management, 3) Production and product quality, 4) Marketing and networks, 5) Farmer member participation, and 6) Farmer group sustainability.

3. Results

1. Assessment of the potential of rubber plantation management according to Good Agricultural Practices (GAP) of farmers.

1) Data on basic personal characteristics, socio-economic conditions, and rubber plantation management conditions showed that farmers had an average age of 53.72 years, completed lower secondary education, had an average education of 7.35 years, and had an average experience in rubber plantation of 14.53 years (52.40%). The majority of farmers (63.30%) operated rubber plantations as a secondary occupation. They

spent their free time during the day doing other agricultural activities, such as longan, mango, or other field crops. This may be because farmers viewed rubber plantations as just a hobby and a source of additional household income. The average household labor force was 3.21 people. Most farmers did not hold social positions. 68.40% of farmers had successors in the agricultural profession. 51.00% of farmers had access to other agricultural capital. 61.58% of farmers did not have land title deeds. According to a 2023 agricultural survey, farmers had an average rubber plantation area of 3.31 Ha, generating an average income of 235,549.33 baht from rubber production. They had an average plantation management expense of 4,621.46 baht per year and had an average debt of 66,450.46 baht. Regarding rubber sales, most farmers sell their rubber products as dry cup lumps to cooperatives or farmer groups of which they are members. Only two cooperatives sell them as wet cup lumps: the Fang-Mae Ai Rubber Cooperative Limited and the Mae Taeng Rubber Cooperative. Most farmers' rubber plantations lack title deeds (87.52%). Meanwhile, farmers possess an average of four types of plantation management technology: lawn mowers, sprayers, pruners, and walk-behind lawn mowers. Officials decided to plant rubber trees from the Rubber Plantation Welfare Organization. (Former Rubber Authority of Thailand) that encouraged rubber planting in the Million Rai Rubber Project. In 2023, farmers contacted agricultural extension officers an average of 6.37 times (Table 1).

Table 1. Basic personal characteristics, socio-economic conditions, and rubber plantation management

Independent variable	Mean	S.D.
Age of farmers (years)	53.72	11.66
Years of education (years)	7.35	4.67
Experience in rubber plantation (years)	14.52	1.91
Main occupation of farmers (1 = main occupation / 0 = auxiliary occupation)	0.47	0.50
Type of labor used in the rubber garden (0 self-made / 1 employed labor)	0.41	0.49
Number of laborers in rubber plantation management (number of people)	3.21	1.28
Cost of rubber plantation in 2023 (Bath)	4,621.46	1,000.89
Income from rubber plantations in 2023 (Bath)	235,549.36	78,752.55
Debt related to rubber plantations of farmers (Bath)	66,450.64	84,052.62
Social Position (1 = Available / 0 = None)	0.07	0.26
Opportunities for farmers to obtain capital resources (0, none, none, none/none)	0.51	0.50
Inheritance of the rubber plantation occupation (1 = successor, 0 = no successor)	0.68	0.46
Number of times to get information (times)	9.47	3.73
Training received (1 = trained / 0 = not trained)	0.51	0.50
Number of times of coordination with agricultural extension officers (number of times)	6.37	3.47
Number of rubber plantation areas (rai) $\cong$ 3.31 Ha	20.60	5.83
Other agricultural activities in rubber plantations (1 = other activities / 0 = no other activities)	0.51	0.50
Land title deed (1 Licensed / 0 Non-Licensed)	0.38	0.33
Receiving assistance from the Rubber Authority of Thailand (1 = received assistance / 0 = did not receive assistance)	1.00	0.00
Number of technologies used for rubber plantation management	4.06	1.02

2) The potential for Good Agricultural Practices (GAP) for rubber farmers in Chiang Mai Province found that most farmers had a high potential for GAP (average 4.13). When considering each aspect, it was found that farmers had the highest potential for management of rubber plantation areas (average 4.16), followed by farmers with the lowest potential for management of rubber trees (making cut marking lines), data recording and inspection (average 4.14), and post-harvest management (average 4.09) (Table 2).

Table 2. The potential for Good Agricultural Practices (GAP) for rubber farmers

variable	Mean	Std. Deviation	Interpretation
Management of rubber plantation areas	4.16	0.45	highest
use of agricultural hazardous substances	4.12	0.45	high
management of farmers' production factors	4.13	0.45	high
management before rubber tapping	4.11	0.45	high
management after rubber tapping	4.12	0.46	high
rubber tapping techniques according to GAP principles	4.13	0.44	high
management of rubber trees (making cuts, dividing lines)	4.14	0.45	high
rubber block production operations	4.13	0.45	high
harvesting products	4.13	0.47	high
post-harvest management	4.09	0.45	high
management of personnel working in rubber plantations	4.13	0.46	high
data recording and inspection	4.14	0.45	high
overview	4.13	0.46	high

Remarks: this is a 6 point application Likert scale by average values are calculated as follows: 5.00 – 4.16 points means the highest level of potential; 4.15 – 3.33 points means a high level of potential; 3.32 – 2.50 points means a medium level of potential; 2.49 – 1.67 points means a low level of potential; 1.66 – 0.84 points means the lowest level of potential; 0.83 – 0.00 points means no potential.

3) Factors Affecting Good Agricultural Practices (GAP) for Rubber Farmers: The Pearson Product-Moment Correlation Coefficient (PMC) found no multicollinearity among the independent variables. Therefore, the researchers conducted a stepwise multiple regression analysis and found that the Multiple Coefficient of Determination (R²) was 0.93, indicating that all independent variables could explain 93.30% of the dependent variable. Of the 21 independent variables, three were significantly positively correlated with the dependent variable at the 0.01 level. First, the farmers' years of education: this means that highly educated farmers have a greater potential to adhere to Good Agricultural Practices (GAP) standards. This may be because education level affects their ability to perceive, understand, and apply knowledge to rubber plantation management. Highly educated farmers tend to have greater access to academic information and modern agricultural technologies. They can learn the principles and requirements of GAP standards, including proper soil and fertilizer management, the safe and correct use of chemicals, pest and disease control, and the harvesting of quality produce in accordance with standards. Furthermore, highly educated farmers are more likely to participate in training, technology transfer, or agricultural extension activities provided by government and private-sector organizations, which help enhance their knowledge and skills in managing rubber plantations in accordance with GAP standards. Second, farmers who make rubber farming their primary occupation are more likely to comply with Good Agricultural Practices (GAP) standards than those with it as a secondary occupation. This may be because their primary occupation is the main source of household income, leading them to prioritize the serious, continuous management of their rubber plantations. These farmers typically dedicate most of their time, labor, and resources to caring for their rubber plantations, including soil and fertilizer management, pest and disease control, proper tapping techniques, and maintaining suitable environmental conditions in the plantation – all crucial components of GAP compliance. and their land title deeds. Rubber farmers in areas with land ownership documents, particularly those with land titles, have greater potential to comply with Good Agricultural Practice (GAP) standards than those in areas without such documentation. This may be attributed to the stability of land tenure as a fundamental factor influencing long-term investment decisions. When farmers are legally confident in their land ownership, they are more willing to invest in improving soil quality, organizing systematic rubber plantations, appropriately using production factors, and conserving natural resources—all key components of GAP

standards. In addition, one independent variable, farmers' access to capital, was significantly positively correlated with the dependent variable at the 0.05 level. Farmers with access to funding for rubber plantation management have greater potential to implement Good Agricultural Practices (GAP) standards than those without such funding. This may be because implementing these standards requires investment in several areas, including production inputs, plantation management, and the use of appropriate agricultural technologies. Farmers with funding can invest in quality rubber varieties, use fertilizers and pesticides correctly according to recommendations, improve planting conditions, such as soil and water management, maintain soil fertility, and implement systematic plantation management (Table 3).

Table 3. Factors Affecting Good Agricultural Practices (GAP) for Rubber Farmers

variable	B	Std. Error	Standardized Coefficients Beta	t	P - value	Collinearity Statistics	
						Tolerance	VIF
(Constant)	3.89	0.04		100.66	0.00		
Years of education (years)	0.03	0.01	0.42	7.01	0.00	1.00	1.00
The main occupation of farmers	0.22	0.04	0.32	5.26	0.00	0.946	1.05
Opportunities for farmers to obtain capital resources	0.09	0.04	0.13	2.18	0.03	0.99	1.00
Land title deed	1.00	0.02	0.96	56.82	0.00	1.00	1.00

a. Dependent Variable: **Good Agricultural Practices (GAP)**

SEest = ± 1.87 , Durbin-Watson = 2.17, R = 0.96, R² = 0.93, Adjusted R² = 0.93, F = 3229.56, P - value = 0.00

4) Guidelines for developing rubber farmer groups towards good agricultural practices for rubber in the form of cup lump rubber.

According to the study Assessment of the potential of rubber plantation management according to Good Agricultural Practices (GAP) of farmers and Factors Affecting Good Agricultural Practices (GAP) for Rubber Farmers and data analysis using the principles of developing the potential of farmer groups according to the 2022 Farmer and Farmer Institution Development Manual of the Rubber Authority of Thailand, in 6 areas, consisting of 1) Farmer group management, 2) Knowledge and skills in rubber plantation management, 3) Production and product quality, 4) Marketing and networking, 5) Farmer member participation, and 6) Creating sustainability for farmer groups, the researcher has guidelines for developing rubber farmer groups towards good agricultural practices for rubber in the form of cup lump rubber.

1) Farmer group management

Farmer group management development should involve member participation in planning and setting rules for rubber trading. This may be stipulated in terms of trading regulations, such as: if rubber is to be sold to the group, it must be formic acid-treated rubber, or it must have a dry rubber content (DRC) greater than or equal to 80 percent. This is to establish clear standards for rubber purchasing by farmer groups.

2) Knowledge and skills in rubber plantation management

Developing farmers' knowledge and skills in rubber plantation management should involve group members in identifying the knowledge or skills they need to develop, and coordinating with relevant agencies to provide training and knowledge. For example, raising production standards and implementing GAP (Good Agricultural Practices) guidelines will help increase production efficiency, reduce costs, and minimize environmental impacts. Furthermore, group members' participation in exchanging experiences, planning rubber tapping, and developing new techniques will foster mutual learning and continuous development.

3) Production and product quality

In developing production and product quality, in addition to setting the rules for purchasing rubber from farmer groups, farmer group leaders should provide consultations, visit the area to offer advice on following good and appropriate agricultural principles, and encourage members to participate in jointly developing product quality standards and conducting participatory inspections.

4) Marketing and networking

Marketing and network development should involve joint market analysis to identify target groups and develop rubber sales channels for farmer groups. For example, group members should participate in a project to delay rubber sales. Farmers will collect rubber and wait to sell during periods of low rubber prices, then sell it during favorable times. Furthermore, they should set a median purchase price for their rubber products, allowing farmers to participate in rubber price determination. Profits from rubber sales by farmer groups should be used as dividends and benefits for group members. Lessons learned from joint marketing activities should inform future planning.

5) Farmer member participation

To foster farmer member participation, regular group meetings should be held to report on performance, listen to feedback, and propose joint solutions. A more diverse communication channel should be used, such as group Line, public address systems, or public relations materials. Furthermore, a transparent and accountable profit-sharing or dividend system should be established, along with incentives such as cooperation points or privileges for highly engaged members.

6) Farmer group sustainability

To build group sustainability, short- and long-term development plans should be established. Transparent accounting and financial management should be implemented. Group members should develop supplementary occupations, such as intercropping and agricultural tourism. Business matching should be established with buyers, factories, or other cooperatives to establish a network for rubber prices and facilitate negotiations with mediators. Group activities for the benefit of neighboring communities, such as tree planting and community service activities, should also be promoted.

Discussion

1) Personal characteristics, socio-economic status, and rubber plantation management. The study found that rubber farmers had an average of 14.53 years of experience in a rubber plantation. They cultivated rubber as a secondary occupation. Farmers spent their free time during the day engaging in other agricultural activities, such as longan, mango, or other field crops. This may be because farmers perceived rubber plantations as just a hobby and a career that generated additional household income, primarily through household labor. According to a 2023 agricultural survey, farmers had an average rubber plantation area of 20.69 rai. Most of this area lacked land title deeds that could be sold or converted into revolving funds. This may be because most farmers cultivated rubber in areas permitted by the Agricultural Land Reform Office, as the government allocated the land for agricultural purposes under the right to cultivate only. The right under Sor Por Kor. 4-01 is only the right to use the land, not the ownership of the land. Farmers earned an average income of 235,549.33 baht from rubber production. Farmers' rubber sales. Most farmers sell their products in the form of dry cup lumps to the cooperatives or farmer groups of which they are members. Only two cooperatives sell them as wet cup lumps: the Fang-Mae Ai Rubber Cooperative Limited.

2) The potential for Good Agricultural Practices (GAP) of rubber farmers in Chiang Mai Province found that most farmers had the highest potential for Good Agricultural Practices (GAP) (average 4.13). This may be because farmers have been promoted and trained to provide knowledge about rubber plantations in line with Good Agricultural Practices (GAP) to support trade policies from the Rubber Authority of Thailand.

3) Factors Affecting Good Agricultural Practices (GAP) for Rubber Farmers

(1) Years of education mean that farmers with higher education levels are more able to develop their potential to comply with Good Agricultural Practices (GAP) for rubber than farmers with lower education levels. This may be because farmers with higher education levels are better able to analyze and compare information and knowledge, make rational decisions, and keep up with new technological developments from

various sources such as the internet, newspapers, research, and social media. They can access information on the benefits of rubber plantation management according to Good Agricultural Practices (GAP). This will broaden their perspectives on managing rubber plantations to meet standards and improve their own productivity. This is consistent with [10], who explained that farmers with higher levels of education are better able to think, analyze, and distinguish in decision-making and to accept innovations effectively. [11] explained that farmers with higher education levels are more interested in learning more and applying it in their own fields, leading to a greater acceptance of appropriate Good Agricultural Practices. This is consistent with [12], who explained that education level is an important factor in enhancing understanding of modern technology. It helps farmers to accurately and comprehensively assess the benefits of innovation and also promotes an open attitude towards change. This is consistent with [13], which explains that when farmers have higher educational attainment, they tend to have easier access to information, making them more open to learning, even when the technology is complex.

(2) The main occupation of the farmers means that farmers who are solely engaged in rubber plantations have a higher potential to comply with Good Agricultural Practices (GAP) for rubber than farmers who cultivate rubber as a secondary occupation. This may be because farmers who cultivate rubber as their primary occupation are better prepared to manage their rubber plantations than those who cultivate it as a secondary occupation. They can devote time to learning, monitoring, and applying insights to increase resource efficiency continuously. This is consistent with the research of [14], which explains that primary farmers are often those who dare to invest in complex and expensive innovations because they see it as a necessary investment for the survival of their business.

(3) Licensed farmer land ownership means that licensed farmers will be more likely to comply with the Good Agricultural Practice Principles for Rubber (GAP) than non-licensed farmers, possibly due to the requirements of the Good Agricultural Practice Principles for Rubber (GAP) standard. The area used to cultivate rubber must comply with the requirements of the relevant laws, with proof of the right to use the land, and farmers who own the land are confident in long-term investments, such as land improvement, installation of irrigation systems, or the introduction of new technologies, etc., because they are confident that they will receive a return on those investments. Consistent with [15], it is explained that farmers with land rights will have more freedom to decide on land use, which crops to grow, and how to manage water resources, and are more likely to adopt and experiment with new technologies than farmers without land rights. And in line with [16], which explains that farmers who own land tend to embrace land development technology more than farmers who do not.

4) Farmer access to capital means that farmers with more access to capital channels will be more likely to comply with the Good Agricultural Practice Principles for Rubber (GAP) than farmers with less access to capital channels, perhaps because they have more access to capital channels. There is sufficient capital to pursue new agricultural knowledge and technologies for managing rubber plantations. In line with [17], farmers who have access to sources of capital or credit are more likely to adopt agricultural technologies, as access to credit helps reduce financial constraints. Enable farmers to invest in new production tools or methods, in line with [18], which explains that farmers who have access to capital sources are more likely to adopt technology. By accessing capital sources, they reduce financial constraints, enabling farmers to invest in technologies that improve production efficiency and reduce costs.

Conclusion

Development of Rubber Farmer Groups towards Good Agricultural Practices (GAP) for Rubber in the Northern Region of Thailand. The researchers assessed the potential of rubber plantations to support farmers in Chiang Mai Province in implementing Good Agricultural Practices (GAP) using quantitative research. They developed a guideline for building rubber farmer groups' capacity for Good Agricultural Practices for rubber using the Participatory Development Theory. The study found that most farmers had a high potential for Good Agricultural Practices (GAP) for rubber (average 4.13). When studying the factors affecting the potential for Good Agricultural Practices (GAP) for rubber farmers, it was found that 4 independent variables influenced the potential for Good Agricultural Practices (GAP) for rubber farmers: 1) farmers' years of education, 2)

farmers' main occupation, 3) farmers' land title deeds, and 4) farmers' access to capital. The researchers proposed six guidelines for developing rubber farmer groups towards good agricultural practices (GAP) for rubber: 1) farmer group management, 2) knowledge and skills in rubber plantation management, 3) production and product quality, 4) marketing and networking, 5) farmer member participation, and 6) group sustainability. To successfully develop farmer potential, the researcher must begin by adjusting farmers' attitudes to build confidence in good agricultural practices (GAP) for rubber. This should then be followed by enhancing farmers' knowledge and understanding of the practices, enabling them to recognize the importance of GAP standards.

Author Contribution

Author Contribution: Conceptualization S. Duangsingtham and P. Prapatigul; Formal analysis, S. Duangsingtham and P. Prapatigul; Investigation S. Duangsingtham and P. Prapatigul; Methodology, S. Duangsingtham, P. Prapatigul, S. Sreshthaputra and N. Phayakka; Supervision, P. Prapatigul; Validation S. Duangsingtham and P. Prapatigul; Writing- original draft S. Duangsingtham and P. Prapatigul ; writing-review and Editing S. Duangsingtham, P. Prapatigul, S. Sreshthaputra and N. Phayakka; All author read and agreed to the Published version of manuscript.

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Tourists' Responses to Immersive Technology in Community-Based Tourism: A Stimulus–Organism–Response Model

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Abstract: Community-based tourism (CBT) has been recognized as an important approach for promoting sustainable tourism, local participation, and community development. However, the role of immersive technology (IMT) in enhancing CBT experiences remains underexplored, particularly how tourists evaluate technology-driven recommendations and respond behaviorally. This study examines the factors influencing tourists' attitudes and responses to the use of IMT in CBT through the stimulus–organism–response (SOR) model. A cross-sectional survey was conducted in April 2026 with 400 tourists who had experience using IMT within the previous three months. Data were analyzed using partial least squares structural equation modeling (PLS-SEM) with SmartPLS. The results show that recommendation reliability and recommendation accuracy significantly and positively influence tourists' attitudes toward using IMT, with recommendation accuracy having the strongest effect. In contrast, experiential graphic design does not significantly affect attitude. Furthermore, attitude toward using IMT significantly influences tourist satisfaction and intention to use IMT, but it does not significantly affect intention toward the destination. These findings confirm attitude as an internal psychological mechanism linking technology-related stimuli with tourists' behavioral responses. The study contributes to the literature by extending the SOR framework to the IMT-based CBT context. It suggests that IMT development for CBT should prioritize accurate, reliable, and useful information rather than focusing only on visual design or technological novelty.

Keywords: Immersive technology (IMT); community-based tourism; tourist responses; stimulus–organism–response (SOR); behavioral intention

1. Introduction

Tourism is among the fastest-growing global industries and is acknowledged as a significant contributor to local economic growth, job creation, and reduced income inequality [1, 2]. Community-based tourism (CBT) is an important strategy for sustainable tourism development, aiming for fair benefit distribution and the participation of local populations in planning, managing, and using tourism development [3, 4]. CBT differs from traditional tourism by focusing on improving the quality of life, economy, and society of local communities, while also ensuring the sustainable conservation of natural resources and the environment. Furthermore, CBT is associated with sustainable

tourism, responsible tourism, and ecotourism, all of which aim to reduce adverse effects on the culture, communities, and environment of tourist destinations [1, 5]. CBT is considered an alternative tourism model aligned with the Sustainable Development Goals (SDGs) and sustainability principles, especially given that the tourism sector contributes substantially to the global economy, accounting for approximately 10 percent of the world's GDP [2].

Changes in tourists' behavior in the digital era, especially the use of digital communication channels to seek information, plan trips, and share experiences, have forced the tourism industry to adapt continuously. Current tourism growth can no longer rely solely on traditional service models; instead, it depends on service providers who can offer diverse innovations and experiences that respond effectively to tourists' needs [6]. In recent years, the tourism industry has increasingly adopted digital technologies to identify solutions, enhance competitiveness, and create new opportunities in the tourism market [7]. At the same time, digital technologies play an important role in enhancing tourist experiences throughout all stages of the travel journey, including the pre-trip, on-site, and post-trip phases, by creating unique, valuable, and expectation-aligned experiences [6]. Accordingly, social media, smartphone applications, augmented reality and virtual reality (AR/VR), Geographic Information Systems (GIS), and e-commerce platforms are examples of digital technologies that have significantly transformed the contemporary tourism industry [8]. These technologies not only make services more efficient and improve communication with tourists, but also enable local communities to promote destinations, attract tourists, monitor tourist behavior, and support sustainable tourism development in a more tangible way.

Digital technologies are known to contribute significantly to the long-term sustainability of the tourism business. However, studies on their application and effects in this context have not been adequately and systematically documented [9]. Previous studies have mainly focused on specific technologies or contexts such as the adoption of AI-driven smart tourism technologies in the UAE [10], the use of immersive technologies in tourism [11], the relationship between perceived risk and the adoption of virtual reality technologies by tourists and travel companies [12], the use of augmented and virtual reality technologies to promote responsible tourism behavior [13], innovation decisions and reluctance to adopt augmented reality technologies in the tourism industry [14], and the use of augmented reality technologies to support the digital transformation of smart tourism ecosystems [15].

However, research on the use of digital technology in Community-based Tourism (CBT) remains limited. Much of the research on community-based tourism (CBT) focuses on entrepreneurs' personalities, their experiences, their sense of belonging to the community, and the problems CBT entrepreneurs face [16]. They also provide guidelines for managing tourism sites and the business sector to promote sustainable tourism and the strategic use of local resources [17] and discuss the problems and barriers to implementing CBT initiatives [18]. The findings indicate that the existing research on the association between the application of digital technology and the promotion of community-based tourism is limited in scope and in explicitly stating the function of digital technology in promoting CBT sustainability.

This study investigates tourists' attitudes towards digital technology in community-based tourism (CBT), with particular attention to the role of immersive technology (IMT) in improving the tourism experience. IMT encompasses various technologies, such as augmented reality (AR), which allows users to interact with virtual content overlaid on the physical world; virtual reality (VR), which offers an interactive simulated environment that replicates real-world experiences, with non-immersive VR available on standard computer screens or digital media without the need for specialized equipment, while immersive VR requires a headset for a fully immersive experience; and mixed reality (MR), which integrates virtual objects with the real environment to enable seamless interaction between the real and virtual worlds [6, 19-22]. In this study, immersive technology (IMT) is operationalized as an IMT-enabled community-based tourism (CBT) prototype developed to support tourists' exploration and decision-making regarding CBT attractions, community activities, travel routes, and destination information in Prachuap Khiri Khan Province. The prototype integrates immersive visual media, interactive tourism information, and recommendation functions. Therefore, IMT in this study does not refer to tourists' general perceptions of all AR, VR, or MR technologies, but specifically refers to their perceptions of the IMT-enabled CBT prototype examined in this research.

This study used the Stimulus–Organism–Response (SOR) model [23], which connects digital technology stimuli with tourists' internal assessments or impressions. It examines behavioral responses to the incorporation of digital technologies in Community-Based Tourism (CBT). To explore the adoption of IMT in the context of CBT, the following research questions (RQs) were formulated:

RQ1: Which stimulus elements affect tourists' opinions toward the adoption of IMT within the framework of CBT?

RQ2: What are the drivers of tourists' responses to the use of IMT in the context of CBT?

1.1 Theoretical framework

The Stimulus-Organism-Response (SOR) model provides a useful theoretical foundation for understanding individual responses to environmental cues or stimuli, which influence cognitive processes, thoughts, feelings, and internal mental states, resulting in behavioral responses that may be positive or negative [23]. The SOR framework has been widely used in tourism research on visitor behavior and digital technology users. A study on the impact of augmented reality (AR) technology in promoting the digital transformation of smart ecotourism firms identified that AR improves immersive experiences, environmental awareness, cultural knowledge, perceived sustainability ideals, and innovation orientation [2]. The SOR model has also been employed to explore the association between stimuli (perceived marketing strategies and motivations), tourists' internal states (positive emotions and satisfaction), and responses (intention to revisit) in hot air balloon festivals [24]. Furthermore, a study on cognitive and emotional responses, attachment, and intention to visit tourist attractions using virtual reality (VR) technology observed that the association with the VR experience affects the intention to visit attractions through VR, and that cognitive responses are more influential on visitor intention than emotional responses [25].

This study used the SOR model to examine tourist behavior toward IMT deployment under community-based tourism (CBT). Digital technology stimuli, including the authenticity of suggestions, the accuracy of information, and graphic design, influence tourists' internal states, which in turn influence their attitudes toward using digital technology. These attitudes are then expected to influence behavioral responses such as satisfaction, intention to adopt innovation, and intention to visit the destination within the CBT framework.

1.2 Research model and hypotheses

The tourism experience comprises several activities and interactions that take place during a tourist's journey and can be divided into three main stages: pre-travel, during travel, and post-travel [26]. At each level, tourists perceive, assess, and respond to information, services, and the destination environment differently. Thus, tourism success depends on developing experiences that satisfy tourists' needs at all stages of their journey. Digital technology, particularly virtual reality and immersive technologies, greatly increases the user experience in modern tourism. Previous research has demonstrated that virtual reality impacts user experience in perception, emotion, behavior, senses, and social interaction [27]. Moreover, boosting customer experience is a major priority for the commercial industry. Previous studies have highlighted that many firms see improving customer experience as a priority and that developing experiences that facilitate emotional connection in the purchasing decision path is a significant marketing trend [28]. Thus, much attention has been paid to improving the customer or tourist experience, especially through the use of digital technologies to enhance the journey at all stages (before, during, and after the trip). Digital technology plays an important role in community-based tourism by facilitating information access, tourists' understanding of attractions, experiential value enhancement, and stimulation of tourists' behavior. These factors are the critical basis for the construction of the study model and hypotheses in Figure 1.

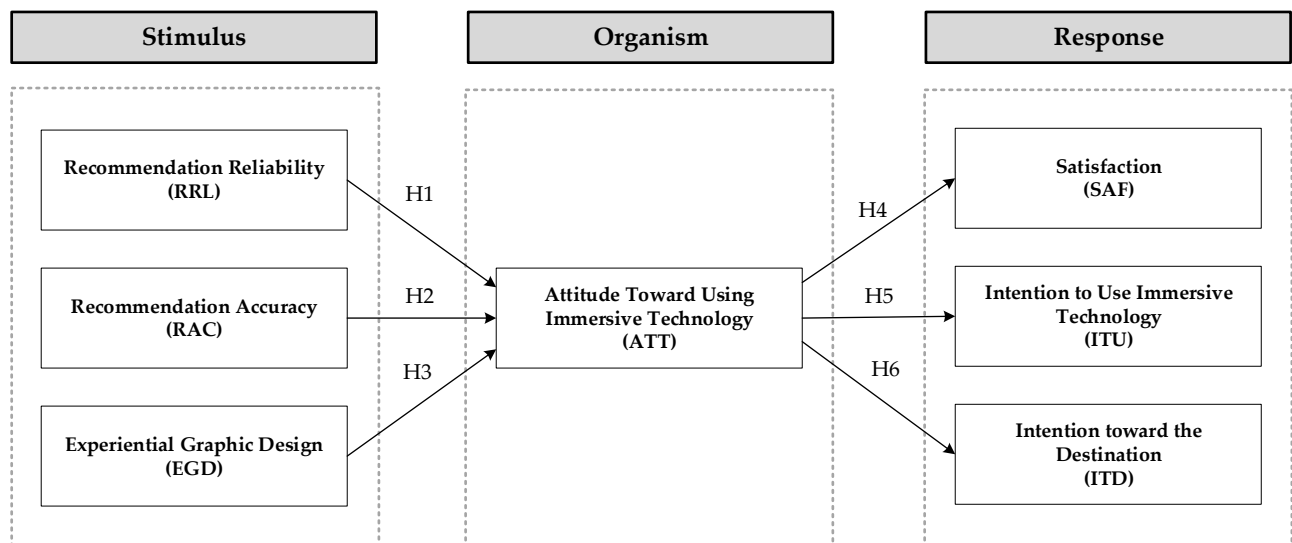


Figure 1. Proposed research model.

In this study, recommendation reliability (RRL) and recommendation accuracy (RAC) are treated as two related but conceptually distinct dimensions of information quality. Drawing on information systems success and information quality perspectives, information quality is not a single attribute but a multidimensional evaluation of whether information is useful, dependable, accurate, relevant, and appropriate for users' decision-making. In the context of the IMT-enabled CBT prototype, RRL refers to tourists' perception that the recommendation process is dependable, consistent, credible, and useful for supporting tourism-related decisions [29]. It reflects whether tourists feel they can rely on the prototype when selecting CBT attractions, routes, or activities.

RAC, in contrast, refers to tourists' perception that the information provided by the prototype is factually correct, precise, and consistent with actual destination conditions. It reflects whether information about attractions, community activities, routes, and services matches reliable external sources, tourists' expectations, and real conditions in the CBT context. Therefore, RRL answers whether tourists can rely on the recommendation, whereas RAC answers whether the information is correct and consistent with reality. Both constructs are needed in the model because tourists may perceive a system as generally dependable and credible while still questioning the correctness of some specific destination details, or they may perceive particular information as accurate without necessarily viewing the overall recommendation process as consistently reliable [30].

The trend of digitalization in society has heightened the challenge of information overload, necessitating the exploration of recommendation systems within digital environments [31]. The credibility of recommendations plays a significant role in users' perceptions and decisions, especially in digital environments with large amounts of information. Kim et al. [32] argue that social recommendations are valuable because they are based on the opinions and experiences of other users, reducing information overload and allowing users to better evaluate the quality of a product or service before making a purchase or use decision. Moreover, social recommendations significantly influence users' behavior, as people tend to prefer information based on others' real experiences rather than information provided only by the provider [33]. In community-based tourism, the reliability of recommendations by digital systems such as chatbots, route-guiding platforms, and geographic information systems increases tourists' confidence in information about attractions, community activities, travel routes, and related services. Credible, accurate, and relevant recommendations enhance tourists' attitudes towards the use of digital technology in community-based tourism. Consequently, this study proposes the following hypothesis:

H1: The credibility of innovative recommendations (RRL) positively influences tourists' attitudes toward the use of IMT (ATT) in community-based tourism.

In addition to the trustworthiness of suggestions, the correctness or precision of these recommendations also plays a key role in user attitudes in digital settings. This is particularly relevant in the context of immersive technologies and recommendation systems that mediate between large volumes of information and users, hence increasing the efficiency of finding, accessing, and consuming information [34, 35]. In interactive digital settings, such as the metaverse or immersive technologies, accurate recommendation systems can bridge the gap between the virtual experience and the user's real-world experience. Unlike the traditional Internet, the metaverse can create a parallel universe and enable real-time interaction that can be integrated with users' real-life experience [36].

According to et al. [37], the accuracy of product recommendation systems boosts functional value, while the system's attractiveness enhances social value and consumer immersion. Immersive technologies and virtual environments provide interactive surroundings and increase the user's involvement and focus on virtual encounters. Recommendation systems in tourism can increase the accuracy, personalization, and quality of experiences in tourism activities, possibly boosting tourism and improving the visitor experience [38]. However, combining recommendation systems with immersive technology in community-based tourism has limitations, particularly in the availability of information on new tourist sites, community activities, and distinct regional settings. Thus, if the system provides accurate, exact, and appropriate recommendations according to tourists' needs, it is likely to create a positive attitude toward using such technology in the context of CBT. Consequently, this study proposed the subsequent hypothesis:

H2: The accuracy of recommendations (RAC) from innovation positively influences tourists' attitudes toward the use of IMT (ATT) in community-based tourism.

Experiential Graphic Design (EGD) is an interdisciplinary approach that combines elements from graphic design, architecture, interior design, product design, and digital media arts. Its primary objective is to enhance user experience through visual communication within a designed environment, thereby improving users' understanding, perception, and emotional connection to the physical space or information presented [39, 40]. EGD employs comprehensive, multisensory design principles to address user perception and interaction patterns with the environment [41, 42]. Experiential graphic designers focus on interactions between users and a physical space, taking into account the context and environment that affect the user experience. The design emphasizes not only visual aesthetics but also practicality, clarity, and navigability within the space or system [39]. Experiential graphic design enhances the presentation of information, community activities, travel routes, and local narratives within community tourism, making them more engaging, comprehensible, and conducive to tourist involvement.

Integrating EGD with immersive technologies (IMTs) like AR, VR, or MR facilitates cross-format experiences, enhances user interaction, and promotes real-time responses between tourists and digital content or the destination environment. Consequently, when experiential graphic design is clear, engaging, and pertinent to the community context, it is likely to foster positive attitudes towards the use of IMTs in community-based tourism. Therefore, this study proposes the following hypothesis:

H3: The experiential graphic design (EGD) from innovation positively influences tourists' attitudes toward the use of IMT (ATT) in community-based tourism.

Attitudes are an individual's evaluation, feelings, or propensity to show a given action in a specific environment [43]. In the context of technology adoption, users' attitudes substantially affect their evaluation of the experience, satisfaction, and intentions to continue using the technology [6]. In tourism, where virtual or immersive technologies are used, tourists' attitudes toward these technologies are important for their perceived value of the experience and behavioral responses. Liu and Sutunarak [44] observed that tourists' attitudes and pleasure towards virtual reality affected their behavioral intentions, enhanced the visiting experience, and promoted the sustainable development of museums. Sujood and Pancy [45] found that the virtual interaction influences user attitudes, which in turn affect the reception of virtual reality experiences in tourism destinations. Moreover, previous research has found that tourist adoption of virtual reality is influenced by their attitudes towards the technology, which in turn influences their satisfaction and loyalty [11].

In this study, attitude toward using IMT is conceptualized as tourists' overall evaluative orientation toward the IMT-enabled CBT prototype, including enjoyment, convenience, perceived customization, and entertainment value. It is therefore broader than usability alone. In community-based tourism, tourists' positive attitudes toward immersive technologies such as AR, VR, or MR are associated with more favorable impressions of their tourism experiences. This includes increased enjoyment, understanding of community stories, participation in events, and greater confidence in using technology to support travel. Attitudes toward usage may influence satisfaction, intention to utilize immersive technology, and intention to travel to a destination in community-based tourism. This study, therefore, proposes the following hypothesis:

H4: Attitude toward using IMT (ATT) positively influences tourist satisfaction (SAF) when utilizing IMT in community-based tourism.

H5: Attitude toward using IMT (ATT) positively influences the intention to use IMT (ITU) within community-based tourism.

H6: Attitude toward using IMT (ATT) positively influences tourists' intentions to visit the destination (ITD).

2. Materials and Methods

2.1 Study participants and setting

This study employed a cross-sectional research design and was conducted in April 2026 in Prachuap Khiri Khan Province, Thailand. Participants were selected using purposive sampling based on the study objectives. The inclusion criterion was tourists who had experience using immersive technology within the previous three months, regardless of gender or occupation. The three-month experience criterion was established to reduce recall bias and ensure that respondents could provide evaluations based on relatively recent interactions with IMT. Because this study examined perceptions of recommendation reliability, recommendation accuracy, experiential graphic design, attitude, satisfaction, and behavioral intention, respondents needed to remember specific details of the technology experience. A longer recall period may increase memory distortion, whereas a much shorter period may substantially narrow the eligible population. Therefore, the three-month criterion was used as a practical balance between recency of experience and respondent availability. Since the study aimed to examine tourists' evaluations of recommendation reliability, recommendation accuracy, experiential graphic design, attitudes, and behavioral responses after using IMT, respondents were required to have interacted with the prototype within the previous three months. Online recruitment through Facebook and LINE was used to reach tourists who were digitally active and likely to have encountered or used IMT-based tourism information. Therefore, the sample should be interpreted as representing digitally active tourists with recent IMT experience, rather than the general population of all CBT tourists in Prachuap Khiri Khan Province. The recruitment and data collection procedures were conducted in accordance with ethical principles for human subject research. The study protocol was approved by the Institutional Review Board of Rajamangala University of Technology Rattanakosin, Thailand (RMUTR-IRB, COA No. 018/2026). Participation was voluntary, and all participants were informed of the research objectives, confidentiality measures, and their right to withdraw from the study at any time.

The research technique was composed of two primary stages. Before the main survey, a pilot test was conducted to assess the reliability and validity of the proposed measurement scale and the clarity and feasibility of the questionnaire. Three specialists in immersive technology assessed the questionnaire, and 30 volunteers participated in the pilot test. Second, the full survey was conducted after improving the questionnaire based on pilot-test feedback and expert input. The minimum required sample size was calculated using G*Power software. Based on an effect size of 0.25, a significance level of 0.05, and statistical power of 0.90, the minimum sample size required for this study was 277 participants [46]. To increase the robustness of the analysis and compensate for incomplete or unusable responses, the target sample size was increased by approximately 45%, resulting in a final target of approximately 400 participants. Data were collected using an online questionnaire distributed through online platforms. Before completing the questionnaire, participants were provided with information about the purpose of the study, confidentiality protection, and the contact details of the researcher and research assistants in case they had questions or

concerns. These procedures were intended to reduce response bias and enhance participants' trust in providing accurate information [47]. Participants who voluntarily agreed to participate were required to confirm their informed consent before proceeding to the questionnaire. All collected data were used solely for research purposes and were handled confidentially. After data analysis, the data were securely destroyed in accordance with the approved research ethics protocol.

2.2 Description of the IMT-enabled CBT prototype and study context

To avoid ambiguity, immersive technology (IMT) in this study refers specifically to an IMT-enabled community-based tourism (CBT) prototype developed to support tourists' exploration and decision-making regarding CBT destinations in Prachuap Khiri Khan Province, Thailand. The prototype was designed as a digital tourism-support tool that combined immersive and interactive media with tourism information and recommendation functions. Its content included CBT attraction information, community activities, local tourism routes, destination-based visual media, and contextual information intended to help tourists better understand the identity, activities, and travel opportunities of CBT destinations. Tourists accessed the prototype primarily through personal digital devices, such as smartphones or tablets. Respondents interacted with the prototype by exploring CBT destinations, viewing visual and contextual tourism content, checking recommended attractions or routes, and evaluating whether the information provided was reliable, accurate, visually understandable, and useful for travel decision-making. The research team introduced the prototype to eligible respondents through its online recruitment channels, and respondents were required to have used or interacted with IMT within the previous three months before completing the questionnaire. Accordingly, the term "IMT" in this study does not refer to immersive technology as a broad abstract category. Rather, it refers to the specific IMT-enabled CBT prototype used in the study setting. This operational definition allows the findings to be interpreted in relation to tourists' evaluations of the prototype's recommendation reliability, recommendation accuracy, experiential graphic design, attitude, satisfaction, intention to use IMT, and intention toward the destination.

2.3 Data collection

The questionnaire was constructed based on the stimulus-organism-response (SOR) conceptual paradigm. It is composed of three sections: Section 1: General information about the respondent (gender, age, education) Section 2: Opinions on the use of immersive innovation prototypes: recommendation reliability (RRL), recommendation accuracy (RAC), experiential graphic design (EGD), attitude towards using immersive technology (ATT), satisfaction (SAF), intention to use immersive technology (ITU) and intention towards the destination (ITD). Section 3: Suggestions are graded on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree), as shown in Table 1.

Table 1. Measurement items of the questionnaire.

Construct	Items	Survey Item	Source
Recommendation Reliability (RRL)	RRL1	The IMT-enabled CBT prototype provides reliable and actionable advice.	Adapted from Kim et al. [32], Zheng et al. [33]
	RRL2	The IMT-enabled CBT prototype provides recommendations that are consistent with and do not contradict previously received information.	
	RRL3	The information provided by the IMT-enabled CBT prototype helps make better decisions about ecotourism.	
	RRL4	The media presented in the IMT-enabled CBT prototype helps increase the perceived credibility and dependability of the tourism recommendations.	

Table 1. Measurement items of the questionnaire. (continue)

Construct	Items	Survey Item	Source
Recommendation Accuracy (RAC)	RAC1	The information provided by the IMT-enabled CBT prototype is accurate when compared to information from other reliable sources.	Adapted from Wang et al. [37]
	RAC2	The information provided by the IMT-enabled CBT prototype about the tourist attractions was accurate and matched my expectations.	
	RAC3	The information about CBT attractions provided by the IMT-enabled CBT prototype is consistent with the actual characteristics and conditions of the destinations.	
	RAC4	Overall, the information provided by the IMT-enabled CBT prototype about tourist attractions is accurate enough to make decisions without needing to verify it with other sources.	
Experiential Graphic Design (EGD)	EGD1	The overall design and content of the media presented in the IMT-enabled CBT prototype are vibrant and engaging.	Adapted from Petković et al. [39]
	EGD2	The scenes depicted and the media elements presented in the IMT-enabled CBT prototype are consistent with the design.	
	EGD3	The media functionality in the IMT-enabled CBT prototype is appropriately designed and user-friendly.	
	EGD4	The media design style in the IMT-enabled CBT prototype is consistent with the tourism context.	
Attitude Toward Using Immersive Technology (ATT)	ATT1	The content presented in the IMT-enabled CBT prototype is engaging and enhances the enjoyment of tourism.	Adapted from Kwangsawad et al. [14], Davis [43], Sujood and Pancy [45]
	ATT2	The IMT-enabled CBT prototype is convenient and easy to access for tourism purposes.	
	ATT3	The IMT-enabled CBT prototype can be customized for different users.	
	ATT4	The IMT-enabled CBT prototype can provide entertainment and enhance the relaxing experience as expected.	
Satisfaction (SAF)	SAF1	I am satisfied with the IMT-enabled CBT prototype's response to searching for tourist information.	Adapted from Liu and Sutunyarak [44]
	SAF2	The IMT-enabled CBT prototype was efficient enough and helped me obtain services quickly and without hassle.	
	SAF3	I am satisfied with the information and advice received from the IMT-enabled CBT prototype.	
	SAF4	Overall, I am satisfied with my experience using the IMT-enabled CBT prototype.	

Table 1. Measurement items of the questionnaire. (continue)

Construct	Items	Survey Item	Source
Satisfaction (SAF)	SAF1	I am satisfied with the IMT-enabled CBT prototype's response to searching for tourist information.	Adapted from Liu and Sutunyarak [44]
	SAF2	The IMT-enabled CBT prototype was efficient enough and helped me obtain services quickly and without hassle.	
	SAF3	I am satisfied with the information and advice received from the IMT-enabled CBT prototype.	
	SAF4	Overall, I am satisfied with my experience using the IMT-enabled CBT prototype.	
Intention to Use Immersive Technology (ITU)	ITU1	I am willing to use the IMT-enabled CBT prototype again in the future.	Adapted from Kwangsawad, et al. [6]
	ITU2	I am willing to use the IMT-enabled CBT prototype as a tool to support tourism planning.	
	ITU3	I plan to recommend the IMT-enabled CBT prototype to others.	
	ITU4	If I have the opportunity, I will use the IMT-enabled CBT prototype for future travel.	
Intention toward the Destination (ITD)	ITD1	I think the tourist attractions shown in the IMT-enabled CBT prototype are suitable for tourism.	Adapted from Kwangsawad et al. [14]
	ITD2	I intend to participate in more tourism activities at the destinations presented in the IMT-enabled CBT prototype.	
	ITD3	My experience using the IMT-enabled CBT prototype increased my likelihood of future travel.	
	ITD4	My experience using the IMT-enabled CBT prototype made me feel interested in visiting the presented places.	

Note: Items with factor loadings below the recommended threshold were removed from the final measurement model before assessing reliability and validity.

2.4 Data analysis

This study employed Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine the relationships among hypothesized variables, utilizing SmartPLS software for data analysis [48]. This is because PLS-SEM has demonstrated effectiveness in predicting factors associated with individual behavior toward technology [6, 14]. It can simultaneously analyze the measurement and structural models, assessing the validity of the research instrument through composite reliability (CR) and average variance extracted (AVE) statistics. PLS-SEM demonstrates considerable flexibility regarding data and sample size [49]. Given these technical advantages, PLS-SEM was an appropriate method aligned with this research's objectives. In addition to assessing path coefficients, t-values, p-values, and collinearity statistics, the explanatory and predictive power of the structural model was evaluated. The coefficient of determination (R^2) and adjusted R^2 were examined for all endogenous constructs, namely attitude toward using immersive technology (ATT), satisfaction (SAF), intention to use immersive technology (ITU), and intention toward the destination (ITD). R^2 was used to assess the extent to which the exogenous constructs explained variance in the endogenous constructs. Predictive relevance was assessed using Q^2 values, where a Q^2 value greater than zero indicates that the model has predictive relevance for the corresponding endogenous construct. In addition, effect size (f^2) was used to evaluate the practical contribution of each exogenous construct to the endogenous constructs. Because all constructs were measured using a single self-report questionnaire collected from the same respondents at one point in time, common method bias (CMB) was assessed before interpreting the structural

model. A full collinearity assessment was performed in PLS-SEM by examining the variance inflation factor (VIF) values of the latent constructs. VIF values below the recommended threshold indicate that common method bias is unlikely to seriously threaten the validity of the results seriously.

3. Results and Discussion

3.1 Descriptive statistics

Table 2. Demographic characteristics of respondents.

Characteristics	Number (N = 400)	Percentage
Gender		
Male	240	60.00
Female	160	40.00
Age		
Less than 20 years old	3	0.75
20–25 years	204	51.00
26–30 years	69	17.25
31–35 years	104	26.00
36–40 years	0	0.00
41–45 years	12	3.00
46–50 years	5	1.25
51 years and above	3	0.75
Education level		
Below high school	6	1.50
High school	55	13.75
Diploma	143	35.75
Bachelor's degree	186	46.50
Master's degree	4	1.00
Ph.D. degree	6	1.50

Table 2 presents the demographic characteristics of the 400 respondents. Most respondents were male (240, 60.00%), while 160 were female (40.00%). Regarding age, the largest group was 20–25 years (204 respondents, 51.00%), followed by 31–35 years (104 respondents, 26.00%) and 26–30 years (69 respondents, 17.25%). In terms of education level, most respondents held a bachelor's degree (186 respondents, 46.50%), followed by a diploma or associate degree (143 respondents, 35.75%) and high school education (55 respondents, 13.75%). The demographic profile indicates that the sample was concentrated among younger, digitally active tourists, particularly those aged 20–25 years and those with diploma or bachelor's degree qualifications. This profile is consistent with the online recruitment approach and the requirement that respondents had recent experience using IMT. However, it also suggests interpreting the findings with caution, as the sample may overrepresent tourists who are more familiar with digital technologies and more willing to participate in online surveys. Therefore, the results should be generalized only to digitally active tourists with recent IMT experience, rather than to all CBT tourists.

3.2 Structural equation modeling analysis

3.2.1 Assessment of the measurement model

Table 3. Measures of internal consistency reliability and convergent validity.

Construct	Items	Loading (> 0.70)	Cronbach's α (> 0.70)	Composite reliability (> 0.70)	AVE(> 0.50)	VIF (<5.0)
Recommendation Reliability (RRL)	RRL1	0.846	0.814	0.815	0.729	1.745
	RRL2	0.863				1.806
	RRL3	0.851				1.827
Recommendation Accuracy (RAC)	RAC1	0.859	0.835	0.869	0.747	1.667
	RAC3	0.818				2.406
	RAC4	0.913				3.061
Experiential Graphic Design (EGD)	EGD2	0.859	0.854	0.891	0.774	2.074
	EGD3	0.939				3.003
	EGD4	0.837				2.069
Attitude Toward Using Immersive Technology (ATT)	ATT1	0.935	0.790	0.855	0.706	2.488
	ATT2	0.797				1.739
	ATT4	0.780				1.683
Satisfaction (SAF)	SAF1	0.896	0.866	0.911	0.786	2.517
	SAF2	0.913				2.208
	SAF3	0.849				2.127
Intention to Use Immersive Technology (ITU)	ITU1	0.824	0.891	0.944	0.755	2.516
	ITU2	0.786				2.429
	ITU3	0.923				4.434
	ITU4	0.933				4.175
Intention toward the Destination (ITD)	ITD1	0.805	0.795	0.811	0.703	1.345
	ITD2	0.848				2.583
	ITD4	0.862				2.908

Table 3 presents the assessment results of internal consistency reliability and convergent validity of the measurement model, based on the criteria suggested by Hair Jr, et al. [50]. The factor loadings of all retained measurement items ranged from 0.780 to 0.939, exceeding the recommended threshold of 0.70. This indicates that each indicator adequately represents its corresponding latent construct. Furthermore, Cronbach's alpha values ranged from 0.790 to 0.891, and composite reliability (CR) values ranged from 0.811 to 0.944; all were above the required threshold of 0.70. These results suggest that the measurement items achieved an adequate level of internal consistency. Regarding convergent validity, the average variance extracted (AVE) values ranged from 0.703 to 0.786, exceeding the recommended threshold of 0.50. This indicates that the measurement model achieved adequate convergent validity, as the indicators explained a sufficient proportion of variance in their respective latent constructs. Furthermore, the variance inflation factor (VIF) values of all indicators ranged from 1.345 to 4.434, which were below the threshold of 5.00. This suggests no serious multicollinearity among the indicators. Overall, the results support the reliability and convergent validity of the measurement model, indicating that it was appropriate for subsequent structural model analysis.

Table 4. Fornell–Larcker criterion analysis.

Construct	ATT	EGD	ITD	ITU	RAC	RRL	SAF
ATT	0.840						
EGD	0.327	0.880					
ITD	0.090	-0.082	0.839				
ITU	0.332	0.083	0.150	0.869			
RAC	0.639	0.405	-0.108	0.137	0.864		
RRL	0.535	0.357	-0.086	0.209	0.433	0.854	
SAF	0.421	0.180	0.117	0.359	0.409	0.259	0.886

As shown in Table 4, the Fornell and Larcker [51] criterion was used to assess discriminant validity among the constructs. The results indicate that the square roots of the AVE values for each construct, presented on the diagonal of the correlation matrix, were greater than the corresponding inter-construct correlations in both the rows and columns. This finding confirms that each construct had adequate discriminant validity. Therefore, the measurement model was considered appropriate for subsequent structural equation model analysis.

Table 5. Heterotrait-Monotrait (HTMT).

Construct	ATT	EGD	ITD	ITU	RAC	RRL	SAF
ATT							
EGD	0.379						
ITD	0.101	0.101					
ITU	0.370	0.088	0.160				
RAC	0.738	0.451	0.119	0.141			
RRL	0.649	0.423	0.109	0.237	0.503		
SAF	0.483	0.206	0.131	0.376	0.444	0.300	

As shown in Table 5, the heterotrait–monotrait ratio (HTMT) was used to assess discriminant validity further further. The results show that all HTMT values were below the recommended threshold of 0.90 [52]. This indicates that all constructs demonstrated adequate discriminant validity, confirming that the measurement model had satisfactory construct validity and was suitable for subsequent structural model analysis. Because recommendation reliability and recommendation accuracy are conceptually related dimensions of information quality, additional attention was given to their discriminant validity. The Fornell–Larcker correlation between RRL and RAC and the HTMT value were both below the recommended thresholds. These results indicate that, although the two constructs are related, respondents could distinguish between the perceived dependability of the recommendation process and the perceived factual correctness of the information provided by the prototype. In addition, the VIF values did not indicate serious multicollinearity, supporting the decision to retain RRL and RAC as separate predictors in the structural model.

3.2.2 Assessment of the structural model

The structural model assessment examined the hypothesized relationships among the constructs. A bootstrapping procedure with 5,000 subsamples was performed to assess the significance and robustness of the structural paths. The evaluation considered path coefficients, t-values, p-values, and full collinearity VIF values. The t-value thresholds were greater than 1.96 for the 5% significance level, greater than 2.58 for the 1% significance level, and greater than 3.29 for the 0.1% significance level. In addition, full collinearity VIF values were examined as a post hoc diagnostic for potential common method bias. As shown in Table 6, all VIF values ranged from 1.000 to 1.350, which were below the recommended threshold. These results suggest that multicollinearity and common method bias were unlikely to be serious concerns in the structural model. The results of hypothesis testing are presented in Figure 2 and Table 6. Recommendation reliability had a positive and significant effect on attitude toward using immersive technology (H1: $\beta = 0.315$, $t = 7.773$, $p < 0.001$), supporting H1. Recommendation accuracy also had a positive and significant effect on attitude toward using immersive technology (H2: $\beta = 0.498$, $t = 12.743$, $p < 0.001$), supporting H2. Among the three stimulus variables, recommendation accuracy was the strongest predictor of attitude, followed by recommendation reliability.

These results indicate that tourists' favorable attitudes toward using the IMT-enabled CBT prototype were mainly shaped by the perceived accuracy and reliability of the information and recommendations provided by the system. In contrast, experiential graphic design did not significantly influence attitude toward using immersive technology (H3: $\beta = 0.013$, $t = 0.349$, $p = 0.728$). Therefore, H3 was not supported. This finding suggests that, in this study, the visual and design-related features of the IMT-enabled CBT prototype did not provide a significant direct contribution to tourists' attitudes after recommendation reliability and recommendation accuracy were considered simultaneously.

Regarding the response variables, attitude toward using immersive technology had a positive and significant effect on satisfaction (H4: $\beta = 0.421$, $t = 10.311$, $p < 0.001$), supporting H4. Attitude also had a positive and significant effect on intention to use immersive technology (H5: $\beta = 0.332$, $t = 7.166$, $p < 0.001$), supporting H5. However, attitude did not significantly influence intention toward the destination (H6: $\beta = 0.090$, $t = 1.661$, $p = 0.097$). Therefore, H6 was not supported. This result indicates that although a positive attitude toward using IMT enhanced tourists' satisfaction and intention to continue using IMT, it was not sufficient on its own to increase tourists' destination intention significantly. Destination intention may depend on additional factors beyond technology-related attitudes, such as travel cost, accessibility, available time, destination attractiveness, personal motivation, and service readiness. Overall, the structural model results supported four hypotheses, namely H1, H2, H4, and H5, while H3 and H6 were not supported. These findings suggest that the SOR model partially explained tourists' responses to the IMT-enabled CBT prototype. The stimulus components related to information quality, particularly recommendation accuracy and recommendation reliability, significantly influenced tourists' attitudes, and attitude subsequently influenced satisfaction and intention to use IMT. However, future studies should further investigate experiential graphic design and destination intention theoretically and empirically.

Table 6. Hypotheses testing.

Hypotheses	Paths	Coefficient (β)	T-Value	P-Value	Full collinearity VIF	Results
H1	Recommendation Reliability (RRL) → Attitude Toward Using Immersive Technology (ATT)	0.315	7.773	0.000***	1.293	Supported
H2	Recommendation Accuracy (RAC) → Attitude Toward Using Immersive Technology (ATT)	0.498	12.743	0.000***	1.350	Supported
H3	Experiential Graphic Design (EGD) → Attitude Toward Using Immersive Technology (ATT)	0.013	0.349	0.728	1.257	Not supported
H4	Attitude Toward Using Immersive Technology (ATT) → Satisfaction (SAF)	0.421	10.311	0.000***	1.000	Supported
H5	Attitude Toward Using Immersive Technology (ATT) → Intention to Use Immersive Technology (ITU)	0.332	7.166	0.000***	1.000	Supported
H6	Attitude Toward Using Immersive Technology (ATT) → Intention toward the Destination (ITD)	0.090	1.661	0.097	1.000	Not supported

Note: *** $p < 0.001$.

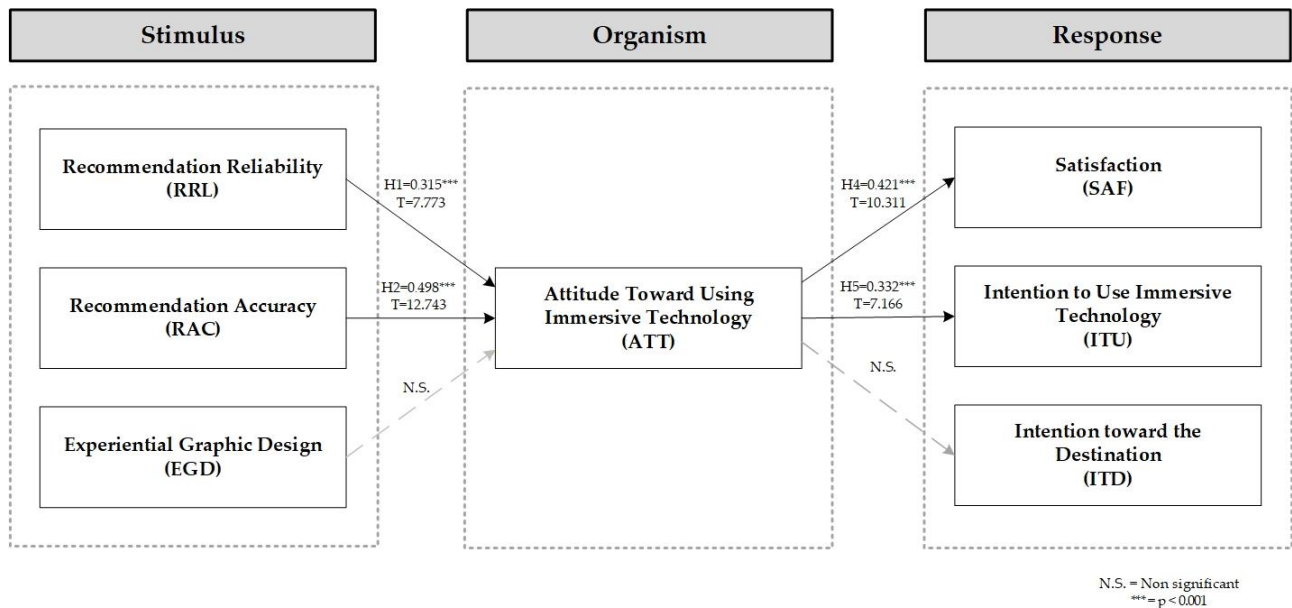


Figure 2. Structural model testing.

The model fit results were evaluated using the Standardized Root Mean Square Residual (SRMR) and the Normed Fit Index (NFI). The SRMR value of the saturated model was 0.066, below the recommended threshold of 0.08, indicating an acceptable fit. The estimated model had an SRMR of 0.086 and an NFI of 0.752. Because global model fit indices in PLS-SEM should be interpreted cautiously and are not the sole basis for model evaluation, this study assessed model adequacy primarily based on measurement reliability, convergent validity, discriminant validity, collinearity assessment, explanatory power, predictive relevance, and effect size.

Table 7. Coefficient of determination and predictive relevance of endogenous constructs.

Construct	R-Squared	Adjusted R-Squared	Predictive relevance (Q^2)
Attitude Toward Using Immersive Technology (ATT)	0.491	0.487	0.481
Intention toward the Destination (ITD)	0.008	0.006	-0.023
Intention to Use Immersive Technology (ITU)	0.110	0.108	0.031
Satisfaction (SAF)	0.177	0.175	0.152

The results in Table 7 indicate that the model explained 49.1% of the variance in attitude toward using immersive technology (ATT), suggesting moderate explanatory power. The model explained 17.7% of the variance in satisfaction (SAF) and 11.0% of the variance in intention to use immersive technology (ITU), indicating relatively weak explanatory power for these response constructs. However, the model explained only 0.8% of the variance in intention toward the destination (ITD), suggesting very limited explanatory power for this construct. Regarding predictive relevance, the Q^2 values for ATT, SAF, and ITU were greater than zero, indicating predictive relevance, whereas the Q^2 value for ITD was negative, suggesting that the model did not demonstrate predictive relevance for intention toward the destination.

Table 8. Effect size (f^2) assessment.

Hypotheses	f-square	Signification
ATT → ITD	0.008	No effect size
ATT → ITU	0.124	Small effect size
ATT → SAF	0.215	Medium effect size
EGD → ATT	0.000	No effect size
RAC → ATT	0.361	Large effect size
RRL → ATT	0.150	Medium effect size

As shown in Table 8, recommendation accuracy had a large effect size on attitude toward using immersive technology ($f^2 = 0.361$), indicating that it was the most practically influential predictor of attitude in the model. Recommendation reliability showed a medium effect size ($f^2 = 0.150$), while experiential graphic design showed no effect size ($f^2 = 0.000$). For the response constructs, attitude toward using immersive technology had a medium effect size on satisfaction ($f^2 = 0.215$), a small effect size on intention to use immersive technology ($f^2 = 0.124$), and no effect size on intention toward the destination ($f^2 = 0.008$).

3.3 Theoretical implications

This study contributes to the theoretical understanding of tourists' responses to immersive technology (IMT) in community-based tourism (CBT) by applying the Stimulus–Organism–Response (SOR) framework. The findings show that technology-related stimuli, particularly recommendation reliability and recommendation accuracy, influence tourists' internal evaluations of IMT, which subsequently shape satisfaction and intention to use IMT. Thus, the SOR framework provides a useful structure for explaining how tourists respond to IMT-enabled CBT experiences. This study enhances our comprehension of the stimulus component within the SOR framework by emphasizing Recommendation Reliability (RRL) and Recommendation Accuracy (RAC) as significant technological stimuli in the context of IMT and CBT. The findings indicate that recommendation reliability positively affects tourist attitudes toward using IMT. This aligns with Kim et al. [32], which indicates that social recommendations can mitigate information overload. It enables users to assess the quality of products, services, or experiences before making decisions. In the realm of Community-Based Tourism (CBT), dependable recommendations from the immersive technology (IMT) system enhance tourists' confidence in information regarding attractions, community activities, travel routes, and associated services.

Moreover, the results suggested that recommendation accuracy was one of the main determinants of tourists' attitudes toward using IMT. This aligns with previous research on recommendation systems, which indicates that correct and appropriate recommendations can enhance user experience by providing more relevant, helpful, and personalized information [11]. The accuracy of suggestions is especially relevant in community-based tourism since travelers generally rely on digital information to evaluate new sites, local activities, and community tourism experiences. Thus, the present research shows that tourists' positive sentiments toward IMT are due not only to the novelty of the technology but also to the quality, accuracy, and utility of the information it provides. The non-significant effect of experiential graphic design (EGD) on attitude toward using IMT requires further theoretical consideration. Although the bivariate correlation between EGD and ATT was positive, the structural path from EGD to ATT was near zero when recommendation reliability and recommendation accuracy were included simultaneously in the model. This suggests that EGD may be associated with tourists' attitudes at a general perceptual level, but it did not provide additional explanatory power beyond the perceived reliability and accuracy of the information provided by the IMT-enabled CBT prototype.

One possible explanation is that tourists in this context evaluated the prototype primarily as a decision-support tool for obtaining reliable and accurate CBT information, rather than as a purely visual or entertainment-oriented immersive medium. Therefore, graphic design may function as a supportive or enabling condition, while information quality plays a more central role in shaping attitudes. Another possible explanation concerns how EGD was operationalized. The retained EGD indicators mainly captured design consistency, user-friendliness, and contextual fit, rather than purely aesthetic or immersive qualities such as visual realism, spatial presence, sensory vividness, or visual attractiveness. Therefore, the non-significant result should not be interpreted as evidence that graphic design is unimportant for IMT. Rather, it indicates that the specific EGD dimension measured in this study did not have a unique direct effect on attitude after accounting for recommendation reliability and recommendation accuracy. Secondly, this study confirms attitude toward using IMT as the organism component, or the internal psychological state, in the SOR framework. Attitude represents tourists' evaluation, feelings, and readiness to use technology and is an important component in technology acceptance studies [49]. The findings indicate that attitude toward using IMT positively influenced satisfaction and intention to use IMT. This is consistent with previous studies

showing that favorable attitudes toward immersive technology can enhance tourists' experiences, satisfaction, and behavioral intention [11, 44, 45].

However, attitude toward using IMT did not significantly influence intention toward the destination. This finding suggests that a favorable evaluation of the IMT-enabled CBT prototype may increase tourists' satisfaction with the technology and their willingness to reuse it, but it may not be sufficient to stimulate destination intention directly. In the CBT context, intention toward a destination may depend on broader travel-related factors, such as destination attractiveness, travel cost, accessibility, available time, service readiness, perceived safety, and tourists' personal motivations. Therefore, the response component of the SOR framework in this study is more strongly reflected in technology-related responses than in destination-related intention. In summary, this study contributes to the SOR framework in the context of IMT and CBT by showing that the credibility and correctness of innovative recommendations serve as technological stimuli that substantially affect tourists' views. Attitudes are an internal process linking views of technology to behavioral responses. The study proposes that research into the acceptability of IMT in tourism should focus on the quality, accuracy, and reliability of the information offered by the technology, in addition to its novelty or attractiveness.

3.4 Practical implications

This study offers practical recommendations for community-based tourism operators, attraction managers, technology developers, and government agencies aiming to implement IMT to improve tourism experiences within the context of CBT, as summarized in Table 9 and illustrated in Figure 3. First, because recommendation accuracy significantly influences tourists' attitudes, technology developers and CBT managers should prioritize accurate information. Attractions, community activities, travel routes, opening hours, costs, safety guidelines, and local best practices must be verified from reliable sources and updated regularly. Second, enhancing the credibility of innovative recommendations is essential to increase tourists' trust in IMT-based tourism services. Community-based tourism platforms must transparently present the information sources and justify the recommendations for routes, activities, or attractions to align with tourists' preferences, including travel time, activity type, accessibility, and suitability for the target demographic. Additionally, local communities, operators, and relevant agencies should be afforded opportunities to engage in the verification and certification of information. This participation is essential to ensure that recommendations accurately represent the area's conditions and foster confidence among tourists. Third, while experiential graphic design did not significantly affect tourists' attitudes in this study, this does not mean visual design lacks importance in practice. This study indicates that graphic design must enhance information clarity and usability. The development of immersive technology (IMT) for Community-Based Tourism (CBT) should prioritize intuitive navigation, clear symbols, easily readable maps, illustrations that reflect community identity, and visual elements that enhance tourists' understanding of the community's stories, activities, routes, and customs, rather than focusing solely on aesthetics.

Fourth, because attitudes toward using IMT positively affect satisfaction and intention to use IMT, entrepreneurs and communities should develop technology experiences that are accessible, fun, and useful to tourists' needs. Examples include viewing community stories at tourism destinations with augmented reality, experiencing a community before a trip through virtual reality, or planning travel routes using interactive maps and Story Maps. Applying these technologies will help tourists better understand the town's identity, interact with local culture and resources, and improve overall satisfaction with the vacation experience. Fifthly, although attitude toward using IMT did not significantly influence intention toward the destination in this study, IMT can still serve as a supportive communication and information tool for CBT destinations. Destination managers should recognize that positive attitudes toward technology alone may not be sufficient to transform tourists' interest into destination intention. Therefore, IMT should be integrated with practical travel support, including booking channels, community contacts, travel information, maps, transportation routes, activity details, costs, and service availability. Connecting immersive experiences with real travel readiness may help strengthen the link between technology engagement and actual destination interest. Government agencies and organizations involved in tourist development must continuously strengthen the community's ability to manage digital resources. Training communities to update tourist information, create

narrative content, validate system recommendations, and use digital technologies. Tourist feedback after the deployment of IMT will ensure it is used as a promotional tool for tourist sites, as well as a tool for enhancing the experience, supporting decision-making, and promoting sustainable development in community-based tourism.

Table 9. Summary of practical implications based on the study findings.

Study finding	Practical meaning	Implementation guidelines	Key stakeholders
H2: Recommendation accuracy had the strongest effect on tourists' attitudes toward using IMT	Tourists place greater importance on accurate and useful information for travel decision-making than on technological novelty alone.	Regularly verify and update information on attractions, community activities, routes, operating hours, costs, and local guidelines.	Technology developers, local communities, destination managers, government agencies
H1: Recommendation reliability positively influences tourists' attitudes toward using IMT	Innovation-based recommendations can create positive attitudes when tourists perceive the information as credible and consistent with the actual local context.	Clearly present information sources, explain the rationale behind recommendations, and involve local communities or relevant agencies in content verification before publication.	Local communities, tourism operators, platform developers
H3: Experiential graphic design did not significantly influence attitude	Visual attractiveness alone may not be sufficient to create positive attitudes toward IMT if the information lacks accuracy and reliability.	Design graphics to emphasize clarity, ease of use, readability, direct communication, and local identity rather than focusing only on aesthetics.	Media designers, IMT developers, local communities
H4: Attitude toward using IMT positively influenced tourist satisfaction	Tourists with positive attitudes toward IMT are more likely to be satisfied with the user experience and the information received.	Design IMT experiences that are accessible, enjoyable, useful, and capable of helping tourists better understand community stories.	Technology developers, CBT operators
H5: Attitude toward using IMT positively influenced intention to use IMT	Positive experiences can encourage tourists to reuse IMT or recommend it to others.	Develop AR, VR, MR, Story Maps, or interactive media that are easy to use, engaging, and useful for tourism planning.	Platform developers, tourism promotion agencies
H6: Attitude toward using IMT did not significantly influence intention toward the destination	A positive attitude toward IMT alone may not be sufficient to increase tourists' destination intention. Destination intention may require additional practical and motivational factors.	Connect IMT with real travel information, such as maps, community contact channels, booking systems, activity details, prices, transportation, accessibility, and service readiness.	Destination managers, local communities, government agencies
System-level implication from the findings	IMT adoption in CBT should be developed as a digital ecosystem that enables communities to manage tourism information independently.	Provide community training on digital content creation, information updating, recommendation validation, and post-use tourist feedback evaluation.	Government agencies, educational institutions, local communities

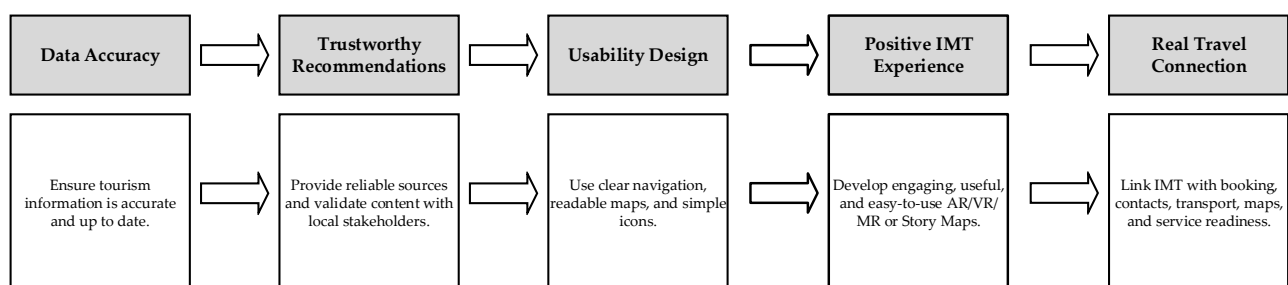


Figure 3. Practical implication framework for applying IMT in community-based tourism (CBT).

3.5 Limitations and future research

The present study has some limitations that should be considered: it uses a cross-sectional study design, collecting data from a single sampling period. It can explain the links between variables to some extent, but it cannot effectively depict long-term changes in tourists' attitudes, satisfaction, or behavioral intentions. Secondly, the study's sample is limited to tourists who have used immersive technology in the past three months in Prachuap Khiri Khan Province, Thailand. Thus, the findings may not fully apply to community-based tourism in other places with different cultural characteristics, tourism resources, technology resources, and tourist behavior. Thirdly, this study evaluates the trustworthiness and accuracy of suggestions and experience graphic design as the main triggers of the SOR paradigm. Tourists' responses toward immersive technology may depend on variables such as trust in technology, perceived benefits, perceived ease of use, enjoyment, immersive experience, community involvement, travel goals, and limits in time, cost, or travel. Fourth, a limitation of this study is that it investigates only tourists' behavioral intentions and therefore cannot determine whether these intentions will translate into future use of the technology or an actual trip to the place. Another important limitation concerns the sampling procedure. Participants were recruited using purposive sampling through online platforms, including Facebook and LINE, and were required to have used IMT within the previous three months. This approach was suitable for reaching respondents with relevant IMT experience; however, it may have introduced selection bias. Tourists reachable through online platforms who voluntarily participate in an online survey may differ from non-participants in digital literacy, technology familiarity, age, education level, and attitudes toward digital tools. The sample's demographic profile, concentrated among younger and relatively well-educated respondents, further suggests that the findings may overrepresent digitally active tourists and should not be generalized to all CBT tourists. Future research should employ more diverse recruitment strategies, such as on-site intercept surveys, offline data collection, stratified sampling by age and gender, and comparisons between IMT users and non-users, to improve representativeness and external validity.

Further research should extend the scope of study to community-based tourism destinations in other regions to assess the differences in community contexts, types of tourism activities, and levels of technological readiness. Future studies could consider longitudinal designs to investigate changes over time in tourists' views, satisfaction, and behaviors after encountering immersive technology. Future studies may also take a mixed-methods approach, integrating quantitative data with qualitative insights gathered through interviews with tourists, tourism operators, and community residents. Such an approach would provide greater insights into the reasons for technological acceptance and rejection. Finally, future studies should include other variables such as perceived value, trust in technology, data privacy, immersive experience, and real travel behavior to construct a more complete model explaining the role of immersive technology in the growth of community-based tourism.

4. Conclusions

This study aimed to explain the factors influencing tourists' attitudes and responses toward the use of immersive technology (IMT) in the context of community-based tourism (CBT) by applying the stimulus–organism–response (SOR) framework. The findings revealed that recommendation reliability and recommendation accuracy provided by the innovation were key stimuli that positively influenced tourists' attitudes toward using IMT, with recommendation accuracy showing the strongest effect. In contrast, experiential graphic design did not significantly influence attitude. These findings indicate that tourists place greater importance on accurate, reliable, and decision-supportive information than on the visual attractiveness of media alone. In addition, attitude toward using IMT positively influenced tourist satisfaction and intention to use IMT, confirming attitude as an internal mechanism linking technology-related stimuli with technology-related behavioral responses. However, attitude toward using IMT did not significantly influence intention toward the destination, suggesting that destination intention may depend on additional travel-related factors beyond tourists' evaluations of the IMT-enabled CBT prototype.

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Development and Physical Characterization of Molded Charcoal Souvenir Products from Rubberwood Charcoal Reinforced with Tea Waste

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Abstract: This research aimed to investigate the physical properties of molded charcoal produced from rubberwood biochar and tea waste, determine the optimal mixing ratio for forming stable products, and evaluate the production cost of the developed souvenir items. Rubberwood charcoal and tea waste were characterized for moisture content, volatile matter, ash content, fixed carbon, iodine adsorption, and moisture adsorption capacity. The rubberwood charcoal exhibited a moisture content of $2.82 \pm 0.17\%$, volatile matter of $85.83 \pm 2.07\%$, ash content of $2.90 \pm 0.18\%$, fixed carbon of $8.45 \pm 1.72\%$, and an iodine adsorption value of 479.94 ± 20.00 mg/g. The tea waste showed a moisture content of $2.75 \pm 0.17\%$ and an ash content of $2.83 \pm 0.18\%$. Four formulations with different weight ratios of charcoal powder to tea waste (3:0, 3:1, 1:1, and 1:3) were prepared using tapioca starch as a binder, then formed into pieces using traditional mooncake molds. The 3:1 ratio was found to be the most suitable, providing compact, crack-free specimens with clear surface patterns, no loose powder after drying, and a slightly brown tea color. Moisture adsorption tests over 3 days confirmed that all formulations absorbed moisture, with the 3:1 formulation offering a good balance between structural integrity and functional performance. A preliminary cost analysis indicated that using 1 kg of mixed raw materials yielded 35 molded charcoal pieces at a total cost of 315.84 THB, or 9.02 THB per piece. The results demonstrate the technical feasibility and economic potential of upcycling rubberwood charcoal and tea waste into culturally inspired, environmentally friendly charcoal-based souvenir products with moisture adsorption capability suitable for community-based product development.

Keywords: Rubberwood biochar; tea waste; molded charcoal products; moisture adsorption; circular economy

1. Introduction

Rubberwood is an economically important crop in southern Thailand, where it is extensively cultivated and serves as a primary source of income for many farmers. Rubber cultivation is mainly aimed at natural latex production for industrial applications. After the latex-producing lifespan ends, rubber trees are felled and supplied to rubberwood processing factories, making rubberwood one of the major raw materials in Thailand's wood-processing

industry. However, rubberwood processing generates substantial quantities of substandard wood residues, which are commonly classified as industrial waste. Although a portion of these residues is utilized as fuel, a large amount remains underutilized despite its potential for value addition through environmentally friendly processing approaches [1, 2]. The conversion of rubberwood residues into biochar represents a promising strategy for waste valorization. Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, typically at temperatures between 300 and 700 °C. This process yields a porous structure with high chemical stability and surface functional groups that contribute to adsorption properties for moisture, odors, and various contaminants [3, 4]. Biochar can be produced from a wide range of agricultural and industrial residues, including coconut shells, rice husks, sugarcane bagasse, and rubberwood residues. Its physicochemical properties, such as moisture content, volatile matter, ash content, fixed carbon, and adsorption capacity, are strongly influenced by feedstock characteristics, pyrolysis conditions, and intended applications [5–8].

In recent years, biochar has gained increasing attention as an environmentally friendly material for product development due to its low production cost and multifunctional properties. In addition to its well-documented use in soil amendment and environmental remediation, biochar has demonstrated potential as an odor- and moisture-adsorbing material for household applications. Biochar-based molded charcoal products can be applied in enclosed environments such as wardrobes, refrigerators, vehicles, and storage spaces, providing practical functionality while adding value to agricultural waste materials [9,10]. When developed as souvenir products, such applications may further contribute to community-based economic activities. Although both biochar and activated carbon are porous carbonaceous materials with adsorption capabilities, they differ substantially in production processes and cost structures. Activated carbon requires additional physical or chemical activation to enhance its specific surface area and adsorption efficiency, making it suitable for industrial-scale applications such as water and air treatment. However, these activation processes are energy-intensive and associated with relatively high production costs [11]. In contrast, biochar can be produced without further activation, resulting in lower energy consumption and better alignment with sustainability and resource-efficiency principles. Despite its lower specific surface area, biochar has demonstrated adsorption potential for odor-causing and volatile compounds, supporting its application in low-cost adsorption systems [12, 13].

To enhance the functional performance of rubberwood biochar, the incorporation of secondary biomass residues has attracted growing interest. Tea waste, a by-product generated in large quantities from households and the beverage industry, contains lignocellulosic components and surface functional groups that may contribute to moisture and adsorption-related performance. Previous studies have demonstrated that tea waste exhibits adsorption potential for moisture and volatile compounds, supporting its suitability as a supplementary material in composite charcoal formulations [14, 15]. The use of traditional mooncake molds provides a practical shaping method for molded charcoal products, enabling the formation of decorative patterns and consistent product forms. Incorporating culturally recognizable forms and design elements into souvenir development can enhance product identity, aesthetic value, and differentiation in tourism-related markets [16, 17]. The development of molded charcoal souvenir products from tea-waste-enhanced rubberwood biochar is consistent with sustainable development principles. This approach supports waste reutilization and value addition, aligning with the Sustainable Development Goals, particularly responsible consumption and production and climate action, as well as Thailand's Bio-Circular-Green Economy model, which emphasizes biomass utilization and environmentally friendly product development [18–20].

Therefore, this study focuses on the development of molded charcoal souvenir products from rubberwood biochar enhanced with tea waste using mooncake molds. The objectives of this research are to investigate the physical properties of rubberwood charcoal and tea waste, determine the optimal mixing ratio for producing structurally stable molded products, and evaluate the production costs of the developed souvenir items. Rubberwood charcoal and tea waste were characterized for moisture content, volatile matter, ash content, fixed carbon, iodine adsorption capacity, and moisture adsorption behavior. The findings of this study aim to provide a scientific basis for sustainable material utilization and product development suitable for community-based commercialization.

2. Materials and Methods

2.1 Materials

Rubberwood biochar powder was used as the primary material in this study. It was obtained from rubberwood residues generated during wood-processing activities in southern Thailand. The residues were carbonized under limited-oxygen conditions to produce biochar, which was then ground and sieved to obtain a uniform particle size suitable for molding and adsorption-related performance. Spent tea leaves collected after beverage brewing were used as a supplementary material. The tea waste was dried and finely ground before use to enhance adsorption performance and add value to the agricultural waste. Tapioca starch was employed as a natural binder to promote adhesion between the rubberwood biochar powder and tea waste, allowing the mixture to be formed into compact shapes with good structural stability. Clean water was used as a solvent to control moisture content and to obtain appropriate consistency for the compression process. The products were molded using mooncake molds with floral patterns, which served as the primary forming molds to produce uniform shapes and decorative surface details. The compression process was performed using manual pressure or a simple compression device to achieve sufficient density and mechanical strength, enabling the molded charcoal products to be removed from the molds without cracking or deformation. The potential susceptibility of the products to microbial or mold growth due to the presence of tapioca starch and tea waste should be noted. To mitigate this risk, all products were thoroughly oven-dried at 85 °C before use and storage. Future investigations should assess the incorporation of natural antifungal agents or the implementation of supplementary heat-treatment protocols to improve the long-term microbial stability and shelf life of the developed products. The compression force applied during molding was not precisely quantified in the present study, which constitutes a limitation affecting process reproducibility. Future studies should employ a calibrated compression device and report the applied pressure in standardized units (N or MPa) to enable reliable replication and comparison across different production contexts.

2.2 Preparation of the molded charcoal souvenir product samples

2.2.1 Preparation of Rubberwood Charcoal

Rubberwood residues were air-dried and subsequently carbonized at 500-800 °C for 4–5 h under controlled oxygen conditions. After completion of the carbonization process, the charcoal was allowed to cool naturally to ambient temperature (Fig. 1a). The resulting rubberwood charcoal was then ground into a fine powder using an electric grinder (OTTO, model CP-390B, 1.8 L capacity). The obtained rubberwood charcoal powder was collected and stored for further experimental investigations (Fig. 1b). It is acknowledged that the reported carbonization temperature range of 500–800 °C represents a wide operational span ($\Delta T = 300$ °C). Biochar physicochemical properties, including surface area, pore structure, volatile matter content, and fixed carbon, are known to vary substantially within this range [5,6]. This range reflects the operational variability of the carbonization equipment used in this study. Future work should target a more precisely controlled pyrolysis temperature to improve batch-to-batch reproducibility and ensure consistency of proximate analysis results.

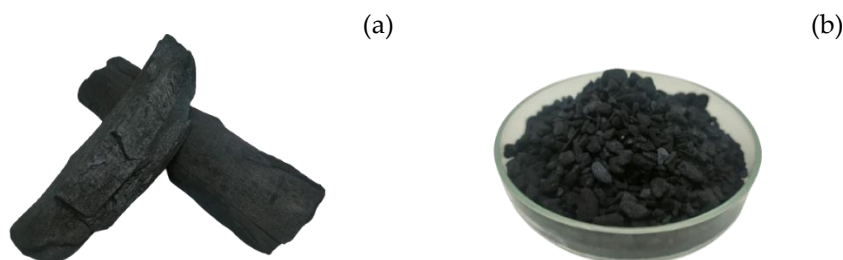


Figure 1. Shows (a) Rubberwood charcoal and (b) ground rubberwood charcoal powder.

2.2.2 Preparation of Tea Waste Powder

Spent tea leaves obtained after beverage brewing were sun-dried and subsequently oven-dried at 85 °C for 24 h to remove residual moisture. The dried tea waste was then ground into a fine powder and stored for further experimental investigation (Figure 2).



Figure 2. Spent tea leaves are collected after the tea brewing process and used to prepare tea powder.

2.2.3 Studying the optimal formula and ratio for molding activated carbon adsorption material fortified with tea waste

Based on investigations into suitable formulations and mixing ratios for molding charcoal products reinforced with tea waste, four formulations were examined by varying the mass ratio (weight ratio) of rubberwood charcoal powder to tea waste powder, as presented in Table 1.

Table 1. Formulations and mass ratios of materials used for molding molded charcoal products

Formulation	Rubberwood charcoal powder (g)	Tea waste powder (g)	Tapioca starch (g)
1	100	0	30
2	75	25	30
3	50	50	30
4	25	75	30

2.2.4 Studying the composition and molding of molded charcoal products reinforced with tea waste using mooncake molds.

Rubberwood charcoal powder, tea waste powder, and tapioca starch were thoroughly mixed according to the different formulations (Formulations 1–4), as summarized in Table 1. Each mixture was portioned into 60 g samples and subsequently molded into charcoal products using a mooncake mold with a peony lotus floral pattern. The molded samples were then oven-dried at 85 °C for 24 h to remove residual moisture. During the molding process, tapioca starch acted as a binding agent, facilitating adhesion between the charcoal powder and tea waste, improving compactness, and enhancing the mechanical strength and shape stability of the molded charcoal products (Figure 3).



Figure 3. Molding of tea waste–reinforced molded charcoal products using a mooncake mold.

2.3 Characteristic behavior of the samples

2.3.1 Analysis of the physical and chemical properties of rubberwood charcoal.

Moisture Content

The moisture content of the molded charcoal product samples was determined in accordance with the ASTM D2867-95 standard method. Porcelain crucibles with lids were first dried in an oven at 150 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was weighed and placed into the pre-dried crucible. The sample was subsequently oven-dried at 150 °C until a constant weight was achieved. After drying, the crucible was cooled in a desiccator before final weighing. The moisture content of the charcoal samples was calculated and expressed as a percentage based on the weight loss during drying, using Equation (1)

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where W_1 is the initial weight of the sample before drying, and W_2 is the weight after drying.

Volatile Matter

The volatile matter content of the molded charcoal product samples was determined according to the ASTM D5832-95 standard method. Porcelain crucibles with lids were first heated to 950 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was accurately weighed and placed into the pre-heated crucible. The crucible was immediately covered with a lid and transferred to a muffle furnace, where it was heated at 950 °C for 7 min. After heating, the crucible was promptly removed from the furnace and allowed to cool to ambient temperature for approximately 20 min, then further cooled in a desiccator. The weight of the charcoal sample after heating was recorded. The volatile matter content was calculated and expressed as a percentage based on the weight loss during heating, using Equation (2)

$$\text{Volatile matter (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (2)$$

where W_1 is the initial weight of the sample before heating, and W_2 is the final weight after heating.

Ash Content

The ash content of the molded charcoal product samples was determined in accordance with the ASTM D2866-94 standard method. Porcelain crucibles with lids were first heated to 650 °C for 3 h, then cooled to room temperature in a desiccator. Approximately 1.0 g of the charcoal sample was accurately weighed and placed into the pre-heated crucible. The crucible was subsequently heated in a muffle furnace at 650 °C with the lid removed until a constant weight was achieved. After combustion, the crucible was cooled in a desiccator before final weighing. The ash content was calculated and expressed as a percentage based on the residual mass after combustion, using Equation (3)

$$\text{Ash Content (\%)} = \frac{W_2}{W_1} \times 100 \quad (3)$$

where W_1 is the initial weight of the charcoal sample before combustion, and W_2 is the weight of the residual ash after combustion.

Fixed Carbon Content

The fixed carbon content of the molded charcoal product samples was determined indirectly from the proximate analysis results. The fixed carbon content was calculated by difference, using the measured moisture, volatile matter, and ash content obtained from the preceding analyses. The percentage of fixed carbon was calculated according to Equation (4)

$$\text{Fixed Carbon (\%)} = 100 - \text{Moisture (\%)} - \text{Volatile matter (\%)} - \text{Ash content (\%)} \quad (4)$$

Iodine Adsorption Analysis (Iodine Number)

The iodine adsorption capacity of the molded charcoal product samples was determined in accordance with the ASTM D4607-94 standard method. Before analysis, the charcoal samples were oven-dried at 120 °C for 3 h and cooled to room temperature in a desiccator. A known mass of the dried charcoal sample was accurately weighed and transferred into a 250 mL Erlenmeyer flask with a stopper. Subsequently, 10.0 mL of 5% (w/v) hydrochloric acid solution was added, and the flask was gently swirled to ensure complete wetting of the charcoal particles. The mixture was then heated at 100 °C for 30 s to remove ash and sulfur impurities. After cooling, 100.0 mL of 0.10 N iodine solution was added to the flask. The flask was immediately stoppered and vigorously shaken for 30 s to allow adsorption equilibrium between the iodine solution and the charcoal sample. The mixture was then filtered through filter paper, and the initial filtrate was discarded until the filter paper became fully saturated. The subsequent filtrate was collected in a 125 mL Erlenmeyer flask. An aliquot of 50.0 mL of the filtrate was pipetted into a 250 mL Erlenmeyer flask and titrated with 0.10 N sodium thiosulfate solution until a pale yellow color was observed. At this point, 2–3 drops of starch indicator were added, producing a blue coloration, and the titration was continued until the solution became colorless. The volume of sodium thiosulfate solution consumed was recorded. The iodine number, expressed as milligrams of iodine adsorbed per gram of charcoal (mg/g), was calculated using Equation (5)

$$X(\text{mg} / \text{g}) = \frac{M_A - (D_F \times B \times S)}{M} \quad (5)$$

where

A is the amount of iodine corresponding to the iodine solution (mg),

B is the amount of iodine corresponding to the sodium thiosulfate solution (mg),

DF is the dilution factor,

S is the volume of sodium thiosulfate solution used in the titration (mL),

M is the mass of the charcoal sample (g),

N_1 is the normality of the sodium thiosulfate solution, and

N_2 is the normality of the iodine solution.

2.3.2 Calculating the cost of souvenir products made from activated charcoal and tea leaves.

The production costs of molded charcoal souvenir products reinforced with tea waste were calculated to evaluate their economic feasibility. The total production cost consisted of three main components: (1) direct material costs, including rubberwood charcoal, tea waste powder, and tapioca starch; (2) direct labor costs, calculated based on a production rate of 10 molded charcoal products souvenir units per hour; and (3) manufacturing overhead costs, which included expenses for water consumption, electricity usage, adhesive materials, and equipment depreciation. Equipment depreciation was calculated using the straight-line depreciation method. The total product cost was determined as the sum of direct material costs, direct labor costs, and manufacturing overhead costs, as expressed in Equation (6)

$$\text{Product cost} = \text{Direct material cost} + \text{Direct labor cost} + \text{Manufacturing overhead cost} \quad (6)$$

3. Results and Discussion

3.1 Effect of formulation and mixture ratio for molding activated carbon adsorption material fortified with tea waste

Physical Properties and Statistical Analysis

The physical properties of rubberwood charcoal and tea waste were statistically analyzed, and the results are summarized in Table 2. One-way analysis of variance (ANOVA) revealed that there were no statistically significant differences ($p > 0.05$) in moisture content and ash content between rubberwood charcoal and tea waste, as indicated by identical superscript letters. These results suggest that tea waste possesses physical characteristics comparable to those of rubberwood charcoal, supporting its suitability as a supplementary material in the molding process. The low moisture and ash contents are advantageous for maintaining product stability and adsorption performance. Figure 4 illustrates the comparative physical properties of the two raw materials.

Table 2. Physical properties of rubberwood charcoal and tea waste used as raw materials for molded charcoal products production

Physical property	Rubberwood charcoal	Tea waste
Moisture content (%)	2.82 ± 0.17^a	2.75 ± 0.17^a
Volatile matter (%)	85.83 ± 2.07	–
Ash content (%)	2.90 ± 0.18^a	2.83 ± 0.18^a
Fixed carbon (%)	8.45 ± 1.72	–
Iodine adsorption capacity (mg/g)	479.94 ± 20.00	–

Note: Values are expressed as mean $\pm$ SD ($n = 3$). Values with the same superscript letter within the same row are not significantly different ($p > 0.05$) according to one-way ANOVA. Analyses were conducted following ASTM standard methods. Volatile matter and fixed carbon were not determined for tea waste, as it had not undergone carbonization. Iodine adsorption capacity was not measured for tea waste in the present study; this constitutes a recognized limitation. Future research should include iodine adsorption analysis of tea waste to comprehensively characterize its contribution to adsorption performance in composite formulations.

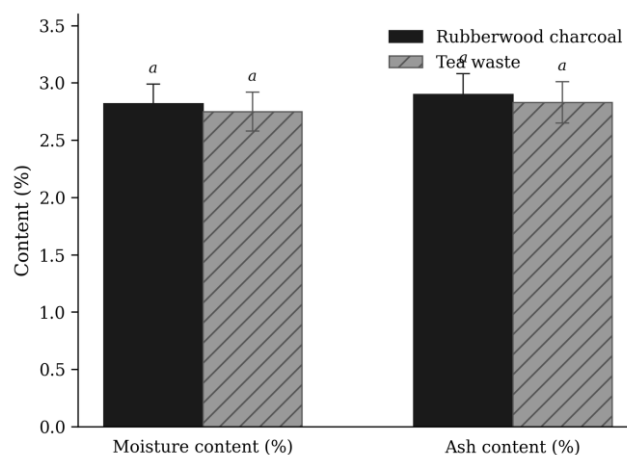


Figure 4. Comparison of the moisture content and ash content between rubberwood charcoal and tea waste

The moisture contents of rubberwood charcoal and tea waste were low. Rubberwood charcoal exhibited a moisture content of $2.82 \pm 0.17\%$, while tea waste showed a moisture content of $2.75 \pm 0.17\%$, with no statistically significant difference between the two materials ($p > 0.05$). These results indicate that both raw materials were sufficiently dry and suitable for the molding and drying processes of molded charcoal products, without causing problems related to shape retention or deterioration of adsorption performance, consistent with previous studies on charcoal-based molded products [21,22]. Rubberwood charcoal showed a volatile matter content of $85.83 \pm 2.07\%$, reflecting the characteristics of charcoal produced under moderate

pyrolysis temperatures, in which some organic components remain within the structure [1]. Volatile matter was not reported for tea waste because it had not undergone carbonization. Nevertheless, an appropriate level of volatile matter can enhance particle adhesion during the molding process, as reported in studies on densified biochar and charcoal briquettes [1, 2]. It should be noted that the reported volatile matter content of $85.83 \pm 2.07\%$ is substantially higher than the typical range of 15–35% reported in the literature for rubberwood charcoal and biochar produced at 500–800 °C [5,6]. This elevated value may reflect batch-to-batch variability associated with the wide carbonization temperature range (500–800 °C, $\Delta T = 300$ °C) applied in this study, partial carbonization of some material fractions, or methodological differences in the proximate analysis procedure. The authors acknowledge this discrepancy and recommend re-verification of the proximate analysis raw data and more precise control of pyrolysis temperature in future studies to improve data reliability and consistency with established literature values. (Figure 5)

The ash contents of rubberwood charcoal and tea waste were comparable, at $2.90 \pm 0.18\%$ and $2.83 \pm 0.18\%$, respectively, and no statistically significant difference was observed ($p > 0.05$). The low ash content indicates a low level of inorganic impurities, a desirable property for adsorption materials, as excessive ash can block pores and reduce adsorption efficiency [4,11]. Rubberwood charcoal had a fixed carbon content of $8.45 \pm 1.72\%$, representing the fraction of carbon remaining after the removal of moisture, volatile matter, and ash. This value reflects the potential of rubberwood charcoal to function as the primary adsorbent material in molded charcoal products. The fixed carbon content of tea waste was not reported because it had not been carbonized. Similar fixed carbon ranges have been reported for biomass-derived charcoals produced at moderate pyrolysis temperatures [4, 19].

The iodine adsorption capacity of rubberwood charcoal was 479.94 ± 20.00 mg/g, indicating an appropriate level of microporosity for the adsorption of odors and small volatile compounds. This moderate-to-relatively high iodine number supports the suitability of rubberwood charcoal for the development of molded charcoal products, particularly in community-based production contexts that emphasize simple processing methods and low production costs [8, 22, 23]

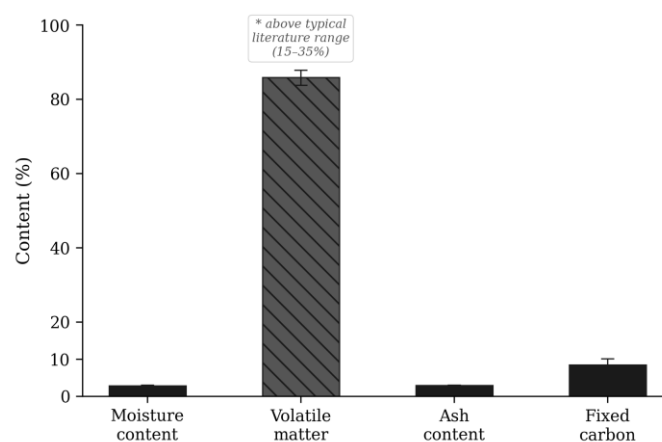


Figure 5. Proximate Analysis Results of Rubberwood Charcoal

3.2 Effect of composition and molding of activated charcoal adsorption material fortified with tea residue using mooncake molds.

The effects of composition on the moldability and structural characteristics of molded charcoal products reinforced with tea waste were investigated using four formulations with different mass ratios of rubberwood biochar powder to tea waste, as summarized in Table 3. When the mixtures were compressed using mooncake molds, clear differences in physical appearance, surface pattern definition, inter-particle cohesion, and shape retention were observed among the formulations, indicating a strong influence of mixture composition on molding behavior. Formulation 1 exhibited strong inter-particle cohesion between rubberwood biochar powder and tea waste, resulting in good moldability and clearly defined surface patterns transferred from the mold. After drying, no loose particles were observed upon manual handling, suggesting adequate particle packing and effective binding interactions between the constituent materials. Formulation 2 demonstrated

molding behavior comparable to, and in some aspects superior to, that of Formulation 1. The charcoal powder and tea waste adhered uniformly, resulting in sharp, well-defined floral patterns on the molded surface. The products retained their shape effectively in both wet and dry conditions, and no particle detachment was detected during handling. These characteristics indicate that formulation 2 possesses optimal material compatibility and consolidation behavior, making it highly suitable for practical application in the production of charcoal products. In contrast, Formulation 3 exhibited the weakest inter-particle adhesion among the tested formulations. The molded products exhibited unclear surface patterns, a friable, powdery texture, and substantial particle detachment upon handling. Poor shape retention after drying was also observed, indicating insufficient consolidation and mechanical integrity. Consequently, this formulation was deemed unsuitable for applications in molded charcoal products.

Formulation 4 showed moderate adhesion between rubberwood biochar powder and tea waste, allowing mold patterns to form to some extent. However, the surface details were less distinct than those observed in Formulations 1 and 2. Although the molded products retained their overall shape after drying, slight particle detachment and reduced surface quality were evident, reflecting inferior mechanical integrity compared with the optimal formulations. Based on these observations, Formulation 2 was selected as the most suitable formulation for molding charcoal products reinforced with tea waste. This formulation provided superior shape retention, clear, well-defined mold patterns, a smooth surface texture, and minimal particle detachment, thereby fulfilling the functional and aesthetic requirements for molded charcoal souvenir products, as summarized in Table 3. It is noted that the present evaluation of moldability was conducted qualitatively. Quantitative mechanical testing, such as compressive strength measurement or drop-test evaluation, was not performed in this study. Future work should incorporate standardized mechanical characterization (e.g., compressive strength in MPa and fracture energy) to provide a more robust, reproducible scientific basis for optimal formulation selection, particularly for souvenir products intended for commercial handling and transport [2, 3].

Overall, the results of the composition and molding study demonstrate that the rubberwood biochar–tea waste ratio plays a critical role in governing moldability, surface pattern definition, particle cohesion, and shape retention of charcoal products produced using mooncake molds. These findings are consistent with previous studies on densified biochar and charcoal-based products, which report that inter-particle adhesion and consolidation behavior are strongly dependent on mixture composition and particle interactions [22–24]. Formulations with balanced proportions of rubberwood biochar and tea waste (Formulations 1 and 2) exhibited strong cohesion, effective particle packing, and stable shape retention after drying, with negligible particle detachment during handling. Such characteristics are essential for achieving sufficient mechanical integrity and aesthetic quality in molded charcoal products [22–24]. In particular, Formulation 2 demonstrated the most favorable overall performance, maintaining structural stability in both wet and dry states while preserving sharp surface details from the mold. Conversely, formulations containing higher proportions of tea waste (Formulation 3) showed poor inter-particle adhesion, friable texture, and inadequate shape retention after drying. This behavior is consistent with reports indicating that excessive incorporation of lignocellulosic or fibrous residues can disrupt particle packing and weaken consolidated carbon structures [24, 25]. Formulation 4 exhibited intermediate behavior, with acceptable overall shape retention but reduced surface definition and slight particle detachment, a trend also reported in composite charcoal and briquette studies employing suboptimal mixture ratios [23, 24, 26] (Table 3).

Table 3. Morphology of molded charcoal products prepared with different biochar–tea waste ratios.

Formulation	Visual appearance	Observed characteristics
1		The charcoal powder exhibited strong cohesion, resulting in good moldability. The molded product retained its shape well, with clearly defined surface patterns. After drying, no loose charcoal particles were observed upon manual handling.
2		Both charcoal powder and tea waste adhered firmly, yielding well-shaped products with sharp, distinct mold patterns. After drying, no particle detachment was observed when touched. Slight brown coloration from tea waste was visible after drying.
3		Poor adhesion between charcoal powder and tea waste was observed. The molded product exhibited unclear surface patterns, a friable and powdery texture, and noticeable particle detachment upon handling. After drying, shape retention was inadequate, and the surface appeared dark brown.
4		Moderate adhesion between charcoal powder and tea waste was observed. The molded product retained its shape to some extent; however, the surface patterns were not well defined. After drying, slight particle detachment was detected upon handling, and the product exhibited a distinct brown coloration.

3.3 Moisture Adsorption Behavior of Molded Deodorizing Charcoal Formulations

The moisture adsorption behavior of molded charcoal products reinforced with tea waste is summarized in Table 4 and illustrated in Figure 6. Moisture uptake increased progressively with exposure time for all formulations. One-way analysis of variance (ANOVA) revealed that the formulation composition significantly influenced moisture adsorption, particularly at longer exposure times ($p < 0.05$). At day 3, Formulation 4 exhibited significantly higher moisture adsorption than Formulation 1, while no significant difference was observed between Formulations 2 and 3 ($p > 0.05$).

Table 4. Moisture adsorption (%) of molded charcoal products reinforced with tea waste at different exposure times

Time (day)	Formulation 1	Formulation 2	Formulation 3	Formulation 4
0	2.34 ± 0.16^a	2.52 ± 0.37^a	2.75 ± 0.55^a	1.67 ± 0.67^a
1	5.52 ± 0.13^a	5.65 ± 0.53^a	5.93 ± 0.48^a	6.12 ± 0.19^a
2	7.23 ± 0.17^a	7.36 ± 0.32^a	7.68 ± 0.61^{ab}	8.25 ± 0.19^b
3	7.94 ± 0.14^a	8.37 ± 0.50^{ab}	8.64 ± 0.75^{ab}	9.18 ± 0.20^b

Note: Values are expressed as mean $\pm$ SD ($n = 3$). Different superscript letters within the same row indicate significant differences at $p < 0.05$ according to one-way ANOVA

At the initial stage (day 0), the moisture adsorption values of all molded charcoal product formulations were low. Formulation 3 exhibited the highest value ($2.75 \pm 0.55\%$), followed by Formulation 2 ($2.52 \pm 0.37\%$) and Formulation 1 ($2.34 \pm 0.16\%$), while Formulation 4 showed the lowest moisture adsorption ($1.67 \pm 0.67\%$). Statistical analysis indicated no significant differences among the formulations ($p > 0.05$). These low initial values are consistent with previous studies reporting minimal moisture uptake in freshly dried charcoal and biochar materials before prolonged exposure to humidity [3, 5]. After 1 day of moisture exposure, the moisture adsorption of all formulations increased markedly. This behavior reflects the initial penetration of water molecules into accessible pores and surface functional groups, as commonly reported for charcoal-

based and biochar-based adsorbents under humid conditions [19, 21]. After 3 days of moisture exposure, Formulation 4 continued to exhibit the highest moisture adsorption and showed a statistically significant difference compared with Formulation 1 and Formulation 2 ($p < 0.05$). The increased moisture uptake at longer exposure times is associated with capillary condensation and enhanced interaction between water molecules and oxygen-containing surface functional groups [11, 21]. The enhanced moisture adsorption at longer exposure times may be associated with interconnected pore structures and water-retention behavior, as reported for coconut waste biochar [8].

Overall, the moisture adsorption of all molded charcoal product formulations increased progressively with increasing exposure time. Formulation 4 demonstrated the highest moisture adsorption capacity, reflecting the influence of a higher tea waste content on the increased hydrophilic surface characteristics and the availability of adsorption sites for water molecules [21, 22]. In contrast, Formulations 1 and 2 exhibited moderate, more stable moisture adsorption behavior, indicating their suitability for molded charcoal products that require a balance between adsorption performance and structural integrity, as illustrated in Figure 6. Similar trends have been reported in studies on mixed biomass charcoal-biochar composites designed for humidity and odor control applications [11,24]. Biochar with high porosity (approximately 56.5%) and water holding capacity (approximately 54%) significantly enhances adsorption-related performance. The porous structure and water-retention capacity of biomass-derived biochar facilitate moisture adsorption. In the present study, the moisture adsorption observed in rubberwood charcoal–tea waste composites may be attributed to the inherent porous structure of rubberwood biochar, together with the lignocellulosic composition of tea waste, which enhances surface roughness, pore accessibility, and the presence of hydrophilic functional groups. These findings highlight the importance of biomass composition in determining the physical properties and moisture adsorption capacity of molded charcoal materials. [8]

3.4 Production Cost Analysis of Deodorizing Charcoal Souvenir Products Reinforced with Tea Waste

Based on the material characterization and performance evaluation, Formulation 2 was selected for cost analysis due to its balanced physical properties, moisture adsorption behavior, and morphological stability. Selecting a formulation with stable structural integrity and moderate adsorption performance is essential to ensure both functional reliability and economic feasibility in molded charcoal products, as reported in previous studies on densified biochar and charcoal-based materials [3,5]. A cost per unit and cost-benefit analysis was conducted to evaluate the economic feasibility of producing molded charcoal products and souvenir products reinforced with tea waste at the community level. Cost analysis is an important component of community-based product development, as it reflects production scalability, affordability, and potential income generation for local producers [19, 21]. Using a total raw material input of 1 kg, the production process yielded 35 molded charcoal pieces. The total production cost was 315.84 THB, corresponding to an average unit cost of 9.024 THB per piece. This cost structure reflects small-scale, community-based production conditions and includes direct materials, direct labor, and manufacturing overhead. Similar cost structures and unit-cost ranges have been reported for molded charcoal and biochar-based household or souvenir products produced under small-scale or community enterprise settings, where low capital investment and simple processing techniques are emphasized [11–15].

Table 5. Production cost per unit of molded charcoal products, souvenir products, reinforced with tea waste

Cost component	Cost per hour (THB)	Cost per unit (THB)
Direct materials	12.50	1.25
Direct labor	42.50	4.25
Manufacturing overhead	35.24	3.52
Total	90.24	9.024

Note: One hour of production yields approximately 10 units of molded charcoal. Unit cost was calculated by allocating hourly production costs to individual products.

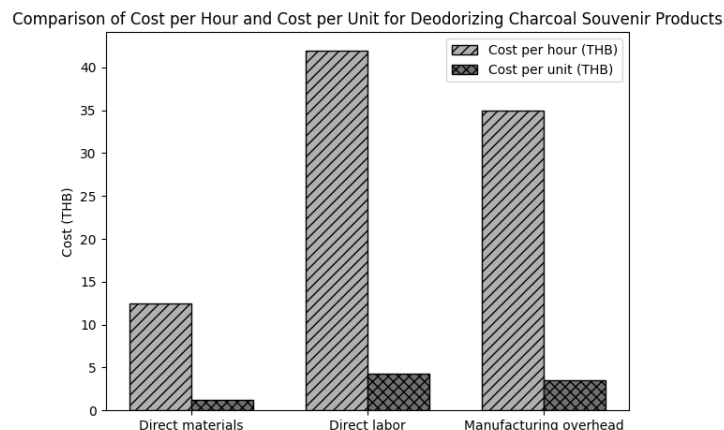


Figure 6. Unit production cost breakdown of molded charcoal products, souvenir products, reinforced with tea waste

Figure 6 compares the production cost per hour and the allocated cost per unit for each cost component. Direct labor exhibits the highest cost in both hourly (42.50 THB/hour) and unit-based (4.25 THB/unit) calculations, indicating that labor intensity is the primary contributor to overall production cost. Manufacturing overhead also accounts for a substantial portion of the cost, reflecting energy consumption, utilities, and equipment depreciation associated with the molding process. In contrast, direct material costs remain relatively low in both representations, highlighting the economic advantage of using rubberwood charcoal residues and tea waste as raw materials. The proportional consistency between hourly and unit costs confirms the appropriateness of allocating production costs based on a standardized output rate of approximately 10 units per hour.

3.5 Cost-Benefit Implications for Community-Based Production

From a cost-benefit perspective, the estimated unit production cost of 9.024 THB indicates that the molded charcoal products can be competitively positioned in local and tourist markets. Comparable handmade or eco-friendly molded charcoal products typically retail for 25-50 THB per piece, depending on packaging, branding, and point of sale. At a conservative selling price of 30 THB per unit, the gross margin would be approximately 20.98 THB per piece, representing a value addition of more than three times the unit production cost. Such value multiplication is consistent with previous reports on small-scale charcoal and biochar-based products developed for community enterprises and souvenir markets [11, 21]. It should be noted that the conservative selling price of 30 THB per unit was estimated based on general market knowledge of comparable eco-friendly and handmade deodorizing products and was not derived from a formal market survey. Future studies should conduct a structured market survey or cite comparable product pricing data from established retail channels or community enterprise reports to provide a stronger empirical basis for the cost-benefit analysis. The use of rubberwood charcoal residues and tea waste further enhances economic efficiency by reducing raw material expenses while simultaneously adding value to agricultural and industrial by-products. This strategy is widely recognized as an effective approach to improving profitability while minimizing waste generation, in accordance with circular-economy and biomass valorization principles [3, 4, 23]. Overall, the cost-performance balance achieved by Formulation 2 demonstrates its suitability for commercialization as a souvenir product. The relatively low production cost, combined with acceptable functional performance and aesthetic quality, supports its potential for sustainable adoption by community enterprises and small-scale producers, which is consistent with prior studies emphasizing low-capital, community-based manufacturing of biochar and charcoal products [11, 21, 24].

Table 6. Cost–Benefit Analysis of Deodorizing Charcoal Product

Item	Value (THB per unit)
Unit production cost	9.024
Selling price (conservative scenario)	30.00
Gross margin per unit	20.98
Value addition (times of production cost)	≈ 3.32 times

The analysis indicates that the product has a relatively low unit production cost compared with its market selling price, resulting in a high gross margin per unit and generating value addition of more than three times the production cost. This finding reflects the strong commercial potential of the molded charcoal products as eco-friendly souvenirs.

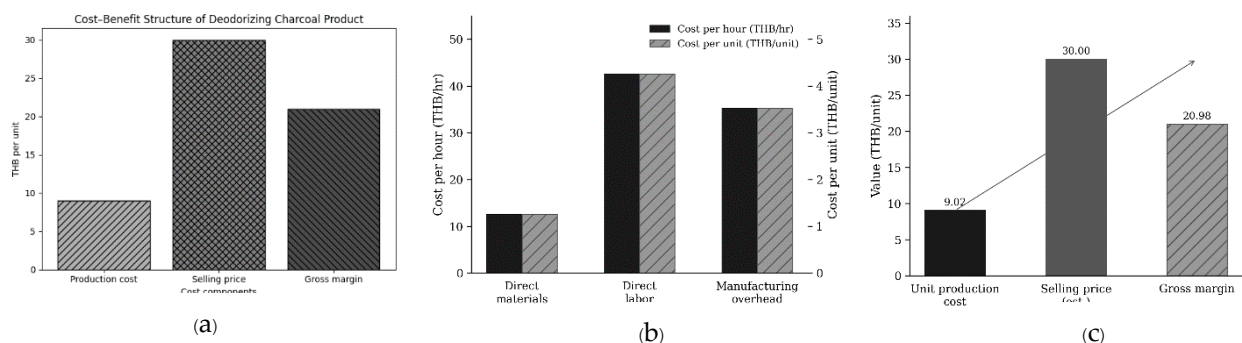


Figure 7. Economic analysis of molded charcoal products: (a) Cost–benefit structure of molded charcoal products souvenir products, (b) Production cost breakdown of molded charcoal products souvenir products, (c) Cost–benefit analysis of molded charcoal products souvenir products.

The graph clearly illustrates the differences among the unit production cost, selling price, and gross margin. The selling price is significantly higher than the production cost, resulting in a high gross margin per unit. This outcome is consistent with the principles of the circular economy and value addition of waste materials derived from rubberwood charcoal and tea waste.

4. Conclusions

This study demonstrates the technical and economic feasibility of producing molded charcoal souvenirs from rubberwood charcoal reinforced with tea waste, through optimized formulation and molding processes. Rubberwood charcoal exhibited suitable physical and adsorption-related properties, including a moderate iodine adsorption capacity indicative of appropriate microporosity for adsorption applications. These characteristics support its potential suitability as the primary adsorbent material for molded charcoal applications. It must be explicitly acknowledged that direct adsorption-related performance testing (e.g., using target gases such as ammonia, hydrogen sulfide, or standardized VOC adsorption experiments) was not conducted in this study. The odor-adsorbing potential of the developed products is therefore inferred from indirect performance indicators, namely iodine adsorption capacity and moisture adsorption behavior. The iodine number serves as a proxy for microporosity and is generally accepted as indicative of adsorption potential, but it does not directly measure adsorption-related performance. Future studies must incorporate quantitative measurements of odor or VOC adsorption to substantiate the molded charcoal claims stated in the title, abstract, and throughout the manuscript. Tea waste showed moisture and ash contents comparable to those of rubberwood charcoal, with no statistically significant differences, indicating good material compatibility. This compatibility enabled tea waste to be incorporated as a supplementary component without adversely affecting molding behavior, drying efficiency, or baseline adsorption performance, while contributing to waste valorization and sustainability. The rubberwood charcoal–tea waste ratio was identified as a critical parameter governing moldability, particle cohesion, surface definition, and shape retention.

Among the evaluated formulations, Formulation 2 provided the most favorable balance between mechanical integrity and functional performance, exhibiting clear mold patterns, stable shape retention, smooth surface texture, and minimal particle detachment. Formulations with excessive tea waste content showed enhanced moisture adsorption but suffered from reduced structural stability, highlighting the trade-off between adsorption capacity and mechanical performance. Moisture adsorption increased progressively with exposure time for all formulations, reflecting the hygroscopic nature of the composite materials. The synergistic interaction between the porous carbon matrix of rubberwood charcoal and the hydrophilic functional groups of tea waste enhanced adsorption performance in optimized formulations. From an economic perspective, the low unit production cost and high gross margin confirm strong commercial potential. Overall, the rubberwood charcoal–tea waste composite, particularly Formulation 2, represents a structurally sound, functionally effective, and economically viable material system for community-based production of molded charcoal products and souvenir products aligned with circular economy principles. It is acknowledged that direct adsorption-related performance testing was not performed in this study, and the molded charcoal claims are supported only by indirect indicators (iodine adsorption capacity and moisture adsorption behavior). Recommended directions for future research include: (1) quantitative odor or VOC adsorption experiments using target gases such as ammonia (NH₃), hydrogen sulfide (H₂S), or acetic acid; (2) standardized mechanical testing including compressive strength and fracture resistance measurements; (3) sensory evaluation and consumer preference studies relevant to souvenir market positioning; (4) long-term microbial stability and antifungal efficacy assessment; (5) more precisely controlled carbonization temperature conditions to improve batch reproducibility and proximate analysis reliability; and (6) a formal market survey to validate commercial viability assumptions.

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Economic Valuation of Timber and Carbon Stock in the Ban Phru Toei Community Forest, Nakhon Si Thammarat Province, Thailand

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Abstract: Community forests provide critical ecosystem services but are frequently undervalued in forest management decisions. This study assessed the economic value of timber resources and quantified the carbon stock of the Ban Phru Toei Community Forest (262 rai; 41.92 ha) in Bang Khan District, Nakhon Si Thammarat Province, Thailand. Twenty-six 20 × 50 m sample plots were systematically established. Tree species richness, density, and stem circumference were recorded; timber volume and above-ground biomass were estimated using published allometric equations. Economic values were derived using the market-price approach, based on 2020 customs import data. A total of 3,812 stems representing 101 species were recorded (1,992 large trees; 1,820 young trees), with a combined density of 146.62 stems per rai. The most abundant species was *Madhuca motleyana* (1,047 stems), followed by *Syzygium aqueum* (346 stems) and *Stemonurus malaccensis* (299 stems). Total timber volume was 2,228.60 m³ (85.72 m³ rai⁻¹). The net timber value of large trees was 25.19 million THB, and the total forest value reached approximately 255.73 million THB. Above-ground biomass in the 26 plots was 24.27 t, yielding a carbon stock of 11.41 t; extrapolated to the entire forest, total carbon was estimated at 114.94 t (0.44 t rai⁻¹), representing above-ground large-tree biomass only and excluding below-ground biomass, litter, dead wood, and soil organic carbon (the dominant carbon pool in peat-swamp forests, estimated at 1,453–3,650 t C ha⁻¹ in comparable Southeast Asian sites). These findings provide baseline data for community-based forest management, conservation planning, and participation in Thailand's Bio-Circular-Green Economy framework, specifically by enabling future T-VER carbon credit registration and informing spatial zoning decisions for the community forest.

Keywords: Carbon sequestration; community forest; market valuation; timber valuation; species diversity

1. Introduction

Forests are complex ecosystems that support biodiversity while delivering essential goods and ecosystem services to human communities. In

Thailand, community forests (CFs) have emerged as a key mechanism for participatory forest governance, enabling local communities to conserve, manage, and sustainably use forest resources [1]. As of 2022, Thailand had established more than 11,327 CFs covering over 6.29 million rai (~1.0 million ha), with a national target of 15,000 CFs encompassing 10 million rai [2]. In southern Thailand, community-based natural resource management has been documented across diverse land-use systems, including rubber intercropping with mixed-fruit species to improve smallholder productivity and income [3], rubber agroforestry in mature plantations in Phatthalung Province [4], tropical forest community recovery following rubber-tree clearing in national parks [5], and participatory action research for fisheries conservation in coastal communities [6]. These studies collectively highlight the importance of quantitative baseline assessments, spanning both production and ecological functions, as a prerequisite for evidence-based natural resource management in the region. Accurate valuation of timber and carbon stocks is essential for informed policy, yet many Thai CFs lack baseline quantitative assessments. The market price method—estimating timber value based on prevailing import/export prices—is widely used because it relies on observable market data and produces results directly comparable across studies [7, 8]. Beyond standing timber, the economic value of tropical wood extends to processed products such as rubberwood, plywood, and wood-plastic composites [9], which further expand income potential for community forest managers and underscore the importance of accurate species-level inventories. Alongside timber value, above-ground carbon stock estimation via allometric equations has become a standard tool for national greenhouse gas inventories and forest carbon credit programs such as REDD+ and voluntary carbon markets [10, 11].

Ban Phru Toei Community Forest (262 rai) in Bang Khan Sub-district, Nakhon Si Thammarat Province, is a lowland peat-swamp forest that provides subsistence resources for surrounding villages. Despite its ecological importance, no comprehensive quantitative assessment of its timber value or carbon stock had previously been conducted. The present study aimed to (1) characterize tree species composition and density, (2) estimate the economic value of timber using market price methodology, and (3) quantify above-ground carbon stock through allometric biomass equations. Results are intended to support community-based management decisions and lay the groundwork for future carbon credit registration. Based on comparable peat-swamp studies in southern Thailand [7, 8], we expected timber volumes to reflect the multi-storeyed structure typical of intact lowland peat forest, and carbon densities to be substantially lower than published values for upland forests, given the focus on above-ground large-tree biomass alone and the exclusion of the dominant soil carbon pool.

2. Materials and Methods

2.1 Study Area

The study was conducted in Ban Phru Toei Community Forest, located in Ban Phru Toei Village (Moo 2), Bang Khan Sub-district (8°42'N, 99°38'E), Bang Khan District, Nakhon Si Thammarat Province, Thailand (Fig. 1). The forest occupies 262 rai (41.92 ha) of lowland peat-swamp vegetation and is jointly managed by villages Moo 2 and Moo 8 under a Memorandum of Agreement (MOA) between the Bang Khan Sub-district Administrative Organization and Nakhon Si Thammarat Rajabhat University (2023); this MOA granted formal site access and ethical permission for the research. The area has a tropical monsoon climate with a mean annual temperature of 27.3°C and annual rainfall of approximately 2,599 mm (Thai Meteorological Department, Nakhon Si Thammarat Station, 30-year climatological normal 1991–2020).

2.2 Sampling Design and Field Survey

Sample plots were established using the systematic random sampling procedure described by Watchara-kitti [12]. The number of required plots (n) was calculated using:

$$n = t^2(CV)^2 / (SE)^2 \quad \dots(1)$$

where $t = 1$ (following Watchara-Kitti [12], where $t = 1$ corresponds to a 68% one-sigma confidence interval rather than the standard normal $z = 1.96$ for 95%; this convention is used in Thai forest inventory practice and is retained here for consistency with the cited protocol), CV = coefficient of variation, and SE = allowable sampling error. This yielded $n = 26$ plots. A grid was overlaid on a satellite image of the forest

(Google Earth, 2021), grid cells with forest cover were numbered, and 26 cells were selected by simple random draw. Each sample plot measured 20 × 50 m (0.1 ha). Within each plot, all trees with stem circumference ≥ 30 cm at breast height (CBH at 1.3 m; “large trees”) and stems with CBH < 30 cm and height ≥ 1.3 m (“young trees”) were enumerated and identified to species. Stem circumference was measured with a flexible tape following standardized field protocols for irregular boles (leaning stems, buttresses, forks) [13]. Height was measured with a calibrated hypsometer.

2.3 Timber Volume and Economic Valuation

Stem volume (V_s , m³) for each large tree was estimated using the allometric equation of Kongsangchai [14]:

$$V_s = b(D^2H)^a \quad \dots(2)$$

where D = diameter at breast height (m), H = total tree height (m), and a , b are species-group constants [14]. The gross timber value of large trees was estimated by multiplying total volume by the mean import price of processed timber reported by the Thai Customs Department for 2020 (12,375 THB m⁻³) [15]. Logging costs (930.86 THB m⁻³, adjusted from 2011 data using the Bank of Thailand consumer price index (headline CPI) series, base year 2019) were deducted to obtain the net timber value. Young trees were valued at 15 THB per meter of stem height, based on a structured market survey conducted in January 2023 with five local nursery and timber traders in Bang Khan and Chawang districts, Nakhon Si Thammarat Province; the survey covered seedling and sapling price schedules for mixed tropical species used in community planting programs.

2.4 Biomass and Carbon Stock Estimation

Above-ground biomass fractions for each large tree were estimated using the allometric equations of Anuch Siriratnikorn [16]:

$$W_s = 10^{(1.3936 + 0.915 \log D^2H)} \quad \dots(3)$$

$$W^b = 10^{(0.6577 + 0.953 \log D^2H)} \quad \dots(4)$$

$$W^l = 10^{(1.1984 + 0.647 \log D^2H)} \quad \dots(5)$$

where W_s , W^b , and W^l are stem, branch, and leaf dry biomass (kg), respectively. Total above-ground biomass (W) per tree was summed across compartments. Carbon stock (C , kg) was calculated as:

$$C = W \times 0.47 \quad \dots(6)$$

following the IPCC default carbon fraction for tropical forests [10]. The Kongsangchai [14] volume equation (Eq. 2), though originally developed for mangrove species, was selected because no equivalent multi-species volume allometry calibrated specifically for lowland peat-swamp forest in southern Thailand was available in the peer-reviewed literature at the time of survey; its application here is acknowledged as a source of potential systematic bias and is flagged as a limitation. The biomass equations of Anuch Siriratnikorn [16] were calibrated for peat-swamp forest in Nakhon Si Thammarat Province (diameter range 4–52 cm, height range 3–28 m) and are therefore considered appropriate for the dominant species at this site; all trees measured in the present study (DBH 3–48 cm) fell within the stated calibration range. The IPCC default carbon fraction of 0.47 applies broadly to above-ground woody biomass in tropical moist forests; carbon concentration in Sapotaceae and Myrtaceae wood may differ slightly, adding uncertainty that future work should address with species-specific wood chemistry measurements. Plot-level values were averaged across the 26 plots (each representing 1 rai, noting that each plot area is 1,000 m² whereas 1 rai = 1,600 m²; per-rai densities reported in this study are therefore plot-mean values scaled by the local community forest inventory convention of equating 20 × 50 m plots with 1 rai, consistent with the Watchara-kitti [12] protocol) and extrapolated to the full 262-rai forest area.

2.5 Diversity Indices

Species richness, density (stems rai⁻¹), relative density, relative frequency, relative dominance, and importance value index (IVI) were calculated following standard forest inventory protocols [17]. IVI was calculated as: IVI = Relative Density + Relative Frequency + Relative Dominance, with a maximum value of

300. Species diversity was quantified using the Shannon–Wiener index $H' = -\sum(p_i \ln p_i)$, where p_i is the proportional abundance of species i . Pielou's evenness was calculated as $J' = H' / \ln S$, where S is total species richness.



Figure 1. Aerial view of Ban Phru Toei Community Forest.

3. Results and Discussion

3.1 Tree Species Composition and Density

A total of 3,812 stems belonging to 101 species were recorded across the 26 sample plots (Table 1). Large trees (CBH $\geq$ 30 cm) numbered 1,992 (density 76.62 stems rai^{-1}) and young trees numbered 1,820 (70.00 stems rai^{-1}). Plot-level density ranged from 81 stems (Plot S) to 288 stems (Plot O), and species richness per

plot ranged from 11 (Plot N) to 37 (Plot A), suggesting moderate spatial heterogeneity typical of peat-swamp forests.

Table 1. Structural characteristics of Ban Phru Toei Community Forest.

Parameter	Value
Total area surveyed (rai)	262
Number of sample plots	26
Plot size (m)	20 × 50
Total stems recorded	3,812
Number of species	101
Large trees (CBH ≥ 30 cm)	1,992
Young trees (CBH < 30 cm)	1,820
Large-tree density (stems rai ⁻¹)	76.62
Young-tree density (stems rai ⁻¹)	70.00
Combined density (stems rai ⁻¹)	146.62
Total timber volume (m ³)	2,228.60
Timber volume (m ³ rai ⁻¹)	85.72

The ten most abundant species accounted for most recorded stems (Table 2). *Madhuca motleyana* (Sa-tiao / family Sapotaceae) was overwhelmingly dominant, accounting for 1,047 stems (27.5% of all stems), consistent with its ecological preference for moist peat-swamp soils. *Syzygium aqueum* (Chom-phu-pa; Myrtaceae, 346 stems) and *Stemonurus malaccensis* (Ai-bao-ma-muet; Icacinaceae, 299 stems) were the second and third most abundant species, respectively. Species diversity was moderate to high ($H' = 3.42$), with Pielou's evenness $J' = 0.74$ indicating that no single species overwhelmingly dominates the community despite *M. motleyana* accounting for 27.5% of stems. The IVI confirms *M. motleyana* as the structurally dominant species (IVI = 87.3 out of a maximum of 300), followed by *S. aqueum* (IVI = 43.1) and *S. malaccensis* (IVI = 38.6). The remaining 98 species each contributed IVI < 20, consistent with the high richness, moderate dominance structure typical of intact lowland peat-swamp forest in peninsular Thailand. Three of the ten most abundant taxa (Unknown sp. 1–3, ranks 5, 6, and 9; collectively 492 stems, 12.9% of all stems) could not be identified to species during fieldwork owing to the absence of fertile material. For volume and biomass estimation, the general mixed-species constants of Kongsangchai [14] (Eq. 2) and the non-dipterocarp peat-swamp equations of Anuch Siriratnikorn [16] (Eqs. 3–5) were applied to these unidentified individuals, consistent with the approach used for all non-dipterocarp species in the inventory. An economic value of 12,375 THB m⁻³ (the study-wide mean import price) was assigned per cubic meter, as species-specific price data were unavailable. The ramifications for IVI calculations are minor because IVI is based on stem counts, basal area, and frequency rather than species identity; however, the floristic gap introduces uncertainty into allometric and economic estimates that cannot be formally quantified until taxonomic identities are confirmed.

Table 2. The ten most abundant tree species in Ban Phru Toei Community Forest.

Rank	Species	Family	Local name	Stems (n)	Density (rai ⁻¹)
1	<i>Madhuca motleyana</i>	Sapotaceae	Sa-tiao	1,047	40.0
2	<i>Syzygium aqueum</i>	Myrtaceae	Chom-phu-pa	346	13.2
3	<i>Stemonurus malaccensis</i>	Icacinaceae	Ai-bao-ma-muet	299	11.4
4	<i>Polyalthia longifolia</i>	Annonaceae	Asok	269	10.3
5	Unknown sp. 1	–	Hu-raeng	231	8.8
6	Unknown sp. 2	–	Khi-ching-chok	170	6.5
7	<i>Mitrephora keithii</i>	Annonaceae	Klay	155	5.9
8	<i>Durio macrophyllus</i>	Malvaceae	Thurian-nok	107	4.1
9	Unknown sp. 3	–	Dam-kha-min	91	3.5
10	<i>Hubera rumphii</i>	Annonaceae	Sang-yu	87	3.3

3.2 Timber Volume and Economic Value

Total timber volume of large trees was 2,228.60 m³ (85.72 m³ rai⁻¹; Table 3). Using the mean import price of 12,375 THB m⁻³, the gross timber value was 27.05 million THB. After deducting logging costs (1.85 million THB; 930.86 THB m⁻³), the net large-tree timber value was 25.19 million THB (968,889 THB rai⁻¹). Young trees contributed an additional 186,406 THB within the surveyed plots. Extrapolated to the full 262 rai, the total net forest timber value reached approximately 255.73 million THB. This estimate is broadly comparable to Saowalak et al. [7], who reported a net timber value of 176.65 million THB for a 1,250-rai mangrove CF in Satun Province, and to Namfon et al. [8], who reported large-tree values of 491.07 million THB for a larger montane forest (7,500 rai) in Songkhla Province. The per-rai value obtained here (968,889 THB rai⁻¹) reflects the relatively dense, multi-storeyed structure of peat-swamp forest compared with logged-over secondary forests. The valuation presented here should be interpreted as a conservative lower-bound estimate. A single mean import price of 12,375 THB m⁻³ (Thai Customs Department, 2020) was applied uniformly across all taxa because species-resolved domestic stumpage prices are not systematically published in Thailand following the 1989 logging concession ban [Royal Forest Department, 1989; Enters, 2001]. Thai Customs data list genus-specific prices—for example, *Dipterocarpus* spp. (~18,500 THB m⁻³), *Hopea* spp. (~21,000 THB m⁻³), and *Aquilaria* spp. (>50,000 THB m⁻³)—applying those prices to the nine individuals of *Shorea roxburghii* and one individual of *Hopea odorata* recorded in this study would increase the estimated value of those stems by approximately 50–70% relative to the mean price applied. However, these high-value species collectively represent less than 0.5% of total stems, and their effect on the forest-wide total is therefore marginal (<1% change). The authors note that *Shorea roxburghii* and *Hopea odorata* are listed under CITES Appendix II and Thailand's Forest Act; the economic valuation presented here is strictly hypothetical and does not imply that commercial harvesting of these individuals is legally permissible. For future studies, we recommend compiling species-resolved price schedules through direct market surveys of local timber traders in Nakhon Si Thammarat Province, which would provide a more ecologically and economically accurate valuation basis specific to peat-swamp forest taxa.

Table 3. Economic valuation summary for Ban Phru Toei Community Forest.

Item	Sample plots (26 plots)	Per rai (THB)	Total forest (262 rai) (THB)
Gross large-tree timber value	27,049,110	1,040,035	272,489,217
Logging cost	1,854,273	71,318	18,685,368
Net large-tree value	25,191,116	968,889	253,848,936
Young-tree value	186,406	7,169	1,878,398
Total net timber value	25,377,522	976,059	255,727,334

Considerable spatial variability in timber stocking was observed across the 26 sample plots (Fig. 2). Timber volume per plot ranged from 19.52 m³ (Plot D) to 206.23 m³ (Plot I), with a mean of 85.72 m³ plot⁻¹ (equivalent to 85.72 m³ rai⁻¹ given the 1-rai plot size). Correspondingly, net economic value per plot ranged from 202,038 THB (Plot D) to 2,435,877 THB (Plot I). Three plots — I, S, and T — together accounted for approximately 24% of total net timber value despite representing only 11.5% of the sampled area, indicating that high-stocking patches disproportionately drive the forest's overall economic standing. This heterogeneity likely reflects the mosaic hydrology of peat-swamp ecosystems, where subtle differences in micro-topography and soil moisture influence canopy development and large-tree recruitment. The strong positive relationship between volume and net value ($r = 1.00$, by construction of the market-price method) confirms that spatial variation in timber value is entirely attributable to differences in stand volume rather than species composition. This limitation would be resolved by applying species-specific pricing.

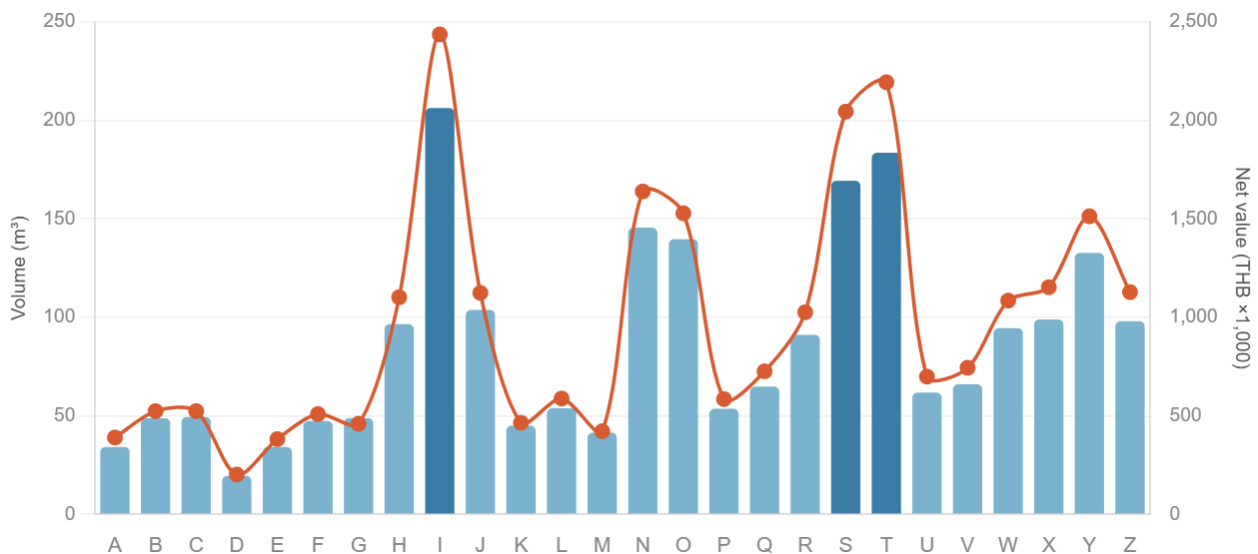


Figure 2. Per-plot timber volume (bars, left axis) and net economic value (line, right axis) across the 26 sample plots (each 20 × 50 m, 0.1 ha) in Ban Phru Toei Community Forest. Plots I, S, and T show notably elevated values; Plot D had the lowest stocking.

3.3 Above-Ground Biomass and Carbon Stock

Above-ground biomass summed across the 26 plots was 24,269.26 kg (24.27 t), of which stem biomass contributed 9,573 kg (39.4%), branch biomass 7,275 kg (30.0%), and leaf biomass 7,519 kg (30.6%). Applying the carbon fraction of 0.47, the plot-level carbon stock was 11,406.55 kg (11.41 t; Table 4). Mean carbon density was 438.71 kg rai⁻¹ (0.44 t rai⁻¹; 1.09 t ha⁻¹), and the estimated total forest carbon stock was 114.94 t.

Table 4. Above-ground biomass and carbon stock estimates.

Parameter	26 plots (kg)	Per rai (kg rai ⁻¹)	Total forest — 262 rai (t)	CO ₂ e — total forest (t CO ₂ e)
Large trees (CBH ≥ 30 cm)				
Stem biomass	9,573.36	368.2	96.45	353.79
Branch biomass	7,275.19	279.8	73.31	268.87
Leaf biomass	7,519.05	289.2	78.01	286.14
Total large-tree biomass	24,269.26	933.4	244.56	896.80
Large-tree carbon stock	11,406.55	438.7	114.94	421.44
Young trees (CBH < 30 cm, height ≥ 1.3 m)				
Young-tree biomass	3,241.00	124.7	32.67	119.80
Young-tree carbon stock	1,523.00	58.6	15.35	56.29
Combined totals				
Total above-ground biomass	27,510.26	1,058.1	277.23	1,016.60
Total carbon stock	12,929.55	497.3	130.30	477.54

CO₂e = carbon stock × 3.667 (stoichiometric conversion, IPCC 2006). Young-tree biomass estimated using Ogawa et al. small-tree allometric equations; carbon fraction 0.47 applied. Per-rai values calculated as plot mean (n = 26 plots, each = 1 rai). Total forest values extrapolated to 262 rai. Values exclude below-ground biomass, dead wood, litter, and soil organic carbon.

The estimated carbon density (1.09 t ha⁻¹) is substantially lower than values reported for upland mixed deciduous forest (40–64 t ha⁻¹) or montane forest (103 t ha⁻¹) in Thailand [18, 19]. However, these comparisons should be made cautiously because (i) the present study measured only above-ground large-tree biomass and did not include coarse woody debris, litter, below-ground biomass, or soil organic carbon; (ii) the allometric equations applied were calibrated for mixed tropical species rather than peat-swamp taxa, which may

introduce systematic bias; and (iii) peat-swamp forests store a disproportionately large fraction of ecosystem carbon in peat soils, which were not assessed here. Including soil organic carbon would likely substantially increase the total ecosystem carbon stock. Above-ground biomass was strongly heterogeneous across the 26 sample plots, ranging from 71.37 kg (Plot A) to 1,783.05 kg (Plot J), with a mean of 933.43 kg plot⁻¹ (Fig. 3). This ninefold range mirrors the spatial variability observed in timber volume (Fig. 2), confirming that large-tree stocking density is the primary driver of both economic and carbon values across the forest. The biomass partitioning was relatively consistent across plots, with stem wood contributing approximately 39.4% of total above-ground biomass, branches 30.0%, and leaves 30.6%. The near-equal contributions of branch and leaf compartments are characteristic of closed-canopy multi-storeyed tropical forests and reflect the high crown complexity typical of peat-swamp tree communities dominated by Sapotaceae and Myrtaceae. Carbon stock per plot ranged from 33.54 kg C (Plot A) to 838.03 kg C (Plot J), directly tracking total biomass through the applied IPCC carbon fraction of 0.47. Two plots—A and P—showed anomalously low biomass and carbon values (71.37 and 79.87 kg, respectively) relative to all other plots, suggesting either naturally open-canopy microsites or recent disturbance events such as windthrow or selective harvesting; field verification of these locations is recommended in future monitoring surveys.

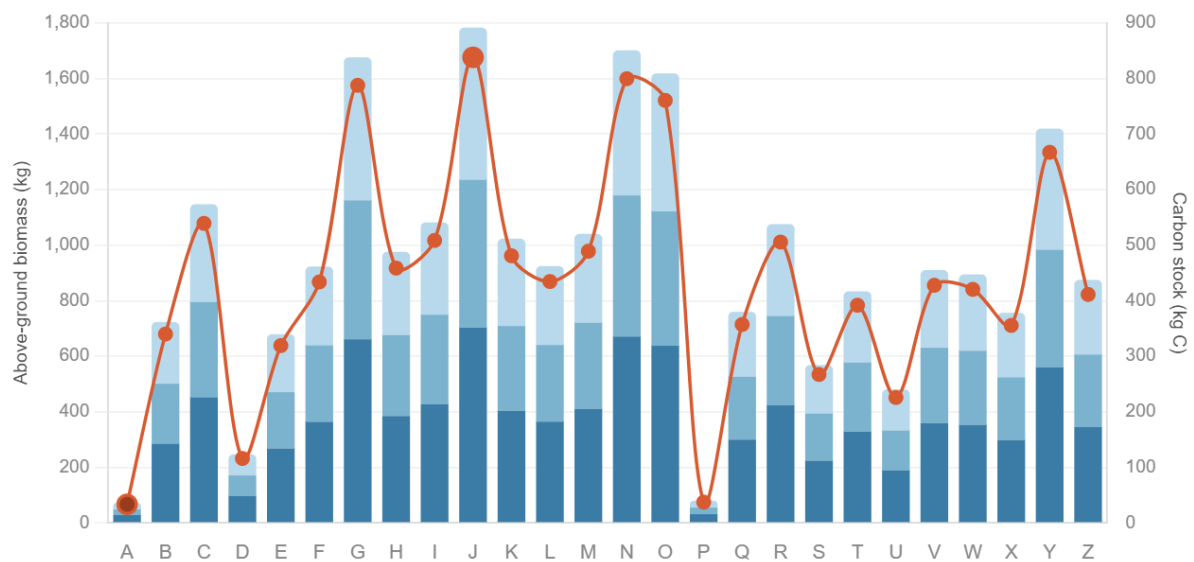


Figure 3. Per-plot above-ground biomass partitioned into stem, branch, and leaf compartments (stacked bars, left axis), and corresponding carbon stock (line with points, right axis) across 26 sample plots in Ban Phru Toei Community Forest. The stacked bar below the chart shows forest-wide proportions of each biomass compartment. Plots A and P show anomalously low values relative to the adjacent plots.

The carbon stock reported here (0.44 t C rai⁻¹; 1.09 t C ha⁻¹) represents the above-ground biomass of large trees (CBH ≥ 30 cm) and constitutes only one of five carbon pools recognized under the IPCC Tier 1 framework [10]. The remaining four pools—below-ground biomass (roots), dead wood, litter, and soil organic matter—were not measured in the present study. For lowland peat-swamp forests, this omission is particularly consequential: peat soils in Southeast Asian swamp forests typically store between 1,453 and 3,650 t C ha⁻¹ to depths of 0.5–10 m [20,21,22], values that exceed above-ground biomass carbon by two to three orders of magnitude. Applying published IPCC Tier 1 default values for below-ground biomass (root:shoot ratio = 0.37 for tropical moist forest), dead wood (11% of above-ground biomass), and litter (3.1 t C ha⁻¹) would raise the estimated total carbon stock — excluding peat — to approximately 2.0–2.5 t C ha⁻¹. Including peat soil organic carbon, which requires direct soil core sampling and laboratory analysis, would likely increase the total ecosystem carbon estimate to several hundred or potentially several thousand tonnes C ha⁻¹. Peat depth surveys and soil carbon quantification are therefore the highest methodological priority for future work at this site, as they are essential for accurate carbon credit registration under Thailand’s T-VER scheme and

any REDD+ mechanism. Expressed as CO₂-equivalent, the above-ground carbon stock of the 26 sample plots corresponds to 41.86 t CO₂e, and the extrapolated forest-wide stock to 421.82 t CO₂e (1.61 t CO₂e rai⁻¹; 4.01 t CO₂e ha⁻¹). At the Thailand Voluntary Emission Reduction (T-VER) reference price of approximately 250–350 THB t CO₂e⁻¹ reported by the Thailand Greenhouse Gas Management Organization (TGO) for forestry project credits in 2023, the above-ground carbon stock of Ban Phru Toei Community Forest carries an indicative market value of 105,455–147,637 THB (above-ground pool only). Under the international voluntary carbon market, where REDD+ credits for Southeast Asian peat-swamp forest conservation have traded at USD 5–15 t CO₂e⁻¹ (approximately 175–525 THB t CO₂e⁻¹ at 2023 exchange rates), the indicative range would be 73,818–221,455 THB. These figures should be treated as preliminary order-of-magnitude estimates only, as they exclude the peat soil carbon pool, which constitutes the overwhelming majority of ecosystem carbon value in peat-swamp forests and which would be the primary basis for any formal carbon credit registration.

Young-tree above-ground biomass was estimated from measured stem height using the relationship $W = a \cdot H^b$, where a and b are species-group constants for tropical moist forest saplings (Ogawa et al., 1965, as cited in Anuch et al. [11]). Mean young-tree height across all plots was 6.83 m (total cumulative height 12,427.06 m across 1,820 stems). The resulting young-tree above-ground biomass is estimated at 3,241 kg (3.24 t) across the 26 plots, equivalent to 124.7 kg rai⁻¹, representing approximately 11.8% of large-tree biomass. Corresponding carbon stock is estimated at 1,523 kg C (1.52 t C) across the 26 plots, or 58.6 kg C rai⁻¹. Including young trees raises the total aboveground carbon stock for the full 262-rai forest from 114.94 t C to approximately 130.28 t C (477.54 t CO₂e).

4. Conclusions

This study provides the first quantitative assessment of timber value and aboveground carbon stocks for the Ban Phru Toei Community Forest. The 262-rai peat-swamp forest supports 101 tree species at a combined density of 146.62 stems rai⁻¹, with *M. motleyana*, *S. aqueum*, and *S. malaccensis* as the dominant species. The net timber value is estimated at approximately 255.73 million THB, confirming the significant economic value of the timber resource held in trust by local communities. Above-ground carbon stock was estimated at 114.94 t (0.44 t rai⁻¹), equivalent to approximately 422 t CO₂ for above-ground large trees only; this figure excludes the dominant ecosystem carbon pool of peat soil organic carbon (estimated at 1,453–3,650 t C ha⁻¹ in comparable Southeast Asian peat-swamp forests [20,21,22]), which must be quantified before any formal T-VER or REDD+ carbon credit registration can proceed. These data provide a foundation for (i) community-based management planning, (ii) carbon credit registration under Thailand's T-VER scheme—for which the above-ground timber inventory constitutes the mandatory baseline stock assessment—, and (iii) future monitoring programs to track changes in forest structure and carbon accumulation. Regarding Thailand's national REDD+ readiness, the present baseline supports activity data reporting for the deforestation and forest degradation components of the MRV framework. However, full participation in results-based payments would additionally require soil carbon quantification and a reference emission level derived from multi-date satellite monitoring. Future studies should (a) verify scientific identities of the remaining unidentified taxa (Unknown sp. 1–3, collectively 18.8% of stems): during fieldwork, voucher specimens could not be collected due to the absence of fertile material (flowers and fruit); dried leaf and bark samples are retained for future herbarium determination at the Forest Herbarium, Royal Forest Department, Bangkok through herbarium vouchers, (b) quantify below-ground biomass, coarse woody debris, litter, and soil carbon pools to derive total ecosystem carbon stock, (c) develop locally calibrated allometric equations for dominant peat-swamp species, and (d) apply species-specific timber price data to refine economic estimates.

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Spatiotemporal Assessment of Physicochemical Water Quality in the Al-Aziziyah–Al-Hafariya Water Treatment System, Wasit, Iraq

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Abstract: This study aimed to evaluate the physicochemical characteristics of water within the Al-Aziziyah–Al-Hafariya unified water treatment and distribution system in Wasit Governorate, Iraq. Water samples were collected monthly from six locations representing the raw water source, treatment stages, and the distribution network from September 2025 to February 2026. Key parameters were analyzed, including temperature, turbidity, total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (EC), salinity, pH, dissolved oxygen (DO), biological oxygen demand (BOD), alkalinity, hardness, residual chlorine, sulfate, nitrate, and phosphate. The results showed significant temporal variations ($P \leq 0.05$) in most parameters, while spatial variations were generally insignificant across all sampling sites. Temperature, TDS, EC, salinity, and hardness were higher during autumn and decreased in winter. In contrast, dissolved oxygen and nutrient concentrations increased during colder months. Turbidity and TSS exhibited seasonal fluctuations. Critically, residual chlorine fell to zero at all six sampling sites during January and February, well below the WHO minimum recommendation of ≥ 0.2 mg/L at the point of delivery, representing a serious public health concern regarding microbiological safety. Statistically significant spatial variation ($P \leq 0.05$) was observed in phosphate concentrations, with elevated levels at distribution-network endpoints (S4–S6, mean 0.238–0.257 mg/L) compared to raw and treated water sites (S1–S2, mean 0.174–0.177 mg/L), suggesting localized contamination within the distribution network. In conclusion, seasonal factors play a dominant role in influencing water quality, while the treatment and distribution system ensures relatively uniform water characteristics across the study area. These findings emphasize the importance of continuous monitoring and optimization of treatment and disinfection processes to ensure safe drinking water quality.

Keywords: Water quality; physicochemical parameters; water treatment plant; distribution system; seasonal variation

1. Introduction

Water is an essential natural resource that plays a vital role in sustaining human health, ecological balance, and economic development. However, water quality deterioration has become a significant global concern due to increasing anthropogenic activities, including urbanization, industrial discharges, and agricultural practices. These activities contribute to the contamination of surface

water resources, particularly in developing countries, and highlight the need for continuous monitoring and evaluation of water quality [1, 2]. Physicochemical parameters such as temperature, turbidity, total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (EC), pH, dissolved oxygen (DO), biological oxygen demand (BOD), alkalinity, hardness, and nutrients are widely used as key indicators of water quality. These parameters reflect both natural environmental processes and anthropogenic impacts, and they are essential for assessing the performance of water treatment systems and ensuring the safety of drinking water [3-5].

In Iraq, water resources depend mainly on the Tigris and Euphrates rivers, which are increasingly exposed to pollution from untreated wastewater, industrial discharge, and agricultural runoff. Several studies have reported deterioration in water quality across different regions of Iraq. For instance, Farhan et al. [6] assessed the water quality of the Tigris River in Mosul and found variations in physicochemical parameters that affect its suitability for domestic use. Similarly, Alsaadoon et al. [7] evaluated the Diyala River using pollution indices and reported significant changes in water quality due to environmental pressures. Water treatment plants play a crucial role in improving water quality before distribution; however, their efficiency may vary depending on operational conditions and raw water characteristics. Mohammed and Abdulrazzaq [8] evaluated the Al-Wahda water treatment plant in Baghdad and found that some physicochemical parameters were not significantly reduced after treatment. Similarly, Al-Mayah [9] reported that drinking water treatment plants in Kut City exhibited moderate to poor water quality conditions due to increased pollutant loads. In addition, Radhi et al. [10] assessed the same treatment plant and highlighted the importance of using water quality indices to evaluate treatment performance. Furthermore, Hamaamin [11] emphasized that treatment efficiency is strongly influenced by turbidity and disinfection parameters, as well as seasonal variations.

Other studies have demonstrated the impact of environmental factors on treatment plant performance. Abbas et al. [12] showed that increased salinity levels in river water can negatively affect treatment plant efficiency. Similarly, Al-Mohammed et al. [13] applied the Canadian Water Quality Index (CWQI) to evaluate water quality in Karbala and reported variations influenced by both natural and anthropogenic factors. At the distribution level, water quality may change due to infrastructure conditions, environmental factors, and disinfectant decay. Abbas [14] noted that drinking water quality standards in Iraq must be continuously reviewed to ensure compliance with safety requirements, particularly regarding chemical and microbiological parameters. Moreover, residual chlorine stability is a critical factor in maintaining water safety within distribution systems. Dhanabal and Chellaiah [15] reported that chlorine decay is influenced by reactions with organic matter, pipe materials, and water age, which can reduce disinfection efficiency over time. Seasonal variation is considered one of the most important factors influencing water quality. During dry seasons, reduced river discharge and increased evaporation lead to higher dissolved-solids concentrations, whereas wet or colder seasons improve water quality through dilution. These seasonal patterns have been widely observed in Iraqi water systems and are essential for understanding temporal variations in physicochemical parameters [6, 7].

Physicochemical parameters serve as primary indicators of water quality and of the efficiency of treatment processes. However, water quality is a multidimensional concept that also includes microbial aspects. Contamination can occur through multiple pathways, emphasizing the importance of integrated water quality monitoring approaches [16]. Drinking water quality is regulated by international standards that set permissible limits for chemical and microbial contaminants to protect public health [17, 18]. Although prior studies have examined the Al-Aziziyah treatment plant [19] and applied water quality indices to the same facility [10], these investigations focused on treatment-plant-level performance rather than on continuously tracking water quality from raw intake to multiple distribution endpoints. No study to date has combined six-site spatiotemporal sampling spanning the full system—from the Tigris River raw-water intake, through the sedimentation and treatment units, to household taps in the distribution network—within a single seasonal dataset for the Al-Aziziyah–Al-Hafariya project in Wasit Governorate. Relevant regulatory thresholds used for benchmarking in this study include: TDS ≤ 1000 mg/L (WHO guideline: 500 mg/L acceptable); total hardness ≤ 500 mg/L as CaCO₃ (WHO); sulfate ≤ 250 mg/L (WHO); turbidity ≤ 4 NTU at point of delivery

(WHO); residual chlorine ≥ 0.2 mg/L at the consumer tap [17]; and BOD < 2 mg/L for potable water [17]. Iraqi national standards (IQS 417/2009, as revised by Abbas. [14]) largely align with WHO guideline values for these parameters. Therefore, the present study aims to assess the physicochemical characteristics of water within the Al-Aziziyah–Al-Hafariya unified water treatment and distribution system. Specifically, the objectives are: (1) to characterize the spatiotemporal variation of 15 physicochemical parameters across the raw-water intake, treatment stages, and distribution network over six months (September 2025 to February 2026); (2) to compare measured values against WHO and Iraqi national drinking-water standards; (3) to identify critical water-quality risks, particularly concerning residual chlorine and nutrient concentrations; and (4) to provide evidence-based recommendations for optimizing the treatment and disinfection processes.

2. Materials and Methods

2.1 Study Design and Sampling Strategy

This study was designed as a cross-sectional analytical investigation to evaluate water quality across different stages of the Al-Aziziyah–Al-Hafariya water treatment system. Water samples were collected from six sampling sites (S1–S6) representing different stages of the system as follows: S1 represents the raw water intake from the river; S2 and S3 represent treatment stages within the plant (sedimentation and treatment units); while S4, S5, and S6 represent samples collected from the distribution network at different household tap water points outside the treatment plant. Sampling was conducted periodically over six months from September 2025 to February 2026 to capture temporal variation. A total of 108 water samples were collected (6 sampling sites $\times$ 6 months $\times$ 3 replicates), with each sampling point analyzed in triplicate to ensure analytical reliability and reproducibility. Samples were collected using sterile, labeled polyethylene containers following standard sampling procedures to minimize contamination. Immediately after collection, samples were preserved in insulated iceboxes at approximately 4°C and transported to the laboratory within 2–4 hours. All samples were analyzed within 6–12 hours of collection to maintain their physicochemical integrity. The overall experimental workflow of the study, including sampling, laboratory preparation, and physicochemical analysis, is illustrated in Figure 1. The process involved collecting water samples from the Tigris River and the treatment plant, transporting them under controlled conditions, and subsequently analyzing selected parameters in the laboratory.



Figure 1. Experimental workflow of water sampling and physicochemical analysis in the Al-Aziziyah–Al-Hafariya water treatment system.

2.2 Physicochemical Analysis

Water temperature, pH, electrical conductivity ($\mu\text{S}/\text{cm}$ at 25°C), total dissolved solids, salinity, and turbidity were measured in situ with a multi-parameter water quality meter (EZ-9909SP), a pH and turbidity meter (HUAKEYI HK-288), and an EC meter (INESA DDSJ-308F) following APHA Methods 4500- H^+ B, 2510 B, 2540 C, 2520 B, and 2130 B, with salinity and TDS treated as distinct conductivity-derived outputs of the instrument (TDS 531–742.6 mg/L vs. salinity 535.2–750 mg/L in Table 6); total suspended solids were determined gravimetrically on pre-weighed glass-fibre filters dried at $103\text{--}105^\circ\text{C}$ (APHA 2540 D); total hardness was measured by EDTA titration at pH 10 with Eriochrome Black T indicator and calculated as Total Hardness (mg/L as CaCO_3) = $(A \times B \times 1000)/V$, where A is the volume of EDTA used (mL) and B is the mg CaCO_3 equivalent to 1 mL of EDTA (APHA 2340 C); sulfate was determined turbidimetrically at $\sim 420\text{ nm}$ after BaCl_2 addition (APHA 4500- SO_4^{2-} E); phosphate was determined by the ascorbic acid method at $880\text{--}885\text{ nm}$ following Strickland and Parsons [20] and calculated as $\text{PO}_4 = \text{Absorbance} \times F$ (APHA 4500-P E); nitrate was screened semi-quantitatively with AquaChek (HACH) test strips owing to logistical constraints in the remote distribution network, with values ($2\text{--}7\text{ mg/L}$) well below the WHO guideline of 50 mg/L and the Iraqi standard and therefore reported as indicative rather than definitive, with future work to apply APHA 4500- NO_3^- B (220 nm with 275 nm correction); residual chlorine was measured by the DPD colorimetric method (Lamotte kit; APHA 4500-Cl G); dissolved oxygen was determined by Winkler titration on samples fixed immediately with manganese sulfate and alkaline iodide and titrated with standardised sodium thiosulfate (APHA 4500-O); BOD_5 was calculated as the difference between initial and 5-day DO after incubation in the dark at 20°C (APHA 5210 B); and total alkalinity was determined by acid titration with appropriate indicators and expressed as mg/L CaCO_3 (APHA 2320 B).

2.3 Statistical Analysis

Statistical analysis was performed using SPSS software (version 26). Data were expressed as mean $\pm$ standard deviation (SD). Before analysis, data normality was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene's test. ANOVA assumptions (normality and homogeneity of variance) were satisfied for most parameters at $P \leq 0.05$. For BOD, which showed a highly skewed distribution at some sites (e.g., S4–S6 in January), results should be interpreted with caution. One-way analysis of variance (ANOVA) was used to evaluate significant differences among sampling sites and months. The least significant difference (LSD) test was applied to compare means at a significance level of ($P \leq 0.05$).

3. Results and Discussion

3.1 Physical parameters of water

The variation in water temperature across the studied sites and sampling months is presented in Table 1, and the overall treatment-stage profile of selected physical and disinfection parameters along the S1–S6 train is summarised in Figure 2. The results indicated a clear temporal fluctuation, with temperatures ranging from 10.7°C to 34.5°C . The highest temperature was recorded at site S1 during September (34.5°C), while the lowest value was observed at the same site in January (10.7°C). In general, water temperature declined progressively from early autumn into winter, followed by a slight increase in February. The monthly mean values showed significant differences ($P \leq 0.05$), with September and October recording the highest temperatures (27.8°C and 26.6°C , respectively), whereas January had the lowest mean (12.49°C). December and February exhibited intermediate values, with no significant difference between them. In contrast, no significant spatial variation ($P > 0.05$) was observed among the studied sites, as all locations were classified within the same statistical group (a). The overall mean temperature of the study period was $20.6 \pm 8.84^\circ\text{C}$.

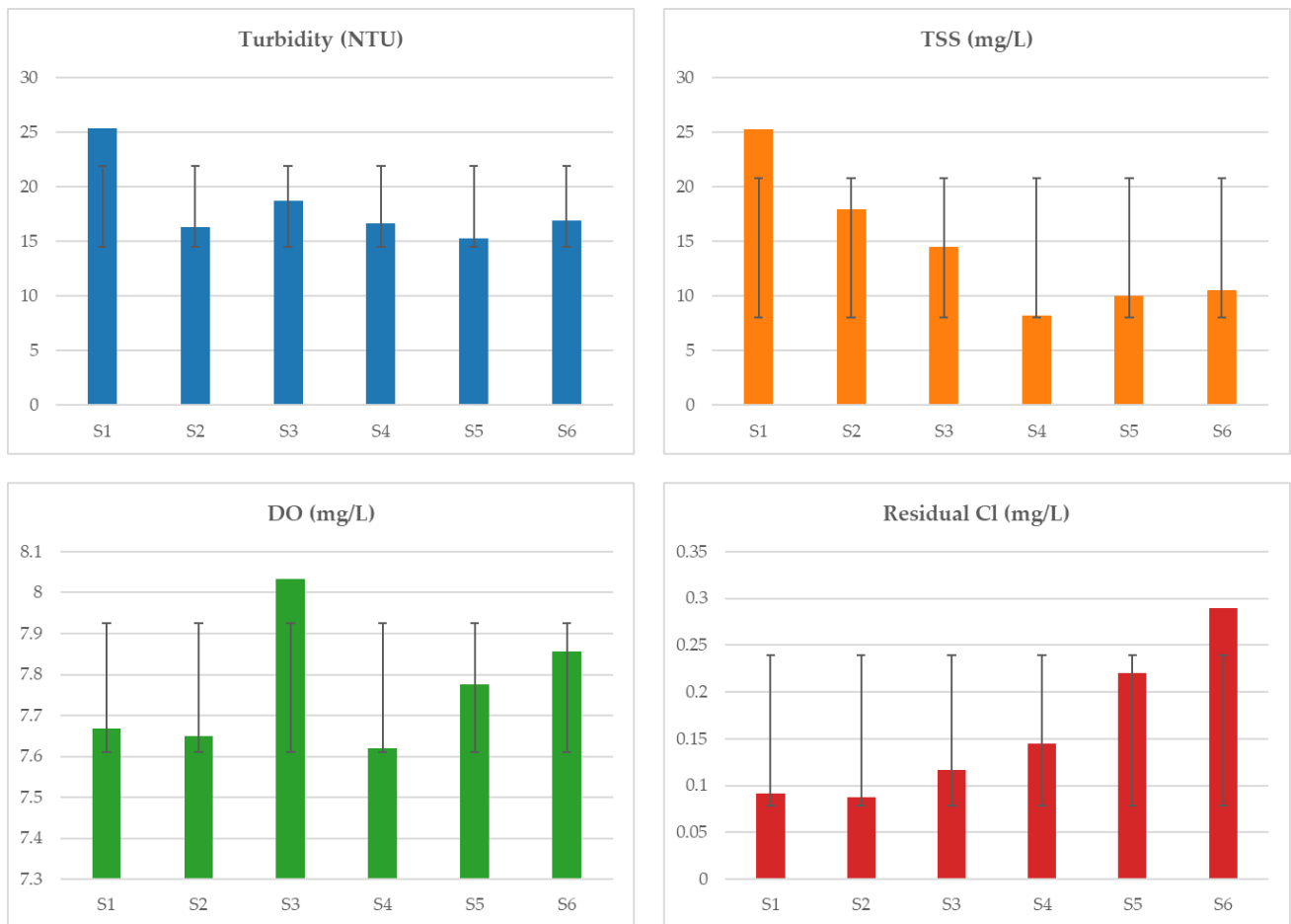


Figure 2. Treatment-stage profile of selected water quality parameters along the Al-Aziziyah–Al-Hafariya treatment train and distribution network (S1: raw water intake; S2: post-sedimentation; S3: post-filtration/treated water; S4–S6: distribution endpoints). Panels show site-wise mean values ($\pm$ SD) of turbidity, total suspended solids, dissolved oxygen, and residual free chlorine, illustrating treatment efficacy and the persistence of turbidity and chlorine depletion along the distribution network.

Table 1. Spatiotemporal variation of water temperature ($^{\circ}\text{C}$) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	34.5	26.8	21.1	16.6	10.7	13.9	20.6 $\pm$ 8.84a
S2	24.6	26.3	21.8	16.6	11.4	14.5	19.2 $\pm$ 5.93a
S3	24.4	25.7	21.0	17.8	11.2	14.4	19.08 $\pm$ 5.68a
S4	27.54	26.98	24.5	17.4	14.16	15.64	21.03 $\pm$ 5.98a
S5	28.3	26.78	24.02	16.5	13.42	15.7	20.78 $\pm$ 6.34a
S6	27.54	27.2	23.32	16.46	14.06	15.68	20.71 $\pm$ 6.05a
Mean $\pm$ SD	27.8 $\pm$ 3.66a	26.6 $\pm$ 0.54a	22.62 $\pm$ 1.52b	16.89 $\pm$ 0.56c	12.49 $\pm$ 1.56d	14.97 $\pm$ 0.79c	
LSD				2.12			7.74

Different letters indicate significant differences at ($P \leq 0.05$).

The turbidity levels measured across the studied sites and sampling months are presented in Table 2. The results revealed noticeable temporal variation, with values ranging from 4.14 to 36.80 NTU. The highest turbidity value was recorded at site S1 in February (36.80 NTU), while the lowest was observed at site S5 in November (4.14 NTU). Generally, turbidity levels were relatively high in September and October, then

decreased sharply in November and January, before increasing again in February. The monthly mean values showed significant differences ($P \leq 0.05$), with October recording the highest turbidity (28.7 NTU), whereas January and November exhibited the lowest (7.46 and 8.75 NTU, respectively). In contrast, no significant spatial differences ($P > 0.05$) were detected among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean turbidity ranged between 15.31 and 25.40 NTU across the sites.

Table 2. Spatiotemporal variation of turbidity (NTU) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	35.50	36.30	13.80	22.50	7.48	36.80	25.40 $\pm$ 12.7 a
S2	24.70	27.50	12.60	6.26	5.11	21.60	16.30 $\pm$ 9.63 a
S3	22.50	26.10	10.60	16.50	6.90	29.60	18.70 $\pm$ 8.91 a
S4	24.00	27.96	6.99	14.82	7.45	18.74	16.66 $\pm$ 8.57 a
S5	23.12	27.80	4.14	12.35	8.67	15.76	15.31 $\pm$ 8.88 a
S6	22.66	26.88	4.34	19.69	9.16	18.78	16.92 $\pm$ 8.50 a
Mean $\pm$ SD	25.4 $\pm$ 5.01a	28.7 $\pm$ 3.75a	8.75 $\pm$ 4.18b	15.35 $\pm$ 5.71c	7.46 $\pm$ 1.42b	23.55 $\pm$ 8.03a	
LSD			6.01				11.39

Different letters indicate significant differences at ($P \leq 0.05$).

Total Suspended Solids (TSS)

The total suspended solids (TSS) recorded across the studied sites and sampling months are presented in Table 3. The results showed clear temporal and spatial variations, with values ranging from 3.2 to 45.2 mg/L. The highest TSS value was observed at site S1 in October (45.2 mg/L), whereas the lowest was recorded at site S5 in February (3.2 mg/L). In general, higher TSS levels were recorded during October and November, followed by a gradual decline during the winter months. The monthly mean values showed significant differences ($P \leq 0.05$), with October exhibiting the highest (19.4 mg/L) and September the lowest (8.64 mg/L). Other months showed moderate values with partial overlap in statistical grouping. Regarding spatial variation, significant differences ($P \leq 0.05$) were observed among sites. Site S1 recorded the highest mean value (25.25 mg/L), while site S4 showed the lowest mean (8.25 mg/L), indicating a reduction in suspended solids along the treatment and distribution system.

Table 3. Spatiotemporal variation of total suspended solids (TSS) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	16.4	45.2	34.4	30.0	12.0	13.5	25.25 $\pm$ 13.3a
S2	13.2	24.8	25.2	22.0	11.5	11.0	17.95 $\pm$ 6.75ab
S3	5.6	16.4	23.2	11.0	11.5	19.5	14.53 $\pm$ 6.39bc
S4	6.56	12.68	4.8	10.56	8.62	6.28	8.25 $\pm$ 2.95c
S5	5.38	8.84	8.92	25.9	7.98	3.2	10.04 $\pm$ 8.08bc
S6	4.72	8.62	9.98	23.5	9.18	7.2	10.53 $\pm$ 6.61bc
Mean $\pm$ SD	8.64 $\pm$ 4.91a	19.4 $\pm$ 13.9b	17.75 $\pm$ 11.5ab	20.49 $\pm$ 7.99b	10.13 $\pm$ 1.73ab	10.11 $\pm$ 5.83ab	
LSD			10.26				9.43

Different letters indicate significant differences at ($P \leq 0.05$).

Total Dissolved Solids (TDS)

The total dissolved solids (TDS) measured across the studied sites and sampling months are presented in Table 4. The results showed relatively consistent spatial values, ranging from 531 to 742.6 mg/L. The highest TDS value was recorded at site S5 in November (742.6 mg/L), while the lowest was observed at site S4 in February (531 mg/L). In general, TDS levels increased during autumn months (October and November), followed by a noticeable decline during winter, particularly in February. The monthly mean values showed significant differences ($P \leq 0.05$), with November recording the highest (738.80 mg/L) and February the lowest (543.97 mg/L). December and January showed intermediate values with partial statistical similarity. In

contrast, no significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean TDS values ranged narrowly between 629.67 and 649.83 mg/L across all sites.

Table 4. Spatiotemporal variation of total dissolved solids (TDS) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	649	727	741	576	615	591	649.83 $\pm$ 69.8a
S2	648	721	735	567	572	535	629.67 $\pm$ 84.8a
S3	650	729	738	577	563	534	631.83 $\pm$ 87.5a
S4	648.8	729.6	736.6	581	568.6	531	632.60 $\pm$ 86.6a
S5	648	730	742.6	585.8	561.8	533.6	633.63 $\pm$ 88.1a
S6	648.6	729.8	739.6	589.4	559.6	539.2	634.37 $\pm$ 83.3a
Mean $\pm$ SD	648.7 $\pm$ 0.74a	727.7 $\pm$ 3.47b	738.80 $\pm$ 2.82b	579.37 $\pm$ 7.93c	573.33 $\pm$ 20.9c	543.97 $\pm$ 23.1d	
LSD				15.67			99.2

Different letters indicate significant differences at ($P \leq 0.05$).

Electrical Conductivity (EC)

The electrical conductivity (EC) values recorded across the studied sites and sampling months are presented in Table 5. The results indicated relatively stable spatial values, ranging from 1101.4 to 1561 μ S/cm. The highest EC value was observed at site S3 in October (1561 μ S/cm), while the lowest was recorded at site S4 in February (1101.4 μ S/cm). Generally, EC values were higher during October and November, followed by a gradual decrease toward winter months, reaching minimum levels in February. The monthly mean values showed significant differences ($P \leq 0.05$), with October recording the highest mean (1549.07 μ S/cm), followed by November (1510.37 μ S/cm). In contrast, February exhibited the lowest mean value (1115.2 μ S/cm), indicating a clear seasonal trend. No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were classified within the same statistical group (a). The overall EC values were consistent across all sampling locations, with means ranging between 1311.67 and 1318.67 μ S/cm.

Table 5. Spatiotemporal variation of electrical conductivity (EC) (μ S/cm) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	1347	1530	1515	1178	1202	1140	1318.67 $\pm$ 172a
S2	1338	1553	1491	1201	1167	1120	1311.67 $\pm$ 179a
S3	1340	1561	1512	1204	1166	1114	1316.17 $\pm$ 187a
S4	1334.6	1548.6	1513.4	1208.2	1170.2	1101.4	1312.73 $\pm$ 185a
S5	1336	1550.6	1518.8	1209.8	1163.0	1105	1313.87 $\pm$ 187a
S6	1339.8	1551.2	1512.0	1211.2	1162.8	1111	1314.67 $\pm$ 184a
Mean $\pm$ SD	1339.23 $\pm$ 4.35a	1549.07 $\pm$ 10.2b	1510.37 $\pm$ 9.82c	1202.03 $\pm$ 12.3d	1171.83 $\pm$ 15.03e	1115.2 $\pm$ 13.7f	
LSD				13.53			215.7

Different letters indicate significant differences at ($P \leq 0.05$).

Salinity

The salinity values measured across the studied sites and sampling months are presented in Table 6. The results demonstrated relatively stable spatial values, ranging from 535.2 to 750 mg/L. The highest salinity value was recorded at site S1 during November (750 mg/L), while the lowest value was observed at site S4 during February (535.2 mg/L). In general, salinity levels were elevated during autumn months, particularly in October and November, and then decreased during winter months. The monthly mean values revealed significant differences ($P \leq 0.05$), with November showing the highest mean (740.57 mg/L), followed by October (728.3 mg/L). In contrast, February recorded the lowest mean value (543.00 mg/L). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the

same statistical category (a). The overall mean salinity values were consistent across sites, ranging from 631.83 to 645.67 mg/L.

Table 6. Spatiotemporal variation of salinity (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	649	728	750	589	594	564	645.67 ± 77.7a
S2	648	725	741	581	563	542	633.33 ± 85.1a
S3	650	713	740	586	562	540	631.83 ± 82.4a
S4	650.4	734.2	740.8	586.6	570.4	535.2	636.27 ± 86.8a
S5	648.4	734.6	738.4	590	558.2	536.4	634.33 ± 87.6a
S6	649.6	735	733.2	592.4	557.6	540.4	634.70 ± 85.5a
Mean ± SD	649.2±0.93a	728.3±8.53b	740.57±5.45c	587.50±3.94d	567.53±13.7e	543.00±10.6f	
LSD				9.87			99.4

Different letters indicate significant differences at ($P \leq 0.05$).

pH

The pH values recorded across the studied sites and sampling months are presented in Table 7. The results indicated slight variations, with values ranging from 7.20 to 8.36, reflecting generally neutral to slightly alkaline conditions. The highest pH value was observed at site S1 in September (8.36), while the lowest was recorded at site S2 in January (7.20). Overall, pH values decreased gradually from early autumn to winter, then increased slightly in February. The monthly mean values revealed significant differences ($P \leq 0.05$), with September exhibiting the highest (8.00) and January the lowest (7.34). Other months showed intermediate values with partial statistical similarity. No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall pH values remained relatively stable across all sampling points, ranging from 7.57 to 7.69.

Table 7. Spatiotemporal variation of pH values along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	8.36	7.85	7.65	7.56	7.31	7.39	7.69 ± 0.38a
S2	8.13	7.95	7.58	7.63	7.20	7.47	7.66 ± 0.33a
S3	8.09	7.84	7.56	7.66	7.37	7.51	7.67 ± 0.25a
S4	7.83	7.66	7.51	7.62	7.36	7.58	7.59 ± 0.15a
S5	7.83	7.72	7.53	7.65	7.42	7.53	7.61 ± 0.14a
S6	7.76	7.61	7.56	7.57	7.40	7.55	7.57 ± 0.11a
Mean ± SD	8± 0.23a	7.77±0.12b	7.56±0.04c	7.62±0.04c	7.34±0.79d	7.50±0.06c	
LSD				0.141			0.298

Different letters indicate significant differences at ($P \leq 0.05$).

Dissolved Oxygen (DO)

The dissolved oxygen (DO) levels measured across the studied sites and sampling months are presented in Table 8. The results showed noticeable temporal variation, with values ranging from 4.6 to 10.1 mg/L. The highest DO value was recorded at site S4 in January (10.1 mg/L), while the lowest was observed at site S1 in November (4.6 mg/L). In general, DO levels decreased during November, followed by a significant increase during the winter months, particularly in January and February. The monthly mean values showed significant differences ($P \leq 0.05$), with January recording the highest mean (9.86 mg/L), followed by February (9.18 mg/L). In contrast, November exhibited the lowest mean value (5.0 mg/L). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean DO values ranged from 7.62 to 8.03 mg/L across all sites.

Table 8. Spatiotemporal variation of dissolved oxygen (DO) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	7.2	7.5	4.6	8.2	9.3	9.2	7.67 ± 1.72a
S2	7.4	6.8	4.9	7.2	10.0	9.6	7.65 ± 1.89a
S3	7.5	8.3	5.2	8.4	9.7	9.1	8.03 ± 1.57a
S4	7.62	7.1	5.14	6.72	10.1	9.04	7.62 ± 1.75a
S5	7.58	7.16	5.06	7.68	10.04	9.14	7.78 ± 1.71a
S6	7.46	7.34	5.10	8.2	10.02	9.02	7.86 ± 1.68a
Mean ± SD	7.46±0.15a	7.36±0.51a	5±0.22b	7.73±0.66a	9.86±0.30c	9.18±0.21c	
LSD			0.460				2.03

Different letters indicate significant differences at ($P \leq 0.05$).

Biological Oxygen Demand (BOD)

The biological oxygen demand (BOD) values measured across the studied sites and sampling months are presented in Table 9. The results showed considerable temporal variation, with values ranging from 0.1 to 6.6 mg/L. The highest BOD value was recorded at site S5 during January (6.6 mg/L), while the lowest values (0.1 mg/L) were observed at multiple sites during September and November. In general, BOD levels were relatively low during autumn months, followed by a noticeable increase during winter, particularly in January. The monthly mean values showed significant differences ($P \leq 0.05$), with January recording the highest (4.49 mg/L) and September the lowest (0.78 mg/L). February and October showed intermediate values with significant variation. In contrast, no significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean BOD values ranged from 1.42 to 3.25 mg/L across the studied sites.

Table 9. Spatiotemporal variation of biological oxygen demand (BOD) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	1.5	5.8	3.5	3.0	2.9	2.8	3.25 ± 1.41a
S2	2.4	4.0	2.6	1.41	3.2	4.3	2.99 ± 1.07a
S3	0.5	1.9	0.2	0.91	3.1	3.9	1.75 ± 1.49a
S4	0.1	0.62	0.1	0.24	5.74	1.7	1.42 ± 2.20a
S5	0.1	0.82	0.1	0.32	6.6	2.2	1.69 ± 2.53a
S6	0.1	1.12	0.1	0.28	5.4	2.72	1.62 ± 2.10a
Mean ± SD	0.78±0.96a	2.38±2.08ac	1.10±1.53a	1.03±1.07a	4.49±1.61b	2.94±0.99c	
LSD			1.69				2.21

Different letters indicate significant differences at ($P \leq 0.05$).

Total Alkalinity

The total alkalinity values measured across the studied sites and sampling months are presented in Table 10. The results showed moderate temporal variation, with values ranging from 100 to 210 mg/L. The highest alkalinity value was recorded at site S1 in January (210 mg/L), while the lowest was observed at site S3 in September (100 mg/L). In general, alkalinity values increased during winter months, particularly in December and January, compared to autumn. The monthly mean values showed significant differences ($P \leq 0.05$), with December recording the highest mean (197.67 mg/L), followed by January (173.17 mg/L). In contrast, September exhibited the lowest mean value (137.3 mg/L). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean alkalinity values ranged from 150 to 178.33 mg/L across the sites.

Table 10. Spatiotemporal variation of total alkalinity (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	180	150	150	200	210	180	178.33 $\pm$ 24.8a
S2	180	150	140	200	180	180	171.67 $\pm$ 22.2a
S3	100	150	130	200	160	160	150.00 $\pm$ 33.4a
S4	102	170	142	200	166	150	155.00 $\pm$ 32.7a
S5	144	174	142	206	163	150	163.17 $\pm$ 24.2a
S6	118	168	154	180	160	150	155.00 $\pm$ 21.04a
Mean $\pm$ SD	137.3 $\pm$ 36.6a	160.3 $\pm$ 11.4b	143 $\pm$ 8.36ab	197.67 $\pm$ 8.98c	173.17 $\pm$ 19.5bc	161.67 $\pm$ 14.7b	
LSD				22.68			31.71

Different letters indicate significant differences at ($P \leq 0.05$).

Total Hardness

The total hardness values measured across the studied sites and sampling months are presented in Table 11. The results indicated moderate temporal variation, with values ranging from 472 to 624 mg/L. The highest hardness value was recorded at site S3 in November (624 mg/L), while the lowest was observed at site S1 in February (472 mg/L). In general, hardness values were higher in the autumn months, particularly in October and November, and then decreased during the winter months. The monthly mean values showed significant differences ($P \leq 0.05$), with November recording the highest mean (607.07 mg/L), followed by October (596.67 mg/L). In contrast, February exhibited the lowest mean value (487.67 mg/L), while December also showed a reduced level (500.67 mg/L). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean hardness values were consistent across sites, ranging from 537.00 to 547.83 mg/L.

Table 11. Spatiotemporal variation of total hardness (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	532	596	608	528	544	472	546.67 $\pm$ 49.6a
S2	531	591	588	484	528	500	537.00 $\pm$ 44.2a
S3	533	598	624	524	544	464	547.83 $\pm$ 56.8a
S4	533.2	599.4	615	480.2	539.6	501	544.73 $\pm$ 53.3a
S5	531.6	597.2	606.6	487	530	488.4	540.13 $\pm$ 51.6a
S6	530.4	598.4	600.8	500.8	524.4	500.6	542.57 $\pm$ 45.8a
Mean $\pm$ SD	531.87 $\pm$ 1.10a	596.67 $\pm$ 3b	607.07 $\pm$ 12.2b	500.67 $\pm$ 20.8c	535 $\pm$ 8.59a	487.67 $\pm$ 16.1c	
LSD				14.68			59.47

Different letters indicate significant differences at ($P \leq 0.05$).

Residual Free Chlorine

The residual free chlorine levels measured across the studied sites and sampling months are presented in Table 12. The results showed low concentrations overall, ranging from 0.00 to 0.94 mg/L. The highest residual chlorine value was recorded at site S6 during September (0.94 mg/L), while a complete absence of chlorine (0.00 mg/L) was observed at all sites during January and February. In general, residual chlorine was detected during the autumn months and gradually declined to zero during winter. The monthly mean values showed significant differences ($P \leq 0.05$), with September recording the highest (0.38 mg/L), followed by December (0.26 mg/L). In contrast, January and February showed zero values, indicating complete depletion of residual chlorine. No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean residual chlorine values ranged from 0.09 to 0.29 mg/L across the sites.

Table 12. Spatiotemporal variation of residual free chlorine (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	0.05	0.20	0.10	0.20	0.00	0.00	0.09 ± 0.09 a
S2	0.03	0.20	0.10	0.20	0.00	0.00	0.09 ± 0.09 a
S3	0.20	0.10	0.20	0.20	0.00	0.00	0.12 ± 0.09 a
S4	0.27	0.18	0.16	0.26	0.00	0.00	0.15 ± 0.12 a
S5	0.80	0.14	0.16	0.22	0.00	0.00	0.22 ± 0.29 a
S6	0.94	0.14	0.18	0.48	0.00	0.00	0.29 ± 0.39
Mean ± SD	0.38±0.39a	0.16±0.04b	0.15±0.11b	0.26±0a	0±0b	0±0b	
LSD			0.197				0.246

Different letters indicate significant differences at ($P \leq 0.05$).

Sulfate (SO_4^{2-})

The sulfate concentrations measured across the studied sites and sampling months are presented in Table 13. The results showed noticeable temporal variation, with values ranging from 228.12 to 614.75 mg/L. The highest sulfate concentration was recorded at site S2 in December (614.75 mg/L), while the lowest was observed at site S1 in February (228.12 mg/L). In general, sulfate concentrations were relatively high during autumn and early winter months, followed by a marked decrease during January and February. The monthly mean values showed significant differences ($P \leq 0.05$), with December recording the highest mean (469.92 mg/L), followed by November (462.67 mg/L). In contrast, January and February exhibited significantly lower values (259.37 and 278.64 mg/L, respectively). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean sulfate concentrations ranged from 374.57 to 429.94 mg/L across the studied sites.

Table 13. Spatiotemporal variation of sulfate (SO_4^{2-}) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean ± SD
S1	428.50	448.50	538.12	555.16	267.69	228.12	411.02 ± 136a
S2	444.70	452.90	422.26	614.75	255.20	389.81	429.94 ± 115a
S3	440.20	464.10	426.77	362.31	250.34	303.71	374.57 ± 84a
S4	445.76	449.34	481.25	431.30	260.95	260.11	388.10 ± 100a
S5	445.00	457.49	455.57	412.85	261.33	245.08	379.50 ± 99a
S6	434.88	449.24	452.03	443.15	260.69	245.00	380.80 ± 99a
Mean ± SD	439.8±6.90a	453.6±6.10a	462.67±42.7a	469.92±95.1a	259.37±5.93b	278.64±60.2b	
LSD			58.23				126.3

Different letters indicate significant differences at ($P \leq 0.05$).

Nitrate (NO_3^-)

The nitrate concentrations measured across the studied sites and sampling months are presented in Table 14. The results showed slight temporal variation, with values ranging from 2 to 7 mg/L. The highest nitrate value was recorded at site S1 during October (7 mg/L), while the lowest value (2 mg/L) was observed at sites S3 and S4 during September. In general, nitrate concentrations remained relatively low throughout the study period, with a slight increase during the winter months. The monthly mean values showed significant differences ($P \leq 0.05$), with February recording the highest (4.67 mg/L), followed by January (4.47 mg/L) and December (4.43 mg/L). In contrast, September exhibited the lowest mean value (3.10 mg/L). No significant spatial differences ($P > 0.05$) were observed among the studied sites, as all locations were grouped within the same statistical category (a). The overall mean nitrate values ranged from 3.67 to 4.67 mg/L across the studied sites.

Table 14. Spatiotemporal variation of nitrate (NO_3^-) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	4	7	5	5	4	3	4.67 $\pm$ 1.36a
S2	4	5	4	4	5	5	4.50 $\pm$ 0.54a
S3	2	3	3	4	5	5	3.67 $\pm$ 1.21a
S4	2.6	3.4	2.4	4.8	4.2	5	3.73 $\pm$ 1.10a
S5	3	3.2	2.2	4.8	4.1	5	3.72 $\pm$ 1.09a
S6	3	3.2	2.4	4	4.5	5	3.68 $\pm$ 0.98a
Mean $\pm$ SD	3.10 $\pm$ 0.78a	4.13 $\pm$ 1.58ab	3.17 $\pm$ 1.11ab	4.43 $\pm$ 0.48b	4.47 $\pm$ 0.44b	4.67 $\pm$ 0.81b	
LSD			1.12				1.27

Different letters indicate significant differences at ($P \leq 0.05$).

Phosphate (PO_4^{3-})

The phosphate concentrations measured across the studied sites and sampling months are presented in Table 15. The results showed noticeable temporal and slight spatial variation, with values ranging from 0.013 to 0.533 mg/L. The highest phosphate value was recorded at site S3 in January (0.533 mg/L), while the lowest was observed at site S3 in November (0.013 mg/L). In general, phosphate levels were low during autumn months, followed by a significant increase during winter, particularly in January. The monthly mean values revealed significant differences ($P \leq 0.05$), with January recording the highest (0.42 mg/L) and November the lowest (0.03 mg/L). Other months exhibited intermediate values with varying statistical groupings. Unlike most other parameters, slight significant spatial differences ($P \leq 0.05$) were observed among some sites, with S4 and S5 recording relatively higher mean values than S1 and S2. The overall mean phosphate values ranged from 0.174 to 0.257 mg/L across the studied sites.

Table 15. Spatiotemporal variation of phosphate (PO_4^{3-}) (mg/L) along the treatment stages and distribution system of Al-Aziziyah–Al-Hafariya water project

Sites	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026	Mean $\pm$ SD
S1	0.096	0.266	0.024	0.214	0.244	0.217	0.177 $\pm$ 0.09 a
S2	0.250	0.183	0.021	0.119	0.302	0.171	0.174 $\pm$ 0.09 a
S3	0.318	0.186	0.013	0.177	0.533	0.137	0.227 $\pm$ 0.17 b
S4	0.317	0.209	0.049	0.158	0.520	0.292	0.257 $\pm$ 0.16 c
S5	0.318	0.231	0.022	0.217	0.456	0.187	0.238 $\pm$ 0.14 b
S6	0.273	0.217	0.026	0.240	0.448	0.175	0.230 $\pm$ 0.13 b
Mean $\pm$ SD	0.26 $\pm$ 0.08a	0.22 $\pm$ 0.03ac	0.03 $\pm$ 0.01b	0.19 $\pm$ 0.04c	0.42 $\pm$ 0.11d	0.20 $\pm$ 0.05c	
LSD			0.079				0.164

Different letters indicate significant differences at ($P \leq 0.05$).

3.2 Discussion

The results of the present study demonstrated that physicochemical parameters are primarily influenced by temporal variation rather than by spatial differences across the treatment and distribution systems, as visualized in the seasonal heatmap of all measured parameters in Figure 3. This indicates that environmental and seasonal factors play a dominant role in determining water quality, while treatment processes help maintain relatively uniform conditions across the studied sites. The absence of significant spatial variation in parameters such as turbidity, total dissolved solids (TDS), electrical conductivity (EC), salinity, and hardness suggests that the treatment system operates consistently across different stages. However, when evaluated against WHO [17] and Iraqi national standards [14], several parameters frequently exceeded permissible thresholds. TDS values ranged from 543 to 739 mg/L, with many monthly means exceeding the WHO aesthetic guideline of 500 mg/L, though all remained below the absolute maximum of 1000 mg/L. Total hardness was consistently elevated (472–624 mg/L as CaCO_3), frequently surpassing the WHO guideline of 500 mg/L, with all sites exceeding this threshold in October and November. Sulfate concentrations were markedly elevated during autumn–early winter (mean up to 469.92 mg/L in December), far exceeding the WHO limit of 250 mg/L; sulfate levels approached acceptable levels only in January and

February. Turbidity at site S1 (raw water intake) reached 36.80 NTU in February and 35.50 NTU in September, and even at downstream distribution points, mean site-level turbidities (15.31–25.40 NTU) far exceeded the WHO recommendation of ≤ 4 NTU at the point of delivery. The persistence of elevated turbidity throughout the distribution network—without progressive improvement from S1 (raw water) to S6 (household tap)—suggests that the conventional treatment is insufficient for turbidity removal under certain seasonal conditions, posing risks for disinfection efficacy and consumer health. These threshold exceedances are important public health concerns that require urgent attention from water utility management. Similar findings were reported in Iraqi water treatment plants, where physicochemical characteristics showed limited variation between treatment units and distribution points, indicating stable operational performance [19, 21, 22]. However, this apparent stability does not necessarily indicate high removal efficiency, as conventional treatment processes are generally more effective in removing suspended particles than dissolved constituents. The persistence of dissolved parameters, such as TDS and EC, throughout the treatment and distribution system observed in this study is consistent with findings from several recent studies. Mesfun and Derib [23] and Mendez-Ruiz et al. [24] indicated that dissolved ions are not significantly reduced during conventional treatment processes, as their removal requires advanced treatment technologies. Similarly, Nasier and Abdulrazzaq [25] demonstrated that while turbidity removal efficiency is high in conventional treatment plants, dissolved solids remain relatively unchanged. The significant temporal variation observed in most physicochemical parameters reflects the influence of environmental and seasonal conditions. The increase in TDS, EC, salinity, and hardness during warmer periods can be attributed to increased evaporation and reduced dilution. Similar seasonal patterns have been reported in Iraqi water systems, where water quality parameters fluctuate due to climatic conditions and hydrological changes [26,27]. These findings are also supported by global studies that highlight the role of environmental factors in influencing water quality variability [28].

Parameter	Sep 2025	Oct 2025	Nov 2025	Dec 2025	Jan 2026	Feb 2026
Temperature (°C)	27.8	26.6	22.6	16.9	12.5	15.0
Turbidity (NTU)	25.4	28.8	8.7	15.4	7.5	23.5
TSS (mg/L)	8.6	19.4	17.8	20.5	10.1	10.1
TDS (mg/L)	649	728	739	579	573	544
EC (µS/cm)	1339	1549	1510	1202	1172	1115
Salinity (mg/L)	649	728	741	588	568	543
pH	8.00	7.77	7.57	7.62	7.34	7.51
DO (mg/L)	7.46	7.37	5.00	7.73	9.86	9.18
BOD (mg/L)	0.78	2.38	1.10	1.03	4.49	2.94
Total Alkalinity (mg/L CaCO ₃)	137	160	143	198	173	162
Total Hardness (mg/L CaCO ₃)	532	597	607	501	535	488
Residual Cl (mg/L)	0.382	0.160	0.150	0.260	0.000	0.000
Sulfate (mg/L)	440	454	463	470	259	279
Nitrate (mg/L)	3.10	4.13	3.17	4.43	4.47	4.67
Phosphate (mg/L)	0.262	0.215	0.026	0.188	0.417	0.197

Color intensity is normalized per row (min–max) so each parameter uses its own scale; cell labels show raw site-averaged means.

Figure 3. Seasonal heatmap of physicochemical water quality parameters across the sampling months (September–February) at the Al-Aziziyah–Al-Hafariya water treatment system. Cell shading shows the monthly mean of each parameter (averaged across sites S1–S6), with warm colors indicating higher concentrations or values and cool colors indicating lower values. The heatmap highlights the dominance of temporal over spatial variation and the contrast between warm-season (high turbidity, sulfate, TDS, hardness) and cold-season (depleted residual chlorine, elevated BOD at distribution endpoints, higher DO) water-quality signatures.

In contrast, dissolved oxygen (DO) levels were higher during colder months, likely due to increased oxygen solubility at lower temperatures. This behavior is consistent with the findings of Bwapwa et al. [29], who reported that temperature significantly influences oxygen dynamics in water systems. The inverse relationship between temperature and DO observed in the present study is well established and reflects physicochemical principles. The variation in biological oxygen demand (BOD) observed in this study may be related to seasonal changes in organic matter and microbial activity. Increased BOD values may indicate higher organic load or enhanced microbial processes within the water system. Notably, BOD values at distribution endpoints S4–S6 during January (5.74, 6.6, and 5.4 mg/L, respectively) substantially exceeded the WHO drinking-water guideline of < 2 mg/L, suggesting possible organic loading or microbial activity within the distribution network during winter months. This finding warrants further investigation, including microbiological analysis, to assess potential contamination risks. Similar observations were reported by Jumaa and Abdulqader [30], who found that environmental conditions and water quality characteristics in Iraqi urban systems influence BOD levels. Residual chlorine represents the most critical public health concern identified in this study. Complete depletion of residual chlorine (0.00 mg/L at all six sites) during January and February constitutes a serious violation of the WHO guideline of ≥ 0.2 mg/L at the point of delivery [17] and the Iraqi national drinking-water standards [14]. The public health implications are significant: the absence of residual chlorine provides no barrier against microbial recontamination during distribution, potentially exposing consumers to waterborne pathogens. Several factors may account for this wintertime depletion: (a) insufficient chlorine dosing at the treatment plant during colder months when operators may underestimate chlorine demand; (b) increased chlorine demand driven by elevated organic matter and turbidity loads observed in November–February; (c) extended water residence time within the distribution network under conditions of reduced consumption; and (d) lower reaction kinetics at lower temperatures that nonetheless allow greater net consumption at prolonged contact times. In comparison, Dhanabal and Chellaiah [15] highlighted that maintaining chlorine stability remains a significant challenge in distribution networks under varying environmental conditions, emphasizing the importance of adaptive dosing strategies. Furthermore, Elsherif et al. [31] demonstrated that hydraulic conditions and network complexity significantly affect disinfectant distribution. Immediate remediation recommendations include: increasing chlorine dosing during the November–February period; installing online residual chlorine monitors at key distribution nodes; and conducting seasonal chlorine demand profiling to adjust dosing schedules proactively. The statistically significant spatial variation in phosphate concentrations ($P \leq 0.05$) is noteworthy, as phosphate was the only parameter to exhibit such spatial differentiation. Mean phosphate concentrations at distribution endpoints S4 (0.257 mg/L), S5 (0.238 mg/L), and S6 (0.230 mg/L) were appreciably higher than at the raw-water site S1 (0.177 mg/L) and treated-water site S2 (0.174 mg/L). This progressive elevation along the distribution pathway—rather than at the raw-water intake—strongly suggests post-treatment contamination, most plausibly from pipe corrosion inhibitors (many of which are phosphate-based), from leaching of aging infrastructure, or from infiltration of phosphate-laden groundwater through pipe defects. Dedicated investigation of the distribution pipes at S4–S6, including infrastructure inspection and source-specific phosphate isotope analysis, is recommended to confirm the contamination route. Similar findings of localized contamination of distribution networks have been reported in Iraqi and regional studies, where localized variations in water quality were associated with infrastructure conditions and environmental factors [22,32]. Several studies have emphasized that the efficiency of water treatment plants is influenced by both raw water quality and operational conditions. Al-Mayah [19] reported that treatment efficiency in the Al-Aziziyah plant is affected by variations in influent water quality. Similarly, Choudhury and Saha [33] highlighted that the operational efficiency of treatment plants depends on multiple factors, including design, maintenance, and environmental conditions. These findings are further supported by recent studies that emphasize the importance of continuous monitoring and optimization of treatment processes [34]. In addition, broader environmental studies have indicated increasing pressure on water resources in Iraq due to pollution and climate change. Ethaib et al. [35] reported that water resources in southern Iraq face significant challenges, including contamination and reduced availability. Similarly, Ali and Abojassim [36] highlighted the presence of heavy metals in drinking water sources, indicating potential health risks. Overall, this study's results

demonstrate that seasonal environmental factors primarily control water quality in the studied system, while treatment and distribution processes help maintain spatial consistency. However, the observed depletion of residual chlorine and localized variation in certain parameters highlight critical issues that require improved monitoring and management to ensure a safe drinking water supply.

4. Conclusions

The results of this study indicate that the physicochemical properties of water in the Al-Aziziyah–Al-Hafariya project are mainly influenced by seasonal changes rather than spatial differences. Most parameters showed higher values during autumn and decreased in winter, while dissolved oxygen and nutrient levels increased during colder months. The absence of significant spatial variation in most parameters reflects the efficiency of the treatment processes and the stability of the distribution system. However, the complete depletion of residual chlorine during winter suggests potential limitations in disinfection efficiency. Additionally, the observed variation in phosphate concentrations indicates possible localized influences within the distribution network. Comparison with the WHO [17] and Iraqi national (IQS 417/2009) standards revealed recurring exceedances of sulfate, total hardness, TDS, and turbidity—parameters not adequately addressed by conventional treatment alone. Overall, the water quality is relatively stable across the system, with seasonal factors being the primary driver of variation. Based on the findings, the following specific recommendations are made: (1) chlorine dosing should be increased during November–February to maintain residual chlorine ≥ 0.2 mg/L at all distribution endpoints; (2) online residual chlorine monitors should be installed at key nodes in the distribution network to enable real-time detection of depletion events; (3) infrastructure at distribution endpoints S4–S6 should be inspected for pipe defects and potential phosphate contamination sources; (4) coagulant dosing and filtration processes should be reviewed to consistently achieve WHO turbidity targets (≤ 4 NTU) at point of delivery; and (5) advanced treatment steps (e.g., nanofiltration or ion exchange) should be evaluated for reducing sulfate and hardness to within WHO guidelines. The study has several limitations: it was conducted at a single treatment plant over 6 months; nitrate was measured using semi-quantitative test strips with limited precision; no GPS coordinates or site map were included; and microbiological parameters were not assessed. Future research should incorporate microbiological monitoring, extend the study period to capture interannual variability, apply a Water Quality Index (WQI) framework for integrated assessment, and include a spatial map of sampling sites to improve reproducibility and verification.

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Evaluation of the Role of Silymarin on Certain Biochemical and Histological Parameters in Male Albino Rats Treated with Monosodium Glutamate

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Abstract: Monosodium glutamate (MSG), a widely used flavor enhancer, can induce hepatic and renal toxicity through oxidative stress, whereas silymarin from *Silybum marianum* has antioxidant and hepatoprotective properties. This study evaluated the protective effect of silymarin against MSG-induced hepatic biochemical and histological alterations, with renal involvement assessed through serum biochemical markers, in male albino rats. Thirty male rats (3–4 months) were randomly assigned to three groups (n = 10) and treated for 30 days: T1 (control, 0.9% saline), T2 (MSG, 15 mg/kg body weight), and T3 (MSG 15 mg/kg + silymarin 8 mg/kg). Serum liver enzymes (AST, ALT, ALP), urea, creatinine, and total protein were measured colorimetrically or enzymatically, and liver tissue was processed for histology. MSG significantly ($P < 0.05$) elevated AST, ALT, ALP, urea, and creatinine, and lowered total protein compared with control; for example, AST rose from 135.2 ± 46.7 to 209.5 ± 64.7 U/L, and creatinine from 1.18 ± 0.37 to 2.67 ± 0.23 $\mu\text{mol/L}$. Co-treatment with silymarin significantly reversed these changes (AST 152.4 ± 74.5 U/L; creatinine 1.58 ± 0.16 $\mu\text{mol/L}$; total protein restored toward control), although several values remained different from control. Histologically, MSG caused hepatocyte degeneration, necrosis, and cytoplasmic vacuolation, with loss of the normal radial architecture, whereas silymarin co-treatment largely restored hepatic structure, reducing necrosis and inflammation. These findings indicate that silymarin at 8 mg/kg exerts a meaningful protective effect against MSG-induced hepatorenal toxicity, consistent with its antioxidant and membrane-stabilizing actions.

Keywords: Silymarin; monosodium glutamate; biochemical parameters; histological changes; liver

1. Introduction

Changes in lifestyle and food marketing have increased the consumption of processed foods, a trend linked to adverse health effects, partly attributable to flavor enhancers such as monosodium glutamate (MSG) used during food processing [1]. Food additives are chemicals added to produce specific sensory effects [2,3]; the best-known is MSG, a white, odorless crystalline powder that dissolves readily in water. It is the sodium salt of the non-essential amino acid glutamic acid, which constitutes about 78% of its mass, with sodium and water accounting for the remaining ~22% [4]. Its chemical name is L-glutamate monohydrate ($\text{C}_5\text{H}_8\text{NO}_4\text{Na}$), with a boiling point of 232°C and a water solubility

of 74 g/10 mL [5,6]. Despite its appetizing taste, high doses of MSG can cause harmful effects, particularly on vital organs such as the liver and kidneys [7].

Chronic exposure or high MSG doses can cause physiological and biochemical disturbances in many organs, attributed to increased reactive oxygen species (ROS) and oxidative stress arising from an imbalance between free radicals and antioxidant systems [8]. This oxidative stress oxidizes lipids, proteins, and nucleic acids, causing cellular damage and dysfunction [9,10]. The liver, central to metabolism and detoxification, is highly susceptible: MSG increases hepatocyte membrane permeability, elevates serum liver enzymes, and induces degeneration, inflammation, and vascular congestion [7,11]. The kidney is likewise a major target: previous studies have reported histological damage to renal units, elevated urea and creatinine, and impaired glomerular filtration linked to oxidative stress and cellular injury [12].

Interest in natural antioxidants to mitigate oxidative damage has grown, with silymarin among the most important; recent studies have demonstrated that diverse phytochemicals—including marjoram extract [13], berberine [14], and chia seed extract [15]—similarly attenuate oxidative stress, reduce lipid peroxidation, and normalize antioxidant enzyme activity in rodent models, underscoring the broad therapeutic potential of plant-derived compounds against ROS-mediated injury. Silymarin, extracted from milk thistle (*Silybum marianum*), comprises a group of flavonolignans, chiefly silybin [16,17]. It has antioxidant and anti-inflammatory activity—inhibiting free-radical formation, reducing lipid peroxidation, strengthening antioxidant defenses, and preserving membrane integrity [18,19]—and shows hepatoprotective and nephroprotective effects by limiting enzyme leakage and oxidative damage and improving functional parameters [20,21]. Given the potential harm of MSG to the liver and kidneys and silymarin's protective properties, the present study evaluated the role of silymarin on selected biochemical parameters—including hepatic enzymes and renal function markers—and on hepatic histology in rats treated with MSG, to determine its capacity to mitigate MSG-induced damage and the mechanisms involved.

2. Materials and Methods

2.1 Animals and housing

Thirty male albino rats (3–4 months old) were obtained from the animal house at the College of Science, University of Kufa. Animals were kept in plastic cages fitted with a dedicated drinking system under standard laboratory conditions (20–25°C) and acclimatized for two weeks. The experiment was conducted at the animal facility of the Department of Biology, College of Education, University of Al-Qadisiyah.

2.2 Experimental design

Rats were randomly divided into three groups of ten and treated for 30 days: T1 (control) received 0.9% saline by oral gavage; T2 received MSG at 15 mg/kg body weight by oral gavage; and T3 received MSG at 15 mg/kg body weight by oral gavage, administered simultaneously with silymarin at 8 mg/kg body weight by oral gavage (concurrent co-treatment).

2.3 Sample collection

At the end of the experiment, animals were anesthetized with ketamine (75 mg/kg, i.p.) combined with xylazine (10 mg/kg, i.p.), and blood was collected directly from the heart using a 5-mL disposable syringe. Samples were incubated at room temperature for 15–20 min, centrifuged at 3000 rpm for 15 min, and the separated serum was stored at –20°C until biochemical analysis.

2.4 Biochemical assays

Serum AST, ALT, and ALP were determined colorimetrically [22] using assay kits (Giese, Italy). Creatinine was measured colorimetrically (Randox), urea by an enzymatic method (bioMérieux), and total protein colorimetrically.

2.5 Histological study

Livers were excised, cleaned of adhering tissue, and fixed in 10% formalin. Fixed tissues were washed and processed using standard histological techniques [23], and stained with hematoxylin and eosin for light-microscopic examination. A pathologist blinded to group assignments performed the histological evaluation.

Lesions were graded semi-quantitatively using a four-point scale applied separately to hepatocyte necrosis, cytoplasmic vacuolation, and inflammatory infiltration: 0 = none; 1 = mild (<10% of the examined tissue affected); 2 = moderate (10–30%); and 3 = severe (>30%). For each animal, five non-overlapping fields per section were scored, and the mean score was used for analysis. Scores are expressed as mean $\pm$ SE, and between-group differences were compared statistically as described in Section 2.6.

2.6 Statistical analysis

Data were analyzed using SPSS (version 25.0; IBM Corp., Armonk, NY, USA). Normality of distribution was assessed with the Shapiro–Wilk test and homogeneity of variance with Levene’s test before parametric analyses. One-way ANOVA was used to compare groups, and post-hoc pairwise comparisons were performed using Tukey’s Honestly Significant Difference (HSD) test; $P < 0.05$ was considered significant [24]. All data are expressed as mean $\pm$ standard error (SE).

3. Results and Discussion

3.1 Liver enzymes

MSG (T2, 15 mg/kg) significantly increased ($P < 0.05$) serum AST, ALT, and ALP compared with control (T1) (Table 1). Co-treatment with silymarin (T3, 8 mg/kg) significantly lowered ($P < 0.05$) these enzymes relative to T2, although they remained significantly above control. The rise in AST, ALT, and ALP in MSG-treated animals, consistent with [25], reflects hepatic tissue damage and increased transaminase release, impairing liver function [26]. Oxidative stress markers were not measured in the present study; the enzyme changes observed here are therefore interpreted in light of a literature-established injury mechanism rather than directly demonstrated. Consistent with that mechanism, previous studies have reported that MSG drives oxidative stress and ROS formation with inhibition of antioxidant enzymes, and increases hepatic malondialdehyde (MDA) and lipid peroxidation, key markers of ROS-mediated damage [27,28]. The marked decrease in enzyme levels after silymarin reflects its anti-inflammatory and antioxidant actions: its flavonoids, phenolic acids, and polyphenols scavenge free radicals, activate antioxidant enzymes, and regulate cell-membrane and mitochondrial permeability, reducing toxin entry [19]. Silybin, a phenolic constituent, has been shown in the literature to lower liver enzymes, serum lipids, and MDA while raising reduced glutathione (GSH) and superoxide dismutase (SOD) activity, restore mitochondrial membrane fluidity, and promote hepatocyte regeneration [29], findings consistent with the hepatoprotective pattern observed in the present study.

Table 1. Effect of silymarin on serum liver enzyme levels in rats treated with monosodium glutamate (MSG).

Group	AST (U/L)	ALT (U/L)	ALP (U/L)
T1	135.20 $\pm$ 46.7 C	80.80 $\pm$ 27 C	197.2 $\pm$ 128 C
T2	209.50 $\pm$ 64.7 A	105 $\pm$ 21.7 A	276.66 $\pm$ 224.6 A
T3	152.40 $\pm$ 74.5 B	85.60 $\pm$ 56.5 B	215.46 $\pm$ 95.8 B
LSD	5.81	4.53	5.62

Values are mean $\pm$ SE. Different letters indicate statistically significant differences ($P < 0.05$) between groups. T1: control (0.9% NaCl); T2: MSG 15 mg/kg for 30 days; T3: MSG 15 mg/kg + silymarin 8 mg/kg for 30 days.

3.2 Renal function and total protein

MSG (T2) significantly increased ($P < 0.05$) serum urea and creatinine and significantly decreased total protein compared with control (Table 2). Concurrent silymarin (T3) significantly reduced urea and creatinine and raised total protein relative to T2, although urea and creatinine remained elevated and total protein lower than control. Renal histology was not assessed in the present study; urea, creatinine, and total protein are therefore reported as supportive biochemical indicators of renal involvement rather than as evidence of structural renal change. The increase in urea and creatinine, consistent with [30], is attributed to MSG-induced renal tissue damage, impaired glomerular filtration, and dysfunction of renal units, with inflammation, hemorrhage, and atrophy of some glomeruli [12]. Enhanced hepatic deamination and detoxification also increase urea production, burdening the kidneys [31]. The decrease in total protein, consistent with [32,33], reflects MSG-induced hepatic damage affecting protein synthesis and function. Silymarin reversed these

changes, in line with [34,35], through its antioxidant, anti-inflammatory, and free-radical-scavenging properties; preservation of renal histology, modulation of nitric oxide pathways, and inhibition of lipid peroxidation restore kidney function and normalize urea and creatinine [21,36].

Table 2. Effect of silymarin on kidney function and total protein in rats treated with monosodium glutamate (MSG).

Group	Total protein (mg/dL)	Urea (mmol/L)	Creatinine (μ mol/L)
T1	6.60 $\pm$ 1.45 A	33.77 $\pm$ 10.6 C	1.18 $\pm$ 0.37 C
T2	4.28 $\pm$ 0.71 C	47.46 $\pm$ 6.69 A	2.67 $\pm$ 0.23 A
T3	6.01 $\pm$ 0.43 B	35.71 $\pm$ 4.59 C	1.58 $\pm$ 0.16 B
LSD	0.56	2.56	0.33

Values are mean $\pm$ SE. Different letters indicate statistically significant differences ($P < 0.05$) between groups. Group definitions are as in Table 1.

3.3 Liver histology

Liver sections from the control group (T1) showed normal architecture, with hepatocytes arranged in regular radial cords around the central vein (Figure 1). The MSG group (T2) showed severe hepatocyte degeneration and necrosis, loss of the normal radial arrangement around the central vein, and disruption of hepatic architecture (Figure 2). In contrast, the MSG + silymarin group (T3) showed normal hepatocyte morphology with a high degree of tissue repair, an absence of inflammatory cells within hepatic vessels, fewer dividing cells than T2, and no necrotic fatty cells, indicating restoration of normal structure (Figure 3). MSG-treated sections exhibited severe fatty degeneration with hepatocyte swelling and increased lipid droplets, consistent with [37]. As reported by Ortiz et al. [38], such degeneration contributes to elevated AST and ALT. Fatty degeneration may result from excessive hepatic fat deposition and an imbalance between triglyceride synthesis and secretion, with accumulation of unsaturated fatty acids and altered lipoprotein profiles [39]. MSG has also been shown to cause hepatocyte necrosis and tissue congestion with inflammatory foci [38], while cytoplasmic vacuolation indicates hepatocyte injury and a defensive response to toxic substances or membrane lysis [40]. The T3 group showed marked repair and improvement of hepatocytes, reflecting the hepatoprotective role of silymarin [29]. Silymarin stabilizes cell membranes and reduces their permeability; its phenolic compounds interact with free radicals to form stable products, scavenge ROS, enhance hepatic antioxidant activity, stimulate protein synthesis, and inhibit lipid peroxidation [41,42]. Silymarin also reduces hepatocyte necrosis, inflammatory infiltration, and collagen deposition, thereby limiting fibrosis and improving liver histology [42].

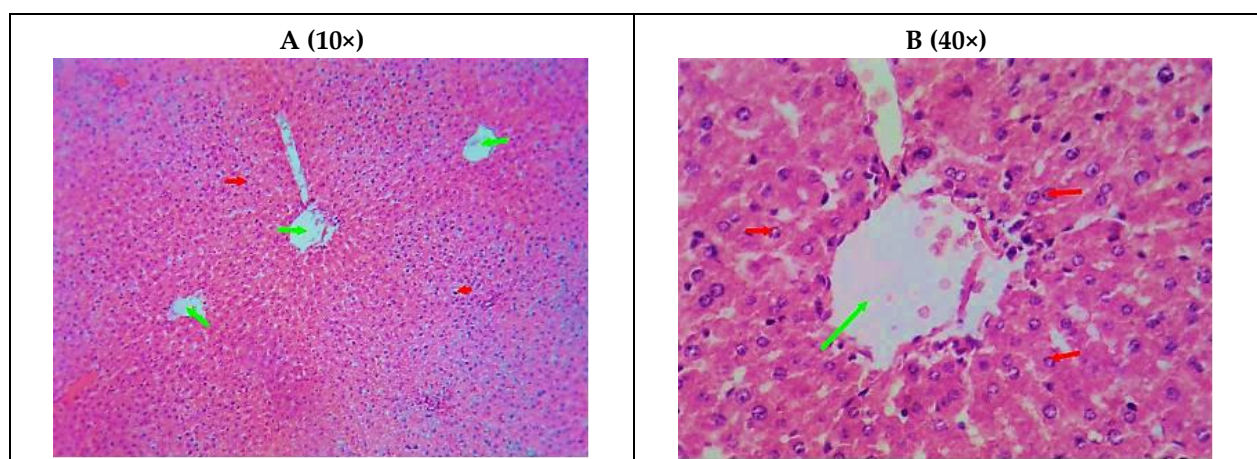


Figure 1. Liver tissue from the control group (T1) at (A) 10 $\times$ and (B) 40 $\times$. The central vein is surrounded by regular cords of hepatocytes (green arrow), with centrally located round nuclei (red arrow).

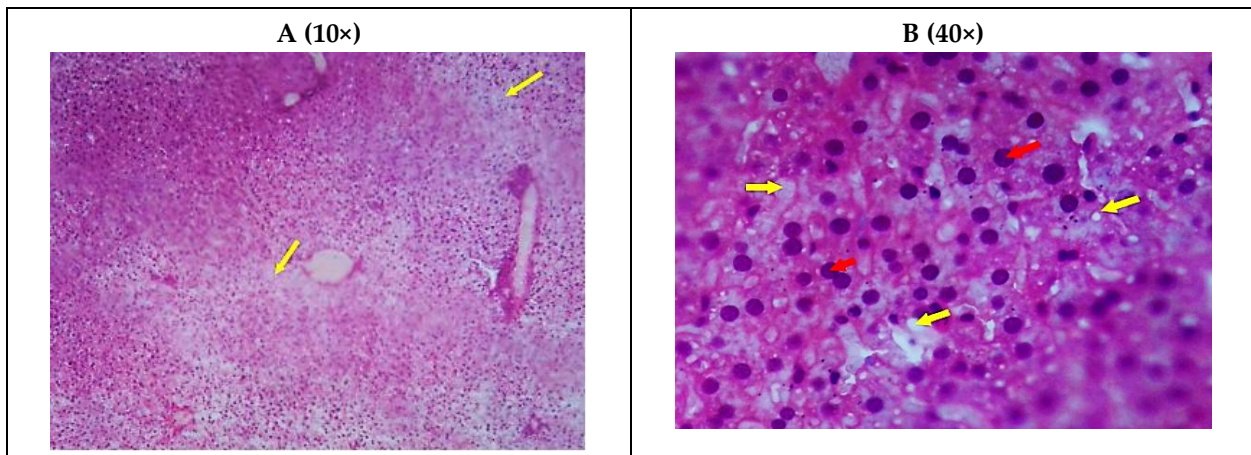


Figure 2. Liver tissue from the MSG group (T2, 15 mg/kg) at (A) 10× and (B) 40×. Many hepatocytes contain clear cytoplasmic vacuoles of varying size (yellow arrow); polygonal hepatocytes with central round nuclei (red arrow) and features of cell death/necrosis (black arrow) are visible.

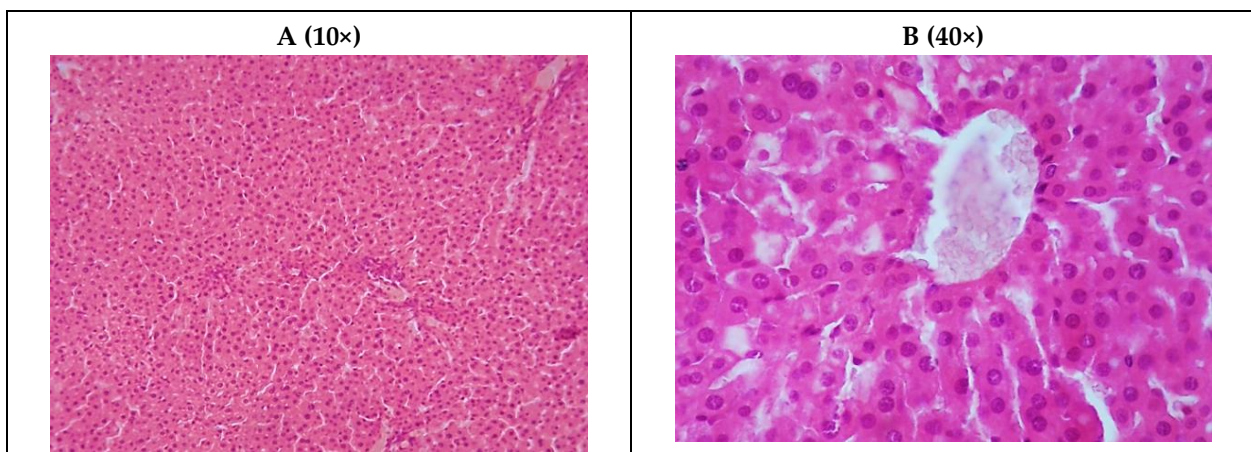


Figure 3. Liver tissue from the MSG + silymarin group (T3, 8 mg/kg) at (A) 10× and (B) 40×. No inflammatory cells are present within the hepatic vein lumen (black arrow), and signs of tissue healing are evident, with fewer dividing cells than the T2 group (blue arrow).

3.4 Discussion

The present study demonstrates that oral administration of monosodium glutamate (MSG) at 15 mg/kg for 30 days induces significant hepatic injury in male albino rats—expressed both biochemically as elevated serum AST, ALT, and ALP and structurally as hepatocyte degeneration, necrosis, and cytoplasmic vacuolation—and that concurrent silymarin (8 mg/kg) substantially mitigates these changes. MSG also disturbed renal function markers and total protein, and silymarin improved these biochemical indices, indicating a broadly hepatoprotective and renal-supportive effect. These observations are consistent with the growing body of evidence that MSG is hepatotoxic and that milk-thistle flavonolignans are protective [7,29]. The elevation of serum transaminases and alkaline phosphatase in MSG-treated animals reflects loss of hepatocyte membrane integrity and leakage of cytosolic enzymes into the circulation, a pattern repeatedly reported in MSG models [25,26]. Although oxidative stress markers were not measured here, the enzyme changes are most plausibly explained by the well-characterized MSG mechanism in which excess reactive oxygen species overwhelm antioxidant defenses, promote lipid peroxidation, and damage cellular membranes [8,27,28]. The pronounced reduction in enzyme activities after silymarin co-treatment is consistent with its capacity to scavenge free radicals, restore antioxidant enzyme activity, and stabilize hepatocyte and mitochondrial membranes, thereby limiting enzyme efflux [19,29]. That several values in the T3 group remained above control suggests that, at the dose tested, protection was substantial but incomplete.

MSG raised serum urea and creatinine and lowered total protein—changes that, although not corroborated by renal histology in this study, accord with reports of MSG-induced impairment of glomerular filtration and renal tubular function [12,30]. Increased urea may also arise from enhanced hepatic deamination accompanying hepatocellular stress [31], while the fall in total protein is generally attributed to compromised hepatic protein synthesis [32,33]. Silymarin attenuated these disturbances, consistent with its documented nephroprotective activity in chemically induced renal injury models [21,34,35] and with the broader nephroprotective potential of plant antioxidants such as *Piper nigrum* [1]. The improvement of total protein toward control further supports a restorative effect on hepatic synthetic function. Histologically, MSG produced fatty degeneration, hepatocyte swelling, necrosis, and cytoplasmic vacuolation with loss of the normal radial architecture, findings that mirror earlier descriptions of MSG hepatotoxicity [37,38]. Fatty change probably reflects an imbalance between triglyceride synthesis and export and the accumulation of lipid within hepatocytes [39], whereas cytoplasmic vacuolation is widely interpreted as a defensive response to toxic injury and incipient membrane damage [40]. In the silymarin group, hepatic architecture was largely preserved, with reduced necrosis and inflammatory infiltration and evidence of tissue repair, consistent with the semi-quantitative reduction in lesion scores and the histological recovery reported for silymarin in other hepatotoxicity models [42].

The protective effects observed here are mechanistically consistent with the pharmacology of silymarin and its principal constituent silybin, which act through antioxidant, anti-inflammatory, and membrane-stabilizing pathways and promote hepatocyte regeneration [16,18,20,41]. By scavenging reactive oxygen species and modulating signaling pathways linked to cell survival and repair, silymarin limits both biochemical and structural manifestations of toxic liver injury [42]. The present results align with a broader literature showing that diverse plant-derived antioxidants, including marjoram, berberine, and chia seed extracts, attenuate oxidative stress and normalize biochemical and histological endpoints in rodent models [13, 14, 15], reinforcing the therapeutic promise of such compounds against xenobiotic-induced organ damage. Several limitations should be acknowledged. Oxidative-stress biomarkers (e.g., malondialdehyde, glutathione, superoxide dismutase) were not measured, so the proposed mechanism remains inferential rather than directly demonstrated; renal histology was not examined, leaving the urea, creatinine, and total-protein changes as supportive biochemical indicators of renal involvement only; and a single MSG and silymarin dose was evaluated. Future studies incorporating direct measurement of oxidative-stress markers, renal tissue examination, and a dose-response design would clarify the mechanisms underlying silymarin's hepatorenal protection and help define the optimal protective dose.

5. Conclusions

In male albino rats, monosodium glutamate (15 mg/kg for 30 days) produced significant hepatic injury, evidenced biochemically by elevated serum AST, ALT, and ALP and histologically by hepatocyte degeneration, necrosis, and cytoplasmic vacuolation with loss of the normal lobular architecture. MSG also disturbed renal function markers, raising serum urea and creatinine and lowering total protein, indicating an associated systemic effect on the kidney and protein metabolism. Concurrent co-treatment with silymarin (8 mg/kg) substantially attenuated these alterations—lowering liver enzymes, improving the renal biochemical markers, restoring total protein toward control values, and markedly preserving hepatic architecture—although several parameters did not return fully to control levels. These findings indicate that silymarin exerts a meaningful, though partial, protective effect against MSG-induced hepatic toxicity and the associated biochemical disturbances, consistent with its established antioxidant and membrane-stabilizing properties. Because oxidative stress markers and renal histology were not assessed in the present study, further work incorporating direct measurement of oxidative-stress biomarkers, renal tissue examination, and a dose-response design is warranted to confirm the underlying mechanisms and define the optimal protective dose.

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Phytochemical and Physicochemical Characterization and Heritability Estimates of Fruit Quality Traits in Selected Coconut (*Cocos nucifera* L.) Populations

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Abstract: Limited information exists on the antioxidant performance of coconut cultivars. This study evaluated the phytochemical and physicochemical profiles of fruit quality traits and assessed genetic variability in response to free-radical-induced damage. Data were analyzed using one-way ANOVA at a 95% confidence level, with genetic parameters computed in RStudio v4.2 and graphical representations generated using OriginLab Pro 2024 v10.1. Results indicated that total phenolic content (TPC) was highest in the Tagnanan population (78.54±2.95), followed by hybrid Matag (62.2±2.60). Total flavonoid content (TFC) similarly peaked in Tagnanan (91.83±7.34), with hybrid Matag recording a comparable value (79.42±7.93). DPPH radical inhibition was greatest in Malayan Dwarf and Tagnanan Tall (58.97±1.21 and 58.26±1.00, respectively). Phenotypic coefficients of variation were 26.46% for TPC, 23.28% for TFC, and 5.87% for DPPH. Corresponding genotypic variations were 25.12%, 21.35%, and 4.85%. Heritability estimates were highest for TPC (90.13%) and TFC (84.09%). Genetic advancement as a percentage of the mean (GAM) indicated gains of 49.13% and 40.33% for TPC and TFC, respectively, whereas DPPH scavenging activity showed only 8.25% genetic gain. Physicochemical analysis identified hybrid Matag and Malayan Dwarf as having the highest protein content (16.77% and 16.47%). Hybrid Matag recorded the highest punching force (109.91±0.33 N) and total soluble solids (5.71%), exceeding those of its parental materials. Tagnanan Tall demonstrated superior antioxidant potential, while hybrid Matag combined strong antioxidant traits with excellent physicochemical properties. Both cultivars are recommended for priority inclusion in coconut breeding programs, with multi-location trials advised to validate findings across diverse environments.

Keywords: Phytochemical; physicochemical; antioxidant; genetic variability; coconut

1. Introduction

Coconut (*Cocos nucifera* L.) is an important plantation crop worldwide, cultivated in over 93 countries and providing livelihoods for millions of people [1]. As a staple crop in many tropical areas, it is often called the “tree of life,” emphasizing its economic and cultural significance [2]. Despite intense competition from oil palm and soybean, it remains a vital resource for small-scale farmers in tropical regions [3]. Significant investment is directed toward edible products made from coconut oil and its kernel, sugar, coconut water, fiber, coco peat, and charcoal, produced in various regions [4]. It thrives on poor soils where other crops fail, requires minimal intensive management, and produces a wide array of products for both domestic use and local and international markets [3]. Polyphenolic compounds are significant secondary

metabolites present in both the edible and non-edible parts of the plants. These plant-derived polyphenols, recognized for their antioxidant properties, have been linked to numerous health benefits, including mitigating the effects of aging and reducing the risk of cancer and cardiovascular disease [5]. The importance of natural phenolic compounds from plant sources is gaining increasing attention from scientists, food producers, and consumers [6]. Regular intake of raw vegetables and fruits abundant in polyphenols is hypothesized to enhance conditions associated with degenerative diseases, including diabetes, cancer, hypertension, and cardiovascular disorders [7]. Coconut flesh is currently underutilized, but identifying its polyphenol compounds and antioxidant potential could transform it into a valuable commercial source. Natural antioxidants, such as those from coconut flesh, are gaining interest due to their safety and fewer side effects than synthetic alternatives [8].

Assessing genetic variability in crops is essential for sustainable production, as crop improvement and genetic diversification rely on the existing variability available to breeders [9]. Genetic divergence analysis measures variation among selected germplasms, facilitating breeders in the targeted selection of genetically diverse parent plants for the efficient implementation of heterosis breeding [10]. Partitioning variability into heritable and non-heritable components enhances our understanding of selection efficiency [11]. Estimates of genotype and phenotype coefficients of variation reveal the level of genetic variability in each germplasm. However, the key factor is the heritable portion of that variation, which significantly influences trait improvement through selection. Assessing heritability alongside genetic advancement enables more effective selection by minimizing environmental effects on total variation, thereby enabling precise identification of potential genotypes. Heritability values (h^2) for a trait can be estimated as the slope of a linear regression of mean values in parents and their progeny [12]. Estimating heritability and genetic advance is crucial for identifying the heritable portion of variability and the genetic gains expected in future generations [13]. High values of the genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), and heritability, coupled with significant genetic gains for total phenols and antioxidant potential, indicate that traits are predominantly governed by additive gene effects, making them dependable targets for effective selection strategies [14]. The PCV is significantly higher than the GCV for most traits, suggesting that environmental factors exert varying levels of influence across the measured characteristics [15]. Genotypes are identified by their physical traits, while genetic advance helps guide selection. Understanding heritability and genetic progress enables breeders to select the best parents for a successful, productive breeding program [15]. Genetic advance indicates the increase in the performance of selected lines relative to the actual population. High genetic advancement provides greater potential for selecting and improving yield-related traits. However, high heritability does not often guarantee high genetic advancement, as reported by Meena et al. [13]. High heritability and high genetic advance as a percentage of the mean are better predictors of selection success than heritability alone [10]. Traits with high heritability and moderate genetic advancement suggest that selecting such traits for improvement can be effective, indicating an important role of non-additive gene action in their inheritance.

Coconuts mature between eleven and thirteen months, during which the water volume inside decreases. Numerous studies have investigated the physicochemical and nutritional properties of coconuts at different maturity stages and cultivars. However, the current study on the physicochemical, phytochemical, and antioxidant properties of the hybrid Matag and its parental materials remains inadequate. No prior study has quantified the heritability and genetic advance of phytochemical traits (TPC, TFC, DPPH) in Tagnanan Tall, Malayan Dwarf, and their F1 hybrid Matag under Malaysian growing conditions, leaving a gap in the literature on the genetic control and selection potential of these health-relevant traits in tropical coconut populations. Therefore, the overall objective was to demonstrate and elucidate how parental materials contributed to the development of pure hybrid Matag in terms of physicochemical and phytochemical contents and antioxidant properties within the populations, and to examine variability, inheritance, and predicted genetic gains in the hybrid population.

2. Materials and Methods

The 22 individuals used for this study comprised palm trees sampled from the three populations (approximately 7 and 8 per population, using a convenience sampling approach) at Pusat Pertanian Teluk Bharu Perak, Malaysia, with a site description of clay-loam soil, a humid tropical climate, and ≤ 15 m elevation at 4°43'N, 100°57'E. The samples were distributed and adopted in a completely randomized design (CRD). The flesh of fresh coconut fruits was collected at full maturity, usually 11 to 12 months after flowering, from the three coconut populations: Tagnanan tall, Malayan red and yellow dwarf, and the hybrid Matag. The flesh was carefully removed from the husk and shell, then cut into smaller pieces for oven-drying. The samples were further ground into fine powder and labeled for further analysis. Selections were made by the palm populations based on the number of mature palms available at the time of data collection.

2.1 Phytochemical Compounds

The total phenolic and flavonoid contents, and the percentage of DPPH free radical scavenging activity were determined. Gallic acid by the Gutfinger [15] method and quercetin by the Zhishen et al. [16] method were used to determine total phenolic and flavonoid contents, respectively, with methanol as the extraction solvent. Folin Ciocalteu reagent, aluminum chloride, sodium carbonate, sodium hydroxide, sodium nitrate, and distilled water were used in the estimation of total phenols and flavonoids in test samples. Instruments used include cotton wool, micropipette 1000, mortar and pestle, orbital shaker, 50 ml Falcon tubes, conical flask, and UV-VIS spectrophotometer (Thermo Fisher Scientific, Multiskan Go UK) for measuring the absorbance of test samples. The antioxidant activity percentage of each sample was determined using the DPPH (2,2-diphenyl-1-picryl-hydrazyl) free radical assay, a standard technique for measuring DPPH. Individual palms from the study populations were used. The fruits were gently dehusked, and the flesh was manually removed from the shell using a flesh remover. The collected flesh was stored at -20 °C for further analysis. The flesh was oven-dried for 5 hours at 105°C, then cut into slices and ground to a fine powder in a mechanical grinder. The finely powdered material was sieved to have a homogeneous particle size ready for solvent extraction. Although this protocol may lead to some thermal degradation of heat-labile phenolics, further studies are recommended to consider freeze-drying or low-temperature vacuum drying to minimize this effect and obtain higher TPC and TFC estimates. Extraction of the solvent was carried out according to the protocol of Kaewseejan and Siriamornpun [17], with some modifications: 5 g of the powdered sample was weighed into a test tube, mixed with 20 ml of 80% methanol, and wrapped in aluminum foil to prevent light penetration. The solution mixture was further agitated for 1 hour on an orbital shaker, and the aqueous extract was obtained after filtering the mixture through filter paper (Whatman number 1). These extracts were then used for phytochemical determinations [18].

2.2 Determination of Total Phenolic Content (TPC)

A gallic acid stock solution was prepared by dissolving 0.1 g of gallic acid in 100 mL of water in a 100 mL volumetric flask. Double-distilled water was added to dilute, and the 100 mL mark was set; the mixture was stirred until completely dissolved in the dark to obtain a homogeneous solution. Different concentrations of the stock solutions (50, 100, 150, 200, 250, and 300 µg/mL) were prepared in a separate 100 mL volumetric flask. Each concentration was diluted to a final volume of 100 mL with double-distilled water in a dark place. Absorbance for each concentration was measured in triplicate using a microplate reader (UV-Vis Spectrophotometer, Thermo Fisher Scientific, Multiskan Go, UK) at 765 nm, yielding a six-point calibration curve over 50–300 µg/mL ($y = 0.0084x + 0.0891$, $R^2 = 0.9879$). The calibration curve was generated using the average absorbance values measured at various concentrations of gallic acid. The total phenolic content (TPC) of the coconut flesh extract was analyzed according to the method of Gutfinger [15], with slight modifications. A stock solution of 10 µg/mL gallic acid in distilled water was prepared to create a standard calibration curve ranging from 50 to 300 µg/mL in a 96-well microplate. A 200 µL aliquot of the extract was mixed with 1 mL of 10% Folin-Ciocalteu phenol reagent, then thoroughly mixed and incubated for 5 minutes. Subsequently, 800 µL of 7.5% sodium carbonate (Na_2CO_3) solution was added to the mixture. The prepared mixture was incubated for 30 minutes in the dark at room temperature. Absorbance readings were recorded at 765 nm using a microplate reader (UV-Vis Spectrophotometer; Thermo Fisher Scientific, Multiskan Go, UK).

Measurements were performed in triplicate, and distilled water was used as a blank control. The TPC was determined using an equation derived from the gallic acid calibration curve, and the results were expressed as milligrams of gallic acid equivalent (mg GAE/g) per gram of dry coconut flesh.

2.3 Determination of Total Flavonoid Content (TFC)

Exactly 10 mg of quercetin was dissolved in 10 mL of 80% methanol to prepare a stock solution. Serial dilutions were prepared from the stock solution at concentrations of 500, 250, 125, 62.5, 31.25, and 15.625 µg/mL. The absorbance at 425 nm was measured with a UV-Vis spectrophotometer ($y=0.0018x+0.0856$, $R^2=0.9845$) to generate a quercetin standard curve for total flavonoid content (TFC) analysis. Each concentration was measured in triplicate, and the calibration curve was plotted using the average absorbance values. The TFC was determined following the method of Zhishen et al. [16], with some modifications. For each sample, 1 mL of aqueous extract was mixed with 0.3 mL of 5% sodium nitrate (NaNO_3) solution. After 5 minutes, 0.3 mL of 10% aluminium chloride (AlCl_3) was added, followed by 2 mL of 1 M sodium hydroxide (NaOH) after 6 minutes. The total volume was adjusted to 10 mL with distilled water, and the mixture was thoroughly mixed. Absorbance was measured at 425 nm using a UV-Vis Spectrophotometer (Thermo Fisher Scientific, Multiskan Go, UK). A blank solution containing all reagents except quercetin was used as a control, and absorbance values were compared with the standard curve to determine the equivalent quercetin concentration. The total flavonoid content was expressed as mg of quercetin equivalents (mg QE/g) per dry weight of the coconut flesh. The TFC was calculated using the linear equation derived from the quercetin calibration curve.

2.4 Preparation of Stock Solution and Determination of DPPH Antioxidant Activity

A 0.1 mM DPPH working solution was prepared by dissolving 0.0224 g of DPPH powder in 100 mL of 80% methanol. The resulting purple mixture was homogenized and stored in a dark bottle at room temperature for later use. The DPPH free radical scavenging activity of the extracts was measured using a modified method from Brand-Williams et al. [19]. In this procedure, 2,850 µL of the fresh DPPH solution was combined with 150 µL of the extract, and the mixture was incubated in the dark for 30 minutes. The absorbance was measured at 510 nm using a UV-Vis spectrophotometer (Thermo Fisher Scientific, Multiskan Go, UK), and the percentage of DPPH inhibition was calculated using the equation:

$$\% \text{ DPPH} = [(\text{Absorbance control} - \text{Absorbance sample}) / \text{Absorbance control}] \times 100$$

Where, Absorbance control = DPPH solution's absorbance without extracts; Absorbance sample = DPPH solution's absorbance with sample extracts.

2.5 Physicochemical Properties

Samples were analyzed for physicochemical characteristics, with data collected in triplicate (analytical, not biological, replicates were performed on each fruit sample). Protein content was calculated using the AOAC 2001.11 standard for the Kjeldahl nitrogen percentage determination in the flesh, using a multiplication factor of 6.25. For every gram of nitrogen in the flesh, there is approximately 6.25% protein. The pH of the flesh was measured using a digital pH meter after the flesh (10 g) was grated and blended with 30 mL of distilled water in a 1:3 ratio. The pH meter was calibrated before the measurements using buffer solutions with pH 4.01 and 7.0. The total soluble solids (TSS) were expressed as °Brix, and the blended sample fruits were filtered and measured with a digital refractometer. Fresh fruit firmness was measured using a penetrometer texture analyzer with a pressure gauge in kg, and the values were converted to newtons (N). The moisture content and dry matter weight were evaluated by drying individual samples for 9 hours at 105°C, with a cooling-off period (overnight) after the first 5 hours of drying to prevent the fresh meat from hardening. Samples were allowed to cool, and the dry weight was recorded. The oven-dried sample was further dried for 3 hours at 105°C, then weighed. This procedure is repeated until the oven-dried meat weight becomes constant; the difference between the original and final oven-dried meat weights is the residual moisture content.

2.6 Data Analysis

The one-way analysis of variance with Duncan's Multiple Range Test at 95% confidence interval and pair-wise comparison of means and LSD using the *linear model*, genetic parameters, GAM, and Broad-sense heritability, which was estimated using the classical formula $H^2 = \sigma^2G / (\sigma^2G + \sigma^2E)$, where variance components were partitioned by one-way ANOVA using the *agricolae* and *variability* package, were all performed by RStudio v4.2. The standard selection intensity ($i = 2.06$, corresponding to a 5% selection proportion) was used for GAM: $i \times \sigma G / \mu \times 100$. OriginLab Pro 2024 v10.1 and Microsoft Excel 365 were used to generate the graphical representation of the data.

3. Results and Discussion

3.1 Phytochemical Compounds

The gallic acid equivalent (GAE $\mu\text{g/mL}$) of the phenolic content was observed to be higher in the Tagnanan tall population and lower in the Malayan dwarf population compared with the hybrid Matag (Table 1). The result revealed that the TPC was significantly and generally higher in the Tagnanan population (78.54 ± 5.15), followed by the hybrid Matag population (62.2 ± 2.60) (Table 1). The result obtained in this study is higher than that previously reported by Ab Mutalib and Jailani [20] for tall coconut. However, it is lower than the result obtained by Keng et al. [21]. The maturity and age of fresh fruits significantly affect the TPC estimation [22]. All of these are due to the distinct genetic backgrounds of tall and dwarf palm types, which can influence the biosynthesis and accumulation of phenolic compounds. Also, hormonal changes and distinct phenolic profiles with varying levels of specific compounds during fruit development and ripening, which differ between dwarf and tall types, can influence phenol biosynthesis. The result also revealed an intermediate hybrid value between the parental populations and the hybrid in the measured phenolic concentration, suggestive of partial dominance (a formal mid-parent value analysis is recommended to confirm this classification). Coconuts exhibit increased phenolic content and antioxidant activity at maturity ages of up to 190 days after pollination, suggesting that the harvest time is also crucial for maximizing phenolic content [23]. The concentration and composition of phenolics in coconut vary greatly depending on the fruit part (mesocarp, testa, cotyledon, water) and maturity stage (young or mature). Notably, young coconut mesocarp extracts have demonstrated potent radical-scavenging activity, sometimes outperforming synthetic antioxidants such as butylhydroxytoluene (BHT) [24].

Table 1. Total phenolic and flavonoid contents and DPPH antioxidant activity

Population	TPC (mg GAE/g DW)	TFC (mg QE/g DW)	DPPH % inhibition
Tagnanan Tall	78.54 ± 2.95^a	91.83 ± 7.34^a	58.26 ± 1.00^{ab}
Malayan dwarf	54.10 ± 2.13^c	66.09 ± 1.03^b	58.97 ± 1.21^a
Hybrid Matag	62.20 ± 0.78^b	79.42 ± 7.93^a	57.06 ± 0.27^b

Data were expressed as mean $\pm$ SD ($n=22$). Letters a, b, and c in the same column are significantly different at the ($p < 0.05$) level.

The total flavonoid content (TFC) results show that the Tagnanan population had the highest TFC (91.83 ± 8.55), followed by the hybrid Matag population (79.42 ± 9.27), as shown in Table 1. The graphical representation shows that the TFC in the Tagnanan population does not differ significantly from that in the hybrid Matag population (Table 1). This implies that the hybrid Matag population exhibited a total flavonoid content comparable to or exceeding that of the higher parent, suggesting dominance (a formal mid-parent heterosis analysis is recommended to confirm). The difference in flavonoid content between tall and hybrid coconut types can be attributed to genetic, environmental, and agronomic factors. Tall coconut types may have genetic traits that promote higher flavonoid accumulation, whereas hybrid types are bred for specific traits like yield or disease resistance, potentially reducing flavonoid content. Environmental factors, such as UV radiation, can stimulate flavonoid production in tall types, whereas controlled conditions in hybrids might reduce this effect. Additionally, differences in maturity stage, evolutionary adaptation, and metabolic pathways may also contribute to the variation in flavonoid content. These differences can impact the

nutritional and industrial value of coconut products. Higher flavonoid content in tall coconut types can enhance their antioxidant properties, potentially provide additional health benefits, and increase their value in pharmaceutical, food, and cosmetic industries. Understanding these differences can inform breeding programs to enhance flavonoid content in coconut varieties, ultimately leading to the development of more nutritious and valuable coconut products. These findings support the study by Arivalagan et al. [7], which revealed that tall and hybrid coconut meat has the highest flavonoid content compared with dwarf-type coconut meat. Flavonoids, as secondary metabolites with established health benefits, can help mitigate chronic diseases, primarily due to their antioxidant properties [20, 25]. These antioxidants are compounds that minimize the production of free radicals or interact with and neutralize them, potentially helping protect cells from oxidative damage [26]. Extraction methods also significantly affect flavonoid content in a sample, with optimized processes yielding up to 115 mg of quercetin equivalents per gram of defatted testa. This suggests that processing methods are crucial in maximizing the flavonoid content [7]. Phenolic and flavonoid compounds, including phenolic acids (like protocatechuic acid, chlorogenic acid, and vanillic acid), catechins, and epicatechins, are consistently reported as the primary contributors to radical scavenging activity in various coconut parts [27, 28]

The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay measures the antioxidant activity of coconut meat by assessing the antioxidant's ability to neutralize the free radicals in the samples. The results of this experiment (Table 1) revealed that the highest per cent inhibition of antioxidants was observed in the parental materials Malayan dwarf and Tagnanan tall (58.97 ± 1.99 and 58.26 ± 1.93 , respectively), which were not significantly different from the hybrid Matag. This indicates that the parental materials have a significant ability to scavenge DPPH free radicals and neutralize them [28, 29]. It also elucidates their potential for use in food products and cosmetics as natural antioxidants [30]. Arivalagan et al. [8] demonstrated that phenolic and flavonoid compounds in coconut meat significantly contribute to its DPPH scavenging activity, showing its potential as a natural source of antioxidants. The DPPH, a secondary plant metabolite, is primarily associated with health benefits, including anti-aging effects, the prevention of age-related diseases, anticancer properties, anti-inflammatory actions, and reduced risk of cardiovascular disease by protecting cells from free-radical damage [31].

3.2 Variability Estimates, Heritability, and Genetic Advance of Phenolic and Flavonoid Compounds and Their Antioxidant Activity

The phenotypic coefficient of variation (PCV) describes the variation in traits due to environmental and genetic factors. The results showed that TPC and TFC recorded PCV values of 26.46% and 23.28%, respectively, among the individuals assessed, with only 5.87% phenotypic variation for the DPPH (Table 2). This indicates low variation in the traits among individuals due to genetic and environmental factors, suggesting that inherited traits were either controlled by a few major genes or influenced by additive gene effects [11]. The TPC and TFC assays are more specific to certain types of compounds, which might exhibit higher variability due to genetic and environmental factors. DPPH assay measures the overall antioxidant activity, which is influenced by various compounds, including phenolics, flavonoids, and other antioxidants. The presence of multiple antioxidant compounds with varying potencies might reduce variability in the DPPH assay. The DPPH assay might not be as sensitive to specific phenolic compounds as the assays for TPC and TFC. This reduced sensitivity could lead to lower variability in the DPPH assay. The genetic control of antioxidant activity might be more complex than that of individual phenolic compounds. This complexity could lead to a more stable DPPH value across different genotypes or environments.

Table 2. Estimation of mean, variability, heritability, and genetic advance as a percentage of mean in phenolic and flavonoid compounds and antioxidant activity in coconut

Traits	Mean $\pm$ SE	PCV (%)	GCV (%)	h ² (%)	GAM (%)
TPC	67.42 $\pm$ 3.24	26.46	25.12	90.13	49.13
TFC	81.43 $\pm$ 4.37	23.28	21.35	84.09	40.33
DPPH	58.12 $\pm$ 1.11	5.87	4.85	68.26	8.25

Data were expressed as mean $\pm$ SE (n=22).

TFC = total flavonoid content; TPC = total phenolic content; PCV = phenotypic coefficient of variation;

GCV = genotypic coefficient of variation; h² = Heritability; GAM = genetic advance as a percentage of the mean.

The phenotypic coefficient of variation describes the variation in traits due to environmental and genetic factors. The result showed that TPC and TFC recorded phenotypic coefficient of variation of 26.46% and 23.28%, respectively, among the individuals assessed, with only 5.87% phenotypic variation for the DPPH (Table 2). This indicates low variation in the traits among individuals, suggesting that these were either inherited traits controlled by a few major genes or influenced by additive gene effects [14]. Similarly, the genotypic variations recorded were 25.12%, 21.35%, and 4.85% for TPC, TFC, and DPPH, respectively. The highest heritability estimate was observed for total phenolic content (90.13%), followed by TFC (84.09%), and the lowest for DPPH (68.26%). The TPC and TFC demonstrated strong heritability along with a high genetic variation coefficient. Cornelius [32] revealed that combining the genotypic coefficient of variation with heritability estimates provides a more precise assessment of selection efficiency. The insignificant variation in TPC and TFC among fruits indicates that the environment had little influence on these traits, and the minimal difference between the phenotypic and genotypic coefficients of variation indicates that both phenotypic and genotypic factors drive trait variation. This is comparable to the findings of Meena et al. [13], who studied the genetic variability in fruit crops. The genetic advancement as a percentage of the mean showed that TPC and TFC had predicted genetic gains of 49.13% and 40.33%, respectively, after selection, with a predicted genetic gain of 8.25% for DPPH scavenging activity (Table 2), thereby neutralizing free radicals during segregation selection. This elucidates that high heritability does not always accompany higher genetic advancement. It also explains that even though there may be less variation in the traits assessed, they have a greater capacity to duplicate these variations and improve genetic inheritance, which will assist researchers in selection for breeding programs. These combinations of genetic parameters may be due to non-additive gene action governing these traits [13].

3.3 Physicochemical Properties

The quality parameters of coconut fruits are mainly determined by their physical properties. The results of the physicochemical analysis revealed that there were no significant differences between the populations, with hybrid Matag and Malayan dwarf populations having the highest protein contents, 16.77% and 16.47%, respectively (Figure 1). However, the Tagnanan population had slightly lower protein content (14.12%) compared to the dwarf and hybrid Matag populations. The findings align with those of Maskromo et al. [28] on the dwarf population, which found that fruit protein content decreases as it matures. The sample population in this study of mature individuals has low protein content. The highest texture punching force (Figure 2) was observed for the meat of the hybrid Matag population with 109.91 $\pm$ 0.33 N, followed by the Tagnanan tall population with 85.87 $\pm$ 0.27 N. The fruit texture analysis shows that there was a significant difference in the fruit mesocarp “hard” among the populations. The texture was expressed as Newton (N) from a conversion of pressure in (kg). The force and energy required to penetrate and remove coconut meat increased with the coconut’s maturity. Immature coconuts typically yield soft, gelatinous meat with a mild flavor that can be easily scooped from the shell with a spoon. In contrast, mature coconuts exhibit much firmer, sweeter meat that adheres more rigidly to the shell, necessitating greater effort for extraction [27]. With limited literature on the physicochemical properties of Tagnanan and hybrid Matag, researchers have observed that the dwarf variety is highly regarded for its flavor, sweetness, and texture, surpassing both hybrid and tall varieties in these attributes [20]. This study reports, for the first time, a notably firmer and more rigid texture

in the hybrid Matag, a product of the cross between Tagnanan tall and Malayan dwarf. Total soluble solids in coconut can serve as a reliable indicator of its sweetness level [33].

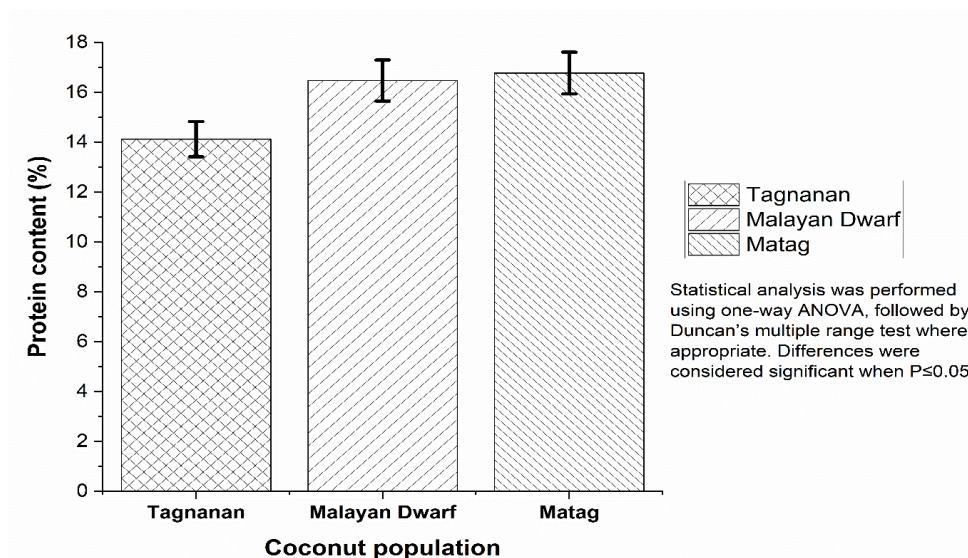


Figure 1. Protein content (%) of coconut fruit meat across three populations — hybrid Matag, Malayan dwarf, and Tagnanan tall — showing variation among genotypes. Values are mean $\pm$ SE (n=22).

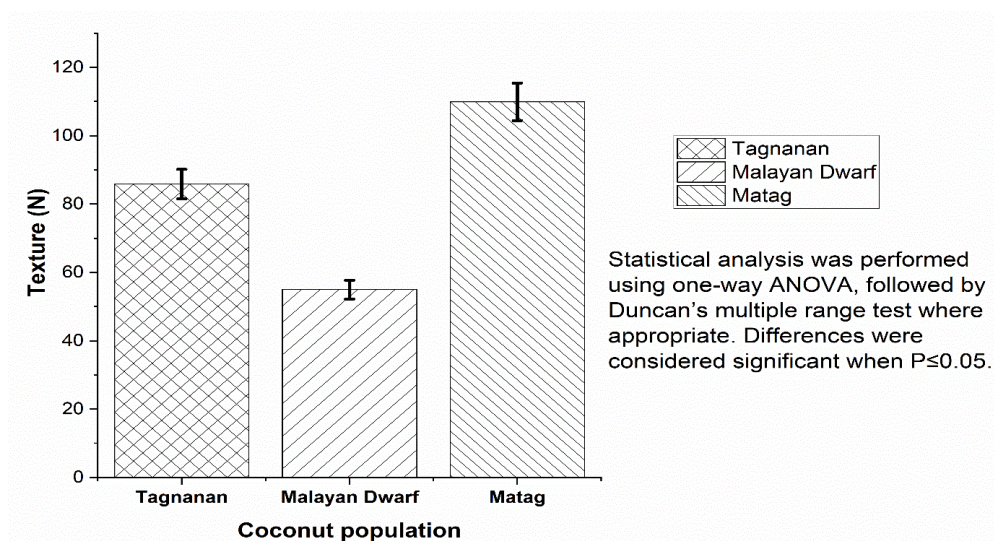


Figure 2. Fruit mesocarp texture (punching force, N) of coconut meat across hybrid Matag, Tagnanan tall, and Malayan dwarf populations. Values are mean $\pm$ SE (n=22).

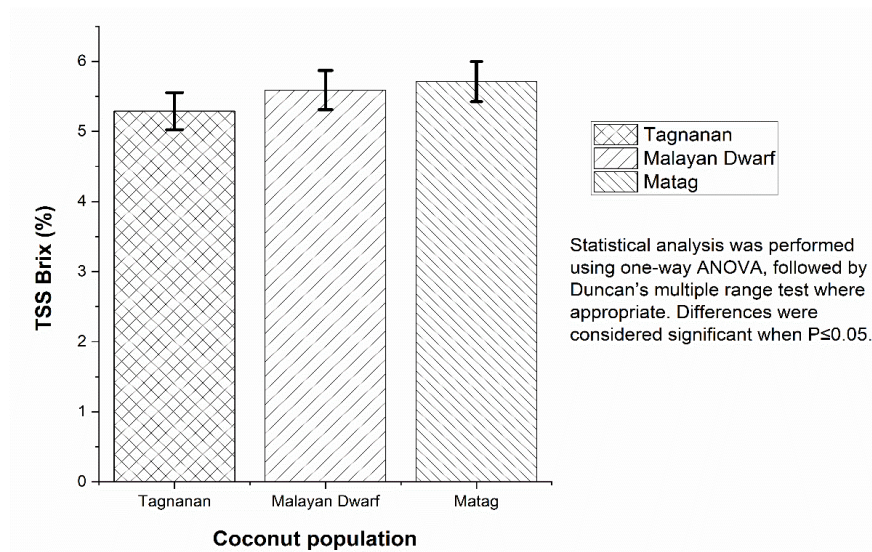


Figure 3. Total soluble solids (TSS, °Brix) of coconut water across hybrid Matag, Tagnanan tall, and Malayan dwarf populations as an indicator of sweetness. Values are mean $\pm$ SE (n=22).

The total soluble solids (TSS, Brix^o) in coconuts can serve as a reliable indicator of their sweetness [34]. The TSS showed significant differences among all the populations, with values measured from the hybrid Matag (5.71%) higher than its parental materials (Figure 3). A study confirmed that coconut contains 5–8% total soluble solids, with trace amounts of amino acids, organic acids, and minerals [23]. These current findings are slightly lower than those reported by Halim et al. [35]. However, it emphasizes that this could be affected by the coconut's harvesting time, typically at 12 months, which slightly reduces TSS content thereafter. There was a significant difference in fruit pH among the populations; all were slightly acidic. Notably, the Malayan dwarf coconut population tended to have higher pH values, followed by the hybrid Matag population (Figure 4). The findings of Ab Mutalib and Jailani [20] revealed higher pH values for hybrid Matag, dwarf pandan, and Malayan tall, confirming this study. The maturity of the fruit determines the pH level; younger fruits are less acidic than mature fruits, which are acidic to neutral in the populations assessed. This agrees with the studies of Tan et al. [29] and Keng et al. [21], which state that younger fruits tend to be more acidic than mature fruits. The dry matter weight was higher in the Tagnanan population (Figure 5). The populations assessed also showed significant differences. This implied that the higher the dry matter content, the lower the moisture content [14]. This trend was also reported by Ibrahim et al. [30], who found that fruits with higher dry matter content tend to have longer shelf lives due to reduced water activity, which can inhibit microbial growth and spoilage. This relationship suggests that as the dry matter content increases, the fruit or plant material becomes drier, and conversely, as moisture content increases, the dry matter content decreases. This is consistent with the principle of conservation of mass, which states that the total mass of a system comprises both dry matter and moisture.

3.4 Mean, Variability, Heritability, and Genetic Advance as Percentage of Mean in Physicochemical Properties of Coconut Populations

Phenotypic coefficient variation revealed significant trait variability, indicating that both genetic and environmental factors contribute to the observed differences. The genotypic variances of all traits were lower than their phenotypic variances. Roy and Shil [32] have established that PCV and GCV measurements exceeding 20% are classified as high, values between 10% and 20% as medium, and values below 10% as low. These results indicated that protein content and fruit texture showed higher variations of 28.75% and 29.36%, respectively, followed by total soluble sugar with a medium variation of 11.61% and dry matter with a variation of 13.56%. However, pH showed the least variation among the individuals evaluated, at 6.12% (Table 3). These suggest relatively low variation in the measured traits, implying that both genetic and environmental factors contribute minimally to the observed differences. The data further imply that the genetic constitution of the fruits predominantly governs their quality, with environmental factors exerting

negligible influence on trait performance. Although there were significant limitations to the palm population selection, convenience sampling was based on the number of mature palms available, implying non-random convenience sampling.

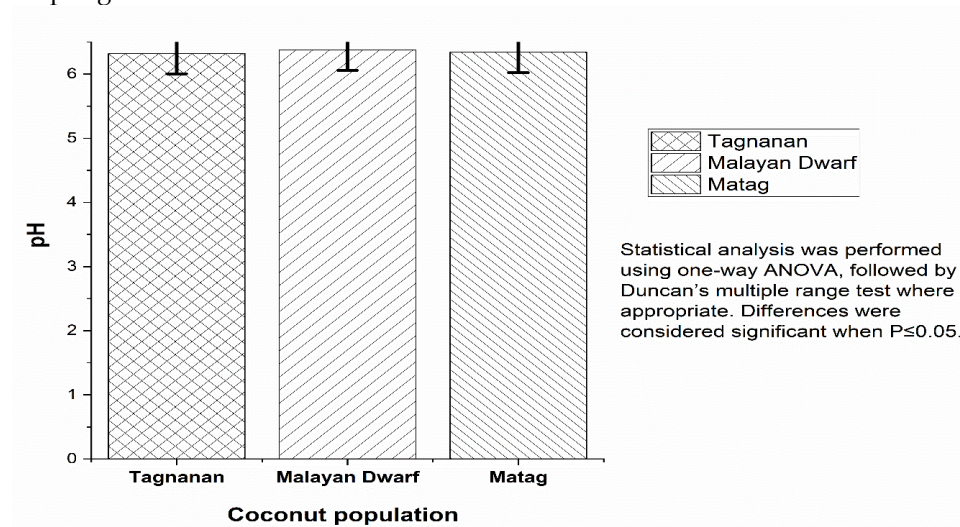


Figure 4. pH of coconut water across hybrid Matag, Tagnanan tall, and Malayan dwarf populations, reflecting fruit acidity at maturity. Values are mean ± SE (n=22).

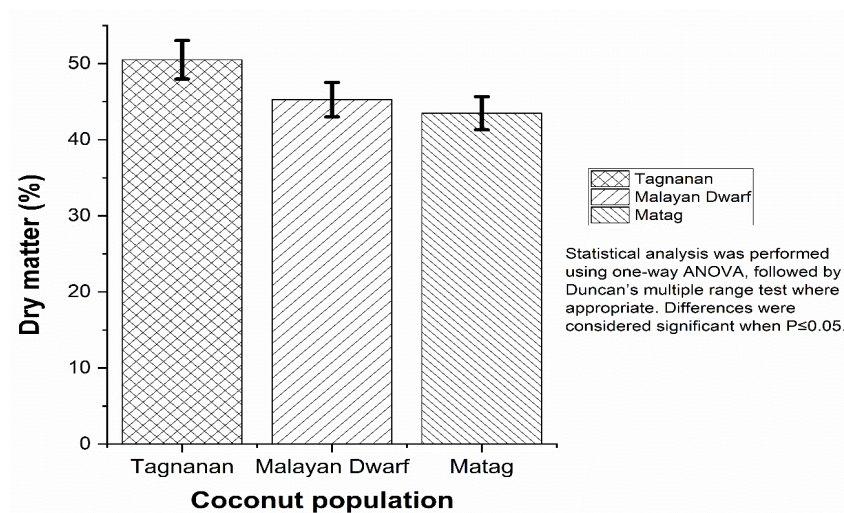


Figure 5. Fruit dry matter content (%) of coconut meat across hybrid Matag, Tagnanan tall, and Malayan dwarf populations, inversely reflecting moisture. Values are mean ± SE (n=22).

Table 3. Mean, Variability, Heritability, and Genetic Advance as a percentage of means in Physicochemical properties of Coconut populations

Traits	Mean ± SE	PCV %	GCV %	h ² %	GAM %
Protein	15.48 ± 2.31	28.75	12.66	19.38	11.48
TSS °Brix	5.49 ± 0.02	11.61	11.59	99.58	23.82
Texture	84.01 ± 0.53	29.36	29.34	99.86	60.39
pH	6.34 ± 0.03	6.12	6.08	98.67	12.43
DRM	47.16 ± 0.80	13.56	13.23	95.25	26.61

Data were expressed as mean ± SE (n=22).

PCV = phenotypic coefficient of variation; GCV = genotypic coefficient of variation; h² = Heritability;

GAM = genetic advance as a percentage of the mean; TSS = total soluble solids; DRM = dry matter

The study on genetic variability also revealed that traits such as dry matter and total soluble solids were predominantly influenced by genotypic factors, as indicated by the close correspondence between GCV and PCV, making these traits promising for selection. Significant genetic improvement was observed in protein content and total soluble solids, indicating that these traits can be enhanced through selective breeding [36]. High heritability and genetic advance were observed for traits like protein content, which are largely governed by additive genetic effects and can be targeted for breeding programs [37]. In another study, high PCV, GCV, and genetic advances were recorded for dry matter content and TSS, suggesting significant scope for improvement in these traits [10]. The variation in the measured traits indicates they are largely unaffected by environmental factors, and the small difference between PCV and GCV suggests that both phenotypic and genotypic factors contribute to the observed variability. PCV values exceeded GCV values across all traits, suggesting a significant environmental impact on trait expression. Similar findings by Dangi et al. [9] revealed that PCV values are higher than GCV values for most traits measured, suggesting that environmental factors influence trait expression and contribute to increased variability.

Heritability estimates for these populations revealed that fruit texture and TSS had the highest heritability, at 99.86% and 99.58%, respectively, followed by pH (98.67%) and dry matter content (95.25%). The protein content, however, showed very low heritability (19.38%). The high heritability of fruit texture, TSS, pH, and dry matter content suggests that nearly all observed variations in these traits are due to genetic differences rather than environmental factors. This means that selective breeding for these traits would likely be highly effective, as they are strongly inherited from one generation to the next. It also indicates that the phenotypic variation is primarily controlled by genetic factors, making these traits good candidates for genetic improvement through breeding programs. These findings align with the study by Kumar et al. [25], which demonstrates that traits with strong genetic control can be effectively improved through selection and breeding because the genetic factors underlying these traits are more stable and heritable. They further clarified that high heritability estimates indicate that a large portion of the variation is due to genetic differences and that selection for the trait should be effective.

On the other hand, the low heritability of protein suggests that this trait is heavily influenced by environmental factors or possibly by non-additive genetic effects such as dominance and epistasis. This aligns with findings in various crops where protein content has been shown to exhibit significant environmental variation, making it a more complex trait to improve through breeding alone [18, 33]. High heritability does not inherently guarantee a high genetic advance. The percentage of genetic advancement of the mean indicated a predicted genetic gain of 60.39% for fruit texture, with dry matter and total soluble sugar recording 26.61% and 23.82%, respectively. The pH has consistently shown low variation and low genetic gain prediction amongst the measured traits, with only 12.43%. These results indicate that, despite the low variation observed in the assessed traits, there is a significant potential for these traits to increase the variability and enhance genetic inheritance.

4. Conclusions

The phytochemical study highlights the potential of coconut fruits as a source of natural antioxidants, with both genetic factors and harvesting time influencing their phenolic and flavonoid content and antioxidant activity. Phytochemical compounds can neutralize free radicals, potentially protecting cells from oxidative damage. Furthermore, processing methods are crucial for maximizing flavonoid content. It also highlights the potential of both parental populations, with their antioxidant activity comparable to, and potentially superior to, that of the hybrid Matag population. The phenotypic and genotypic coefficient of variations in TPC and TFC show a low variation of the traits among individuals in terms of genetic and environmental factors, coupled with high heritability, showing that these traits were either inherited characteristics regulated by a limited number of major genes or influenced by additive gene effects, with their scavenging activities showing a very low variation among the traits measured. This clarifies the effectiveness of selection: despite limited variation within traits, existing variation can be leveraged to replicate and enhance desirable genetic traits, ultimately improving inheritance. Physicochemical analysis revealed that hybrid Matag and Malayan dwarf populations have the highest protein content. The highest punching force was observed for the meat of hybrid Matag, and the TSS of coconut meat obtained from hybrid Matag was higher than that of its parental materials.

There was also a high coefficient of variation in protein content and the fruit texture. The genetic constitution of the fruits predominantly governs their quality, with environmental factors exerting negligible influence on trait performance. Significant genetic gains were observed in protein content and TSS, suggesting that these traits can be improved through selection. High heritability was observed for all measured traits except protein content, and PCV was higher than GCV for all traits. The percentage of genetic advancement of the mean indicated predicted genetic gains for fruit texture, dry matter, and TSS, revealing significant potential for these traits to increase variability and enhance genetic inheritance. The overall findings show significant variability among the traits studied, with promising phytochemical and physicochemical profiles that warrant further investigation in multi-location trials. These findings provide valuable information for coconut breeding programs and the development of new coconut varieties with desirable traits.

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Influence of Chicken Manure, Pig Manure, Cattle Manure, and Coconut Peat on the Growth and Yield of Melon (*Cucumis melo* L.) cv. Thunder Gold 1497

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Abstract: This study investigated the effects of organic growing media mixtures derived from chicken manure, pig manure, cattle manure, and coconut peat on the growth rate, yield quality, and production cost of melon (*Cucumis melo* L.) cultivar Thunder Gold 1497. The evaluated parameters included the growth rates of plant height, leaf width, leaf number, and stem diameter, as well as fruit sweetness (°Brix), fruit weight, and growing media cost. Mixture ratios were formulated using a mixture experimental design. The results showed that growing media composition significantly affected plant height, leaf width, leaf number, fruit weight, and fruit sweetness ($p < 0.05$). Cattle manure played a dominant role in enhancing fruit weight and stabilizing plant growth, while pig manure positively influenced fruit sweetness. Optimization using the desirability function indicated that a mixture of 50.00% cattle manure and 50.00% coco peat provided the highest desirability value (0.916), resulting in high growth performance, improved fruit quality, and reduced growing media cost.

Keywords: Mixture experimental design; organic growing media; melon; yield quality; growth rate

1. Introduction

Melon (*Cucumis melo* L.) is a highly valued economic crop. It is widely cultivated in many countries, including Thailand, due to its sweet taste and high nutritional value, particularly vitamin A and vitamin C [1]. Melon can be grown in almost all regions of Thailand because it grows well in warm to moderately hot climates, with an optimal temperature range of 25–30 °C. It requires well-drained soil or growing media and does not tolerate waterlogging. In melon production, achieving high-quality attributes such as sweetness and crispness requires proper management of production factors, particularly nutrient supply and growing media, which directly influence plant growth. Consequently, melon is an important crop in both domestic and international markets. Melon production is commonly conducted in greenhouses to facilitate pest control and reduce damage from rainfall, a major factor in leaf mold and root rot [2].

In Thailand, disease-free and readily available organic materials such as Coconut Peat, raw rice husks, and rice husk charcoal are commonly used as growing media [3]. As a result, the use of natural organic growing materials, including animal manure and agricultural waste, has gained increasing popularity because these materials improve the physical, chemical, and biological properties of growing media while reducing dependence on chemical

fertilizers. Each type of manure possesses distinct properties. Chicken manure is a rich source of nitrogen and phosphorus and is suitable for promoting leaf and stem growth [4]. Cattle manure improves the structure of growing media and enhances water-holding capacity, whereas pig manure provides balanced micronutrients and stimulates microbial activity within the growing media. However, inappropriate use of manure proportions can lead to salinity accumulation or nutrient imbalance, negatively affecting plant growth [5].

Several studies have reported that the combined use of coconut shavings and manure can improve the physical and chemical properties of growing media [6]. Studies by Qiu et al. [7] and Su and Zhang [8] found that mixing organic materials at appropriate ratios improved the quality of growing media and seedling germination. For example, the combination of rice husk ash and coconut shavings positively affected the growth of cucumber seedlings (*Cucumis sativus* L.). Similarly, Imtiaz [9] and Mejía et al. [10] reported that compost mixed with coconut shavings enhanced the growth of tomato seedlings and melons in hydroponic systems. Additionally, the use of agricultural waste materials such as sawdust, rice husk charcoal, and sugar mill sludge increased melon yield under greenhouse conditions [11]. Ab Rauf and Shahrudin [12] reported that the combination of coconut shavings (coir) with cattle manure or compost significantly promoted seedling growth and root development in melon. This finding is consistent with previous studies by Mazuela and Urrestarazu [13] and Aydi et al. [14], which demonstrated that mixed organic growing media can enhance chlorophyll content, improve nutrient accumulation in leaves, and increase fruit quality, including sweetness and firmness. The beneficial effects of such mixtures are largely attributed to the complementary physical and chemical properties of organic substrates, where coconut-based materials improve aeration and drainage, while manure provides essential nutrients and enhances water-holding capacity.

In addition, several studies have highlighted the importance of combining different types of organic manures to improve plant growth and soil fertility. For example, Diacono and Montemurro [15] and Edmeades [16] reported that mixed organic amendments significantly improve soil structure, nutrient availability, and microbial activity, thereby enhancing crop productivity. Similarly, Adekiya et al. [17] and Ojo et al. [18] found that the combined application of different manures resulted in greater plant growth and yield than using a single manure source, due to synergistic effects on nutrient release and soil physical properties. These findings support the concept that integrating multiple organic materials can create a more balanced growing environment for optimal plant development. Furthermore, previous studies by Ceglie et al. [19] and Myers et al. [20] used a mixture experimental design in combination with response surface methodology (RSM) to determine optimal proportions of growing media components to maximize responses such as yield and fruit sweetness. These approaches have been widely recognized as effective tools for optimizing agricultural inputs. Consistent with these findings Choudhary and Machavaram [21] demonstrated that optimized organic amendments significantly improved crop yield and fruit quality. Therefore, the objective of this research was to investigate the effects of mixing chicken manure, pig manure, cattle manure, and coco peat on melon growth and yield. A mixture experimental design was employed to determine the optimal growing media ratio affecting growth parameters, including plant height growth rate, leaf width growth rate, leaf number growth rate, and stem diameter growth rate. Yield-related parameters included fruit sweetness (°Brix), fruit weight, and growing media cost. The analysis was conducted under greenhouse conditions using Design-Expert version 7.0 to identify appropriate growing media compositions and provide practical guidance for farmers and entrepreneurs, thereby promoting sustainable commercial production of organic melons.

2. Materials and Methods

Thunder Gold 1497 (Sweet Green) melon seeds were transplanted into 104-cell seedling trays filled with peat moss. The seedlings were watered thoroughly twice daily (morning and evening). After 15 days of growth, the seedlings were transplanted into 8 × 13-inch white planting bags containing mixed growing media prepared according to each experimental formulation. The planting spacing was 40 × 50 cm. between plants. During cultivation, lateral shoots emerging from nodes 1 to 8 were pruned, while shoots from nodes 9 to 12 and above were retained. When the fruit reached approximately the size of a chicken egg, only one fruit was retained per plant. Subsequently, the 25th leaf was removed to terminate vegetative growth and promote

nutrient allocation toward fruit development. Melon fruits were harvested approximately 35–40 days after fruit set, based on external indicators such as skin color, aroma, netting development, and the appearance of cracks around the fruit peduncle. The experiment was conducted in a closed-system greenhouse with controlled temperature (25–32 °C) and relative humidity (60–75%). Plants were grown in growing media corresponding to each formulation, and drip irrigation was applied to supply water according to plant requirements at each growth stage. Chemical fertilizers were applied weekly during the first 30 days using a N- P- K fertilizer (15–15–15) at a rate of 5 g per plant. From 31 days after planting, a N- P- K fertilizer (20–8–20) was applied at 10 g per plant once per week. At 56–60 days after planting, a N- P- K fertilizer (15–5–35) was applied at a rate of 10–15 g per plant. In addition, drip irrigation was adjusted to provide approximately 1,500 mL of water per plant. The experiment was arranged in a completely randomized design (CRD) with one plant per replicate. The experimental design is presented in Table 1. [22]

2.1 Data Collection

Melon growth and yield parameters were analyzed, including plant height measured at 45 days after seeding. Plant height was measured from the soil surface at the base of the plant to the base of the fully expanded leaf using a measuring tape. The number of main leaves and the size of the third fully expanded leaf were recorded three weeks after transplanting. Leaf width was measured at the widest point using a ruler. Stem diameter was measured at the thickest part above the cotyledon using a vernier caliper. Fruit weight (g) was determined using a digital scale with a resolution of 0.01 g. Fruit sweetness was measured as total soluble solids (°Brix) using a refractometer, with juice extracted from the center of the fruit pulp. All measurements were recorded as the average of three plants per mixture ratio. Growth rate (%) was calculated using Equation (1), and the resulting data were used to analyze factors affecting melon growth and yield quality [19, 20].

$$\text{growth rate (\%)} = \frac{\text{Final measurement value} - \text{Initial measurement value}}{\text{Initial measurement value}} \times 100 \quad (1)$$

2.2 Mixture experimental design

A mixture experimental design was employed to determine the optimal proportions of animal manure and coconut shavings using statistical models. The total proportion of growing media was fixed at 100% (wt%) of the total volume [19]. Chicken manure (A), pig manure (B), cattle manure (C), and coconut shavings (D) were defined within a range of 0–100% of the mixture, as shown in Table 1. Experimental design, modeling, and response analysis were performed using Design-Expert software version 7.0 (Stat-Ease Inc., USA), following the principles of mixture design described [11]. For the preparation of the growing media and organic manures, coco peat was initially soaked in water for 24 h and subsequently washed repeatedly until the electrical conductivity (EC) value decreased to 0.3 dS cm⁻¹, which was considered suitable for melon cultivation. In addition, four types of animal manure were composted before use. The composting process involved applying 1 g of microbial inoculant (PD1), 1 kg of molasses, and 20 L of water, which were thoroughly mixed and evenly applied to each compost pile containing 100 kg of cattle manure, pig manure, chicken manure, and goat manure, respectively. During the composting period, water was supplied daily to maintain adequate moisture content, and each compost pile was manually turned three times per week to improve aeration and oxygen availability. This practice enhanced microbial activity and promoted efficient decomposition of organic matter.



Figure 1. Shows the growth of melons grown in a soilless crop regime.

Table 1. Typical nutrient composition of various animal manures.

Animal manure	Total Nitrogen (kg/t)	Total Phosphate (kg/t)	Total Potash (kg/t)	Ammonium Nitrogen (kg/t)	Nitrate Nitrogen (kg/t)	Dry Matter (%)
Broiler	30	25	18	6.2	0.2	60
Pig	7	8	6.0	0.9	0.1	25
Cattle	6	8	3.2	0.5	0.1	25

Table 2. Ingredients and limitations of ingredients used in experimental design

Ingredients	Factors	Ratio Limitations (Percentage)
Chicken manure	A	$0 \leq A \leq 50$
Pig manure	B	$0 \leq B \leq 50$
Cattle manure	C	$0 \leq C \leq 50$
Coconut shavings	D	$50 \leq D \leq 100$

3. Experimental results and discussion of results

The experimental results presented in Table 2 were used to select appropriate statistical regression models and to perform analysis of variance for the growth rate of melon plant height, leaf width growth rate, leaf number growth rate, stem diameter growth rate, fruit sweetness ($^{\circ}\text{Brix}$), fruit weight, and growing media cost using Design-Expert software version 7.0. The pseudo-components included melon plant height growth rate, leaf width growth rate, leaf number growth rate, stem diameter growth rate, fruit sweetness ($^{\circ}\text{Brix}$), fruit weight, and growing media cost, as expressed in Equations (2)–(8), respectively. The results indicated that linear models adequately described the growth rates of melon plant height and stem diameter, fruit weight, fruit sweetness, and growing media cost. In contrast, the growth rates of leaf width and leaf number were best fitted by special cubic models. The selection of these models was based on their p-values, all of which were less than 0.05 at the selected significance level, indicating that the regression models were statistically significant and suitable for describing the experimental data. In addition, the coefficients of determination (R^2) and predicted R^2 values for all selected models were relatively high and close to unity, further confirming the adequacy and reliability of the regression models.

Table 3. The Results of Growth Rate of Plant Height, Growth rate of the number of leaves, and growth rate of the number of leaves. Growth rate of stem size, yield weight, and sweetness

No.	A	B	C	D	Plant height (%)	Width of leaf (%)	Number of leaves per plant	Stem girth (%)	Weight (g)	Sweetness (Brix)	Cost (Baht)
1	0	0	0	100	22.5	5.3	16.67	6.56	320.24	8.5	20.2
2	25	25	0	50	42.8	11.52	18.89	8.26	780.72	13.2	10.8
3	50	0	0	50	28.4	7.74	12.04	12.22	520	10.8	10.8
4	31.228	6.07	6.408	56.294	32.6	5.3	9.03	10.1	615.84	11.5	12
5	0	0	50	50	48.2	14.47	31.48	18.75	920.05	12.6	10.8
6	0	0	25	75	35.2	6.17	20.37	8.64	620.53	11.7	15.5
7	12.5	12.5	12.5	62.5	40.95	10.36	15.74	15.12	740.5	12.1	13.2
8	0	25	0	75	32.8	6.29	13.33	7.22	480.29	11.5	15.5
9	0	50	0	50	38.6	8.08	15.74	4.45	650.32	14.2	10.8
10	12.251	12.52	12.474	62.756	37.2	11.37	14.81	12.22	695.09	12.3	13.2
11	5.888	6.139	6.474	81.499	29.59	11.11	20.83	11.9	545.54	10.4	16.7
12	5.97	31.482	6.487	56.062	40.25	9.55	20	12.12	760.86	13.3	12
13	5.971	6.096	31.51	56.423	44.6	13.08	13.89	22.22	810.15	11.7	12
14	0	25	25	50	43.44	12.04	11.11	17.22	785.89	14.5	10.8
15	25	0	25	50	38.08	5.63	11.11	11.64	720.44	12.6	10.8
16	25	0	0	75	25.4	7	15.56	11.42	420.22	11.5	15.5

$$\text{Melon Height Growth Rate} = 34.67A + 37.24B + 74.12C + 22.26D - 227.01AB - 1.69AC - 0.17AD + 34.96BD + 752.19ABD - 518.47AC(A-C) \quad (2)$$

$$\text{Leaf Width Growth Rate} = 6.33A + 14.04B + 53.34C + 5.30D + 857.17AB - 994.53AC - 7.73AD - 2237.31BC - 6.35BD - 59.39CD - 3161.36ABC - 1598.73ABD + 1813ACD + 4499.20BCD \quad (3)$$

$$\text{Leaf Growth Rate} = 10.18A + 16.75B + 44.41C + 16.68D - 171.21AC - 180.52BC + 1074.14BC(B-C) \quad (4)$$

$$\text{Growth rate of stem size} = 19.02A - 10.56B + 63.14C + 7.39D - 59.92AC - 893BC + 23.19BD - 64.85CD + 1974.52BCD - 686.51AC(A-C) \quad (5)$$

$$\text{Melon Fruit Weight} = 688.91A + 988.12B + 1528.47C + 327.71D - 14723.7AB + 34.17AD - 42.71BD + 35680.69 - 8433.07AB(A-B) \quad (6)$$

$$\text{Sweetness} = 2.16A + 20.40B + 17.44C + 8.68D + 8.53AD \quad (7)$$

$$\text{Cost} = 1.41A + 1.41B + 1.41C + 20.19D - 0.02AB - 0.02AC - 0.01BC + 15.85ABC + 6.73BC(B-C) \quad (8)$$

Based on the regression Equations (2)–(8), response surface contours were constructed. The contour plots for melon plant height growth rate, leaf width growth rate, leaf number growth rate, stem diameter growth rate, fruit sweetness (°Brix), fruit weight, and growing media cost are presented in Figures 2(a)–8(a), respectively. The plots indicate normal data dispersion, with no apparent outliers or abnormal patterns. Figures 2(b)–8(b) present the constant variance plots for melon plant height growth rate, leaf width growth rate, leaf number growth rate, stem diameter growth rate, fruit sweetness (°Brix), fruit weight, and growing media cost. These plots illustrate the relationship between residuals and predicted values. The results show no clear relationship between stochastic deviation and predicted values, indicating homoscedasticity of the data. Figures 2(c–e)–8(c–e) show the trace plots of each response, which were used to analyze the influence of individual components on melon growth and yield based on the trends of the response curves. Linear or curved trends indicate the extent to which mixture components affect changes in melon growth rate and yield. The analysis revealed that increasing the proportions of chicken manure (A), pig manure (B), and coconut shavings (D) decreased melon plant height growth rate, whereas increasing the proportion of cattle manure (C) increased melon plant height growth rate.

An increase in the proportions of chicken manure, pig manure, cattle manure, and coconut shavings tended to improve both leaf width growth rate and leaf number growth rate. Similarly, increasing the proportions of chicken manure, cattle manure, and coconut shavings was associated with higher stem diameter growth rates, whereas a higher proportion of pig manure tended to reduce stem diameter growth rates. In terms of melon yield, greater proportions of chicken manure, pig manure, and cattle manure were associated with increased fruit weight, while a higher proportion of coconut shavings tended to decrease fruit weight. Fruit sweetness increased with higher proportions of pig and cattle manure, whereas higher proportions of chicken manure and coconut shavings were associated with reduced sweetness. From an economic perspective, increasing the proportion of animal manure contributed to lowering overall growing media costs, whereas a higher proportion of coconut shavings increased costs.

The optimal mixture ratio was determined by simultaneously optimizing melon growth, fruit quality, and growing media cost. Overlay contour analysis identified a formulation consisting of 50.00% cattle manure and 50.00% coconut shavings as the optimal treatment. Under this condition, melon plants achieved plant height, leaf width, leaf number, and stem diameter growth rates of 48.19%, 14.47%, 30.55%, and 19.05%, respectively, together with a fruit sweetness of 12.97 °Brix, an average fruit weight of 928.09 g, and a growing media cost of 10.80 THB per bag. The overall desirability value was 0.916, indicating a favorable balance among growth, yield, quality, and economic responses. These findings are consistent with previous studies demonstrating that optimized organic substrates can improve plant growth, productivity, and crop quality by enhancing the physical and nutritional properties of the growing medium [23]. The superior performance of

this mixture may be attributed to the complementary functions of cattle manure and coconut-based materials. Cattle manure has been reported to improve nutrient availability, water-holding capacity, and microbial activity, thereby enhancing root development and nutrient uptake efficiency [23]. In contrast, coconut shavings improve substrate aeration and drainage, which are essential for maintaining adequate oxygen supply for root respiration and preventing waterlogging [24]. The combination of these materials therefore provides a balanced root-zone environment that supports vegetative growth and yield performance. Furthermore, the present findings are consistent with those of Phankaen and Kumpanuch [25], who demonstrated that proper management of EC, pH, and nutrient availability in controlled cultivation systems significantly improved melon fruit weight, sweetness, and overall fruit quality. Similarly, Pimonrat et al. [26] reported that excessive accumulation of organic substrate components could increase EC and pH levels, thereby negatively affecting melon growth and biomass accumulation. These findings support the present study, indicating that balanced proportions of organic materials are essential for maintaining suitable root-zone conditions, improving nutrient uptake efficiency, and enhancing melon productivity and fruit quality. From a physiological perspective, improved root-zone conditions may enhance water and nutrient absorption, thereby supporting photosynthetic activity and assimilate production, which are necessary for fruit [27]. Enhanced translocation of photoassimilates to developing fruits is likely associated with increased fruit weight and sugar accumulation, as reflected by the observed fruit sweetness of 12.97 °Brix. Similar findings have been reported in studies where optimized organic substrates improved both yield and fruit quality, particularly soluble solids content and fruit development [28]. Therefore, the 50:50 mixture ratio appears to provide an effective balance between the physical and nutritional properties of the growing medium. However, the optimal ratio identified in this study may vary depending on environmental conditions, crop management practices, and melon cultivar differences.

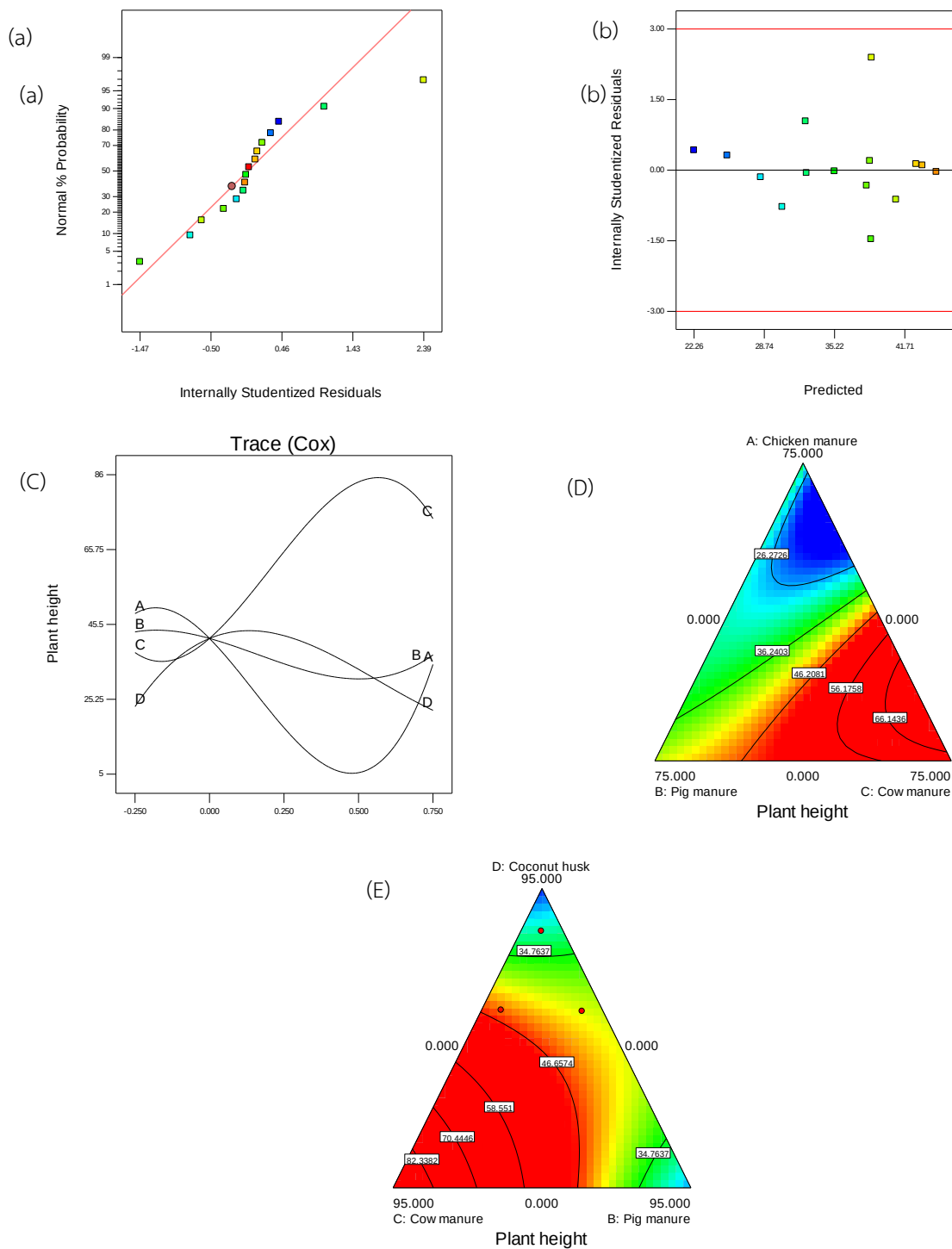


Figure 2. Random residual plot for the growth rate of melon plant height: (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of plant height growth rate (%), and (D–E) response contour plots of melon plant height growth rate.

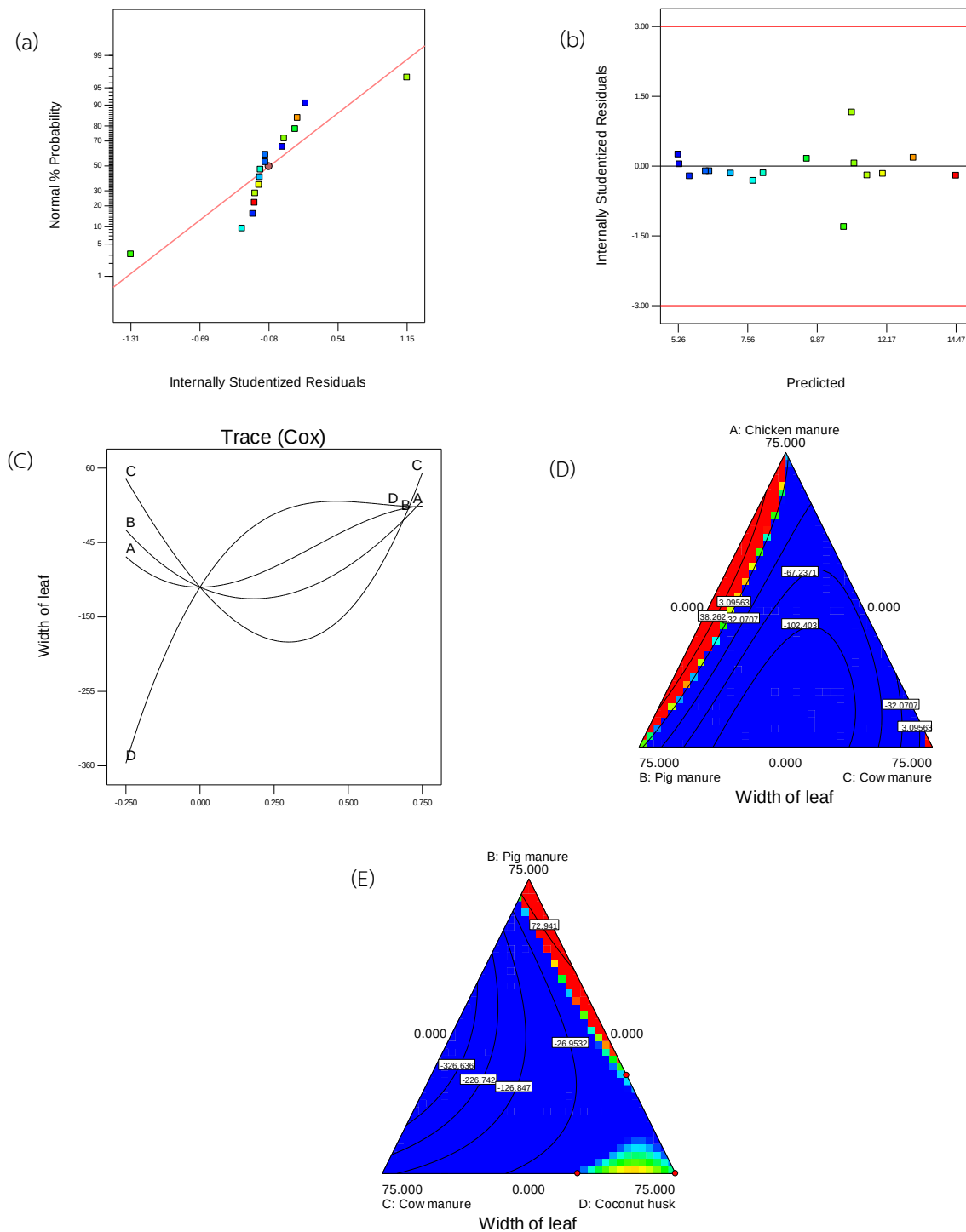
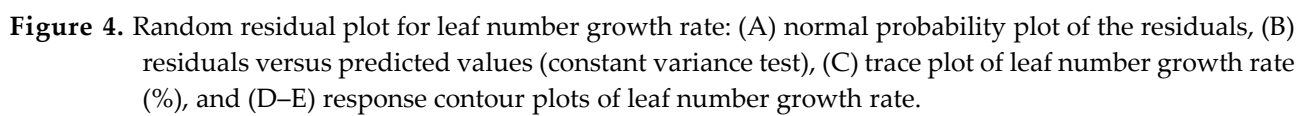


Figure 3. Random residual plot for leaf width growth rate: (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of leaf width growth rate (%), and (D–E) response contour plots of leaf width growth rate.



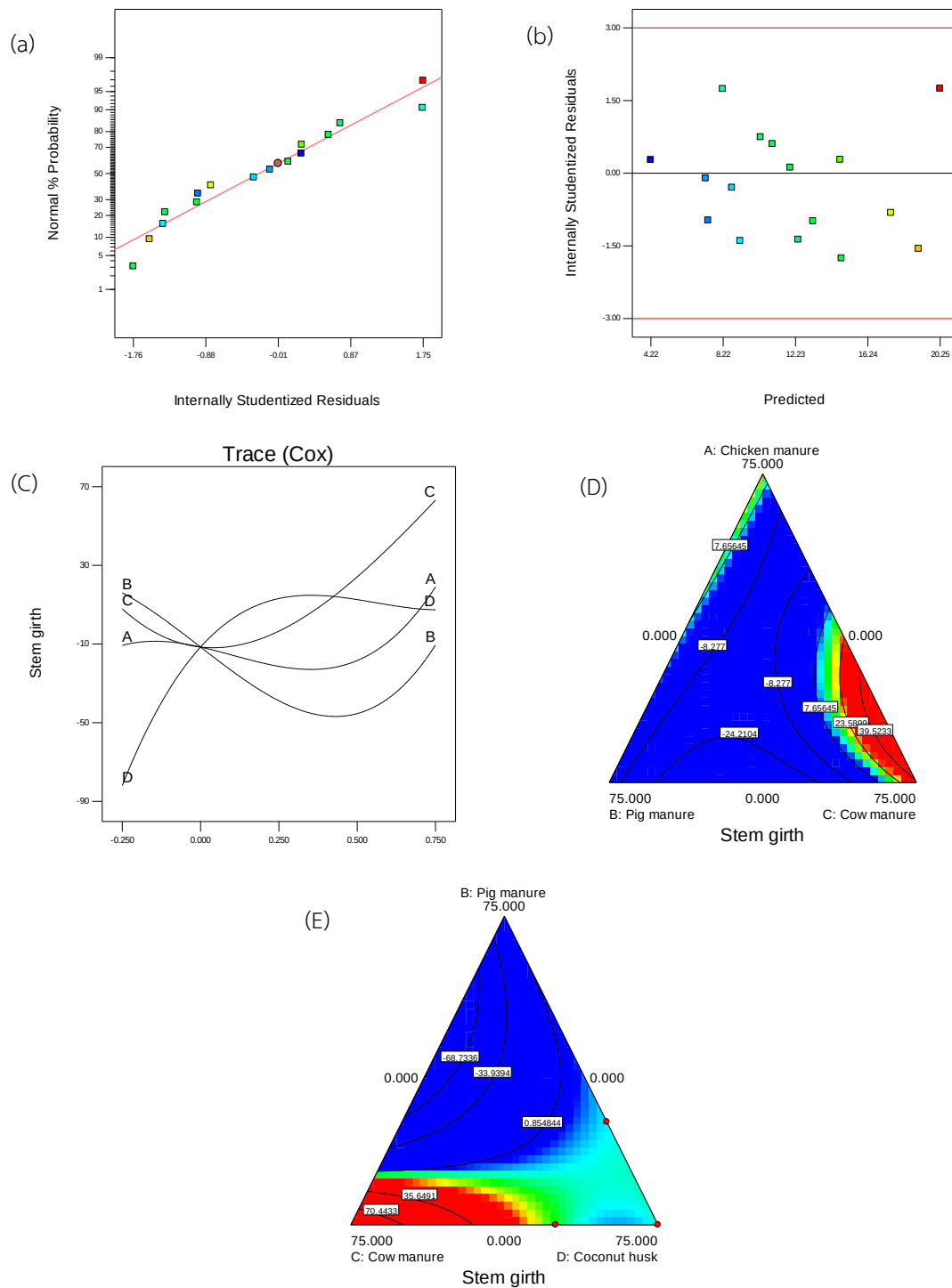


Figure 5. Random residual plot for stem diameter growth rate: (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of stem diameter growth rate (%), and (D–E) response contour plots of stem diameter growth rate.

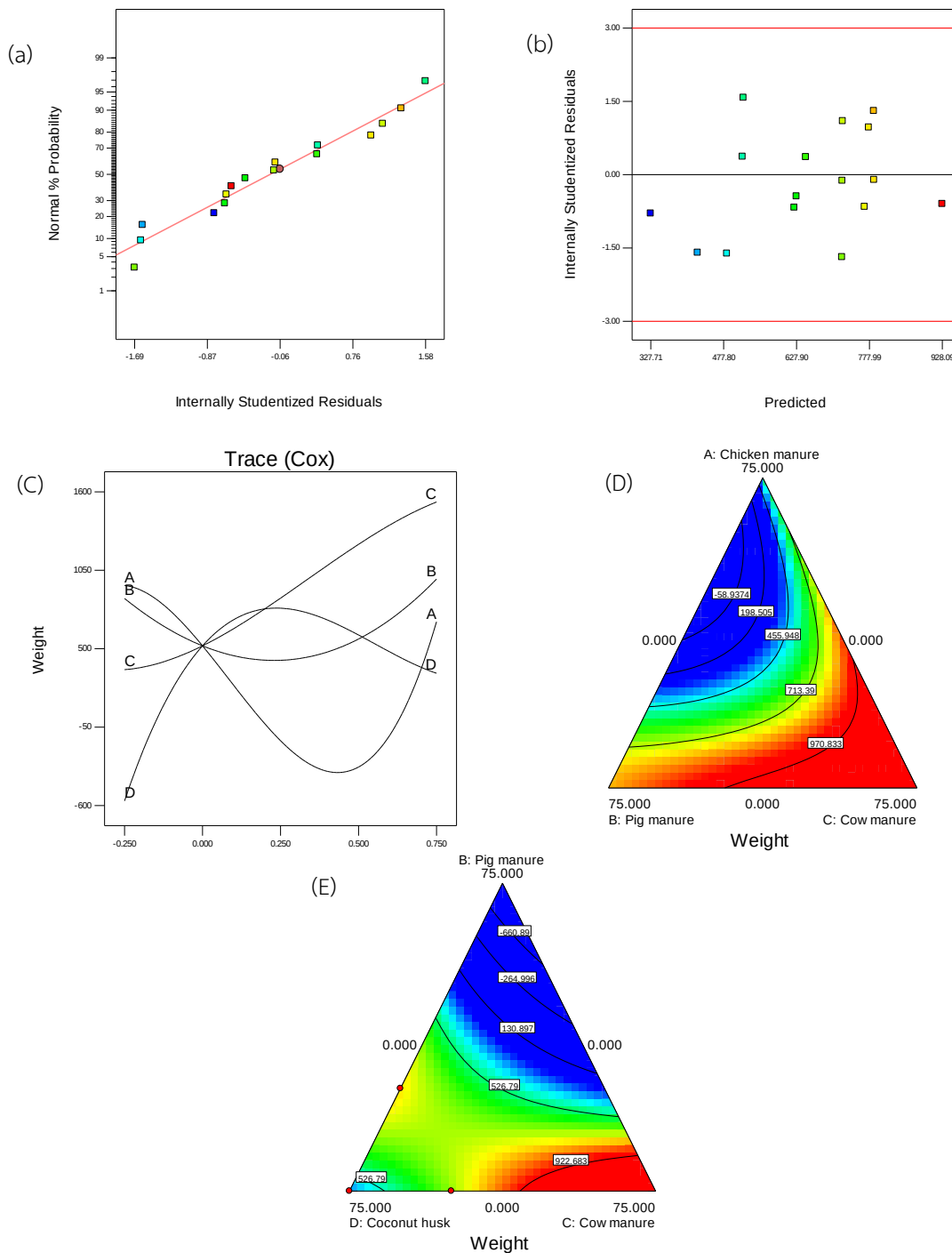


Figure 6. Random residual plot for melon fruit weight: (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of fruit weight (g), and (D–E) response contour plots of melon fruit weight.

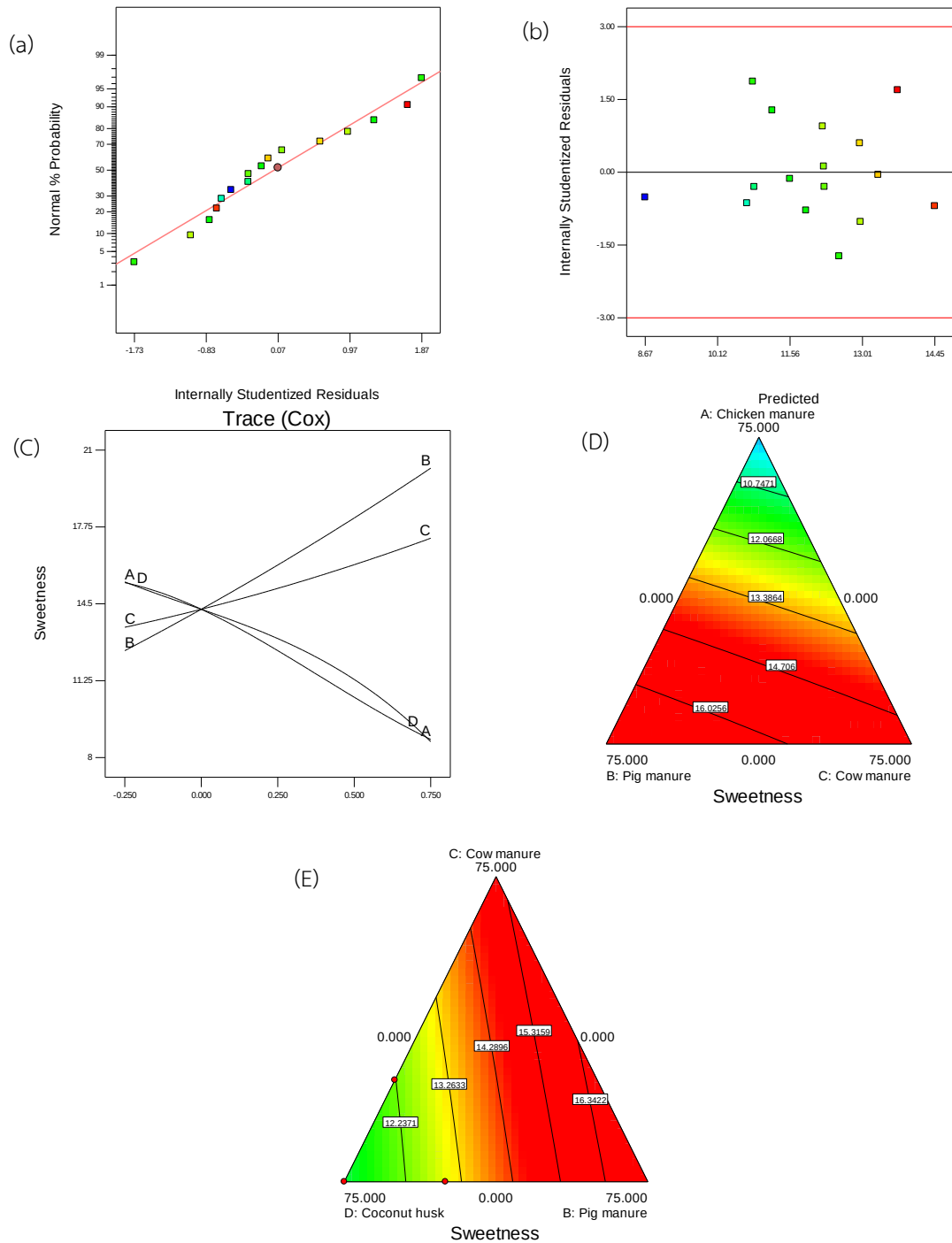


Figure 7. Random residual plot for fruit sweetness (°Brix): (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of fruit sweetness (°Brix), and (D–E) response contour plots of fruit sweetness.

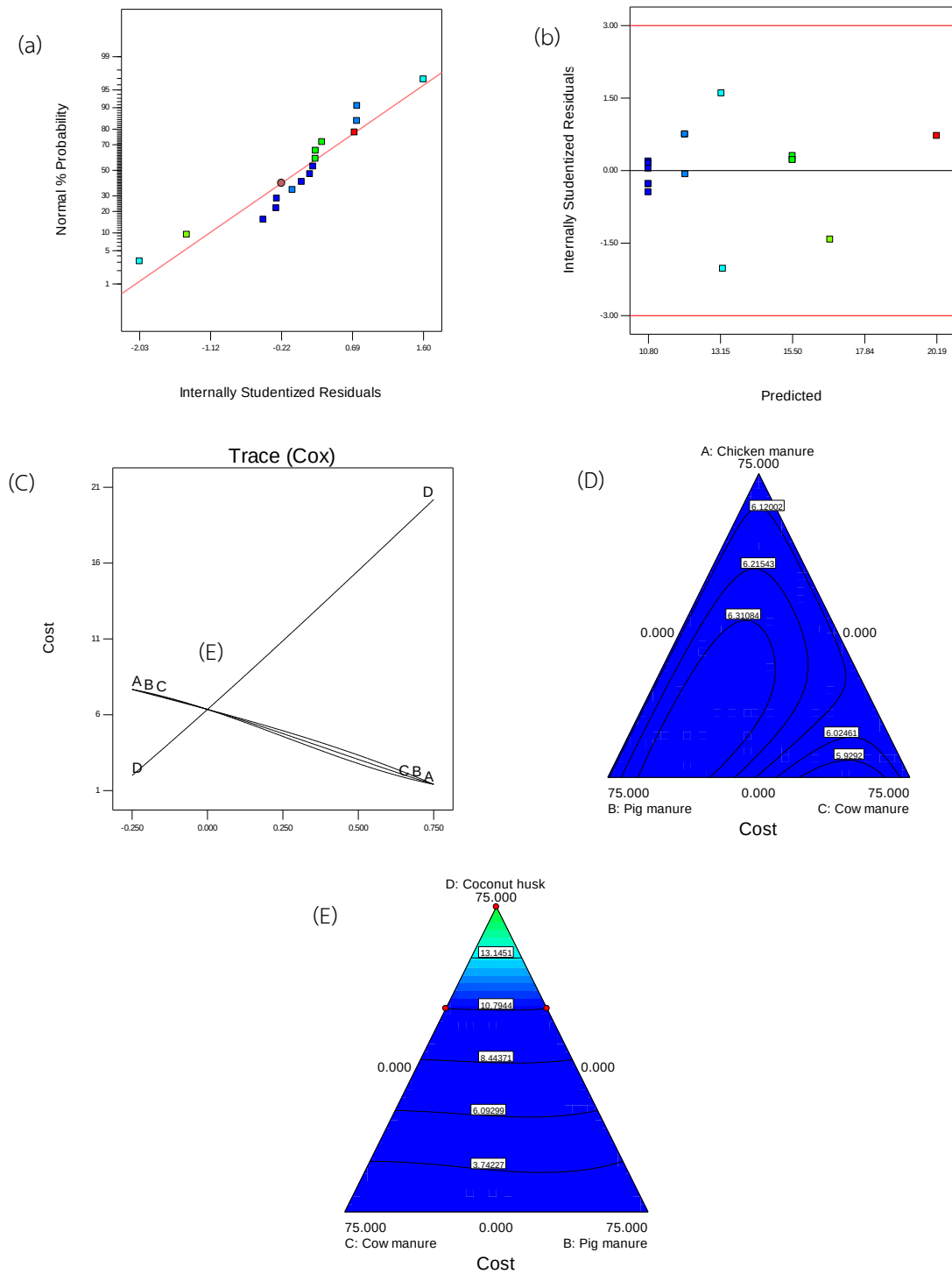


Figure 8. Random residual plot for growing media cost (THB): (A) normal probability plot of the residuals, (B) residuals versus predicted values (constant variance test), (C) trace plot of growing media cost (THB), and (D–E) response contour plots of growing media cost.

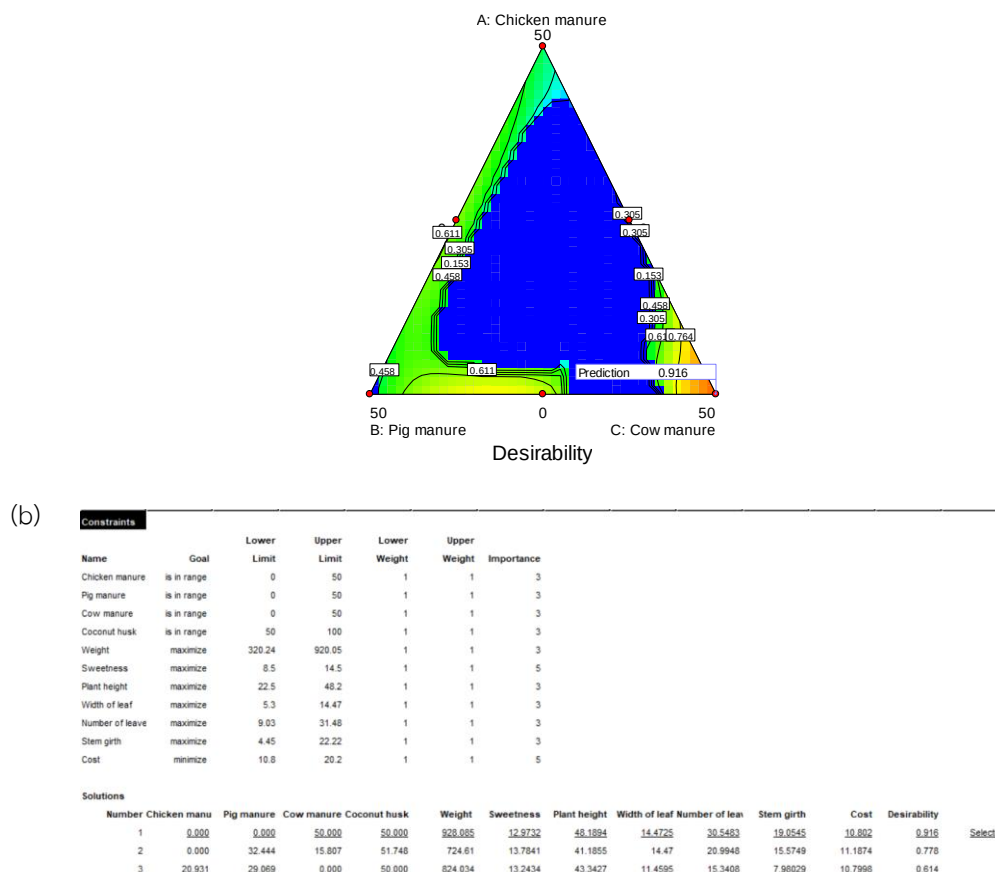


Figure 9. Optimal points of the growing media mixture: (A) overlay plot indicating the optimal region of the growing media mixture and (B) desirability function plot illustrating the optimization results.

4. Conclusions

This study demonstrates that mixture design is an effective tool for determining the optimal proportions of organic growing media to optimize the growth and yield quality of the melon cultivar Thunder Gold 1497 under greenhouse conditions. The analysis of growth responses, yield quality, and production costs showed that mixtures of different types of manure and coconut shavings significantly influenced plant responses. In particular, cattle manure played a prominent role in enhancing fruit weight, productivity, and growth stability, while pig manure positively affected the accumulation of fruit sweetness. Optimizing melon growing media using the desirability function revealed that a mixture of 50.00% cattle manure and 50.00% coconut shavings yielded the highest overall desirability (0.916). Under this optimal condition, the melon plants achieved a plant height growth rate of 48.19%, a leaf width growth rate of 14.47%, a leaf number growth rate of 30.55%, a stem diameter growth rate of 19.05%, a fruit sweetness value of 12.97 °Brix, an average fruit weight of 928.09 g, and a growing media cost of 10.80 THB per bag. This study provides a practical guideline for developing effective and sustainable organic growing media formulations for commercial melon production and can be extended to other economic crops cultivated under greenhouse systems or modern agricultural practices. Future studies should focus on the long-term effects of organic growing media on substrate properties to strengthen knowledge on sustainable management of organic growing media at the agricultural industry level.

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Towards Sustainable Electric Vehicle Charging: A Comprehensive Review of Methods, Energy Sources, Charging Technologies, Converter Configurations, and Various Optimization Strategies

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Abstract: The changeover from gasoline or petrol engines to electric vehicles (EVs) is motivated by advanced technologies that enhance EV adoption, efficiency, and accessibility. EVs address key challenges by reducing carbon emissions and dependence on fossil fuels. Some key factors, such as EV sources, EV charging methods, EV technologies, converters used in EVs for battery charging, optimization methods incorporated, battery charging times, and EV prices across different sources, should be reviewed to motivate industrialists, researchers, and investors in EVs. This study provides a comprehensive analysis of EV charging technologies, different EV Charging stations (EVCs), converters, EV charging system structures, and optimization techniques used to improve performance. Renewable energy-based EVCs utilize locally available energy resources to reduce reliance on fossil fuels. Recent advances in power converter topologies improve power quality and enable flexible AC/DC operation. EV charging methods include wireless charging, battery swapping, and pantograph systems. To meet diverse user demands, EV technologies integrate hybrid systems, fuel cells, batteries, and renewable sources. Optimization techniques enable efficient charging/discharging, grid code compliance, optimal charging station placement, coordinated multi-EV charging, and energy management. This study examines the factors influencing EVs and charging infrastructure, the challenges they face, and future directions, emphasizing the need for coordinated efforts by manufacturers, transport agencies, and governments to support sustainable, large-scale EV adoption.

Keywords: Electric vehicles; EV charging station; EV technologies; converters; optimization

1. Introduction

The exploitation of renewables and electrification may be delayed without adequate time for development; otherwise, this leads to higher CO₂ emissions and higher energy prices for consumers. The oil and gas industry's top brass know that the energy shift is underway. Refiners will be highly dependent on transportation for fuel and oil. Passenger automobiles and trade automobiles are the main contributors to the world's overall carbon footprint [1]. The transition from internal combustion engines to EVs has substantial environmental benefits, particularly in reducing emissions, improving fuel efficiency, and enhancing sustainability [2]. Advances in EV technology, renewable energy integration, and autonomous systems are driving

developments in smart grids, energy management, and battery technologies. However, inadequate charging infrastructure can increase grid stress, necessitating power systems that can manage bidirectional power exchange from decentralized renewable sources such as PV and wind energy [3].

New technologies are needed to support rapid EV development, including advanced battery expertise, faster EV adoption, and improved battery designs [4]. V2G technology lets EVs supply power back to the grid when idle, supporting grid stability and generating income for the owner [5]. Fast charging relies on smart, networked infrastructure that integrates EVs with DERs and is supported by software control, GPS, and real-time monitoring to enable efficient bidirectional power flow. To meet the growing needs of EVs, transition to renewable energy, and support the energy-intensive advancement of AI, a clean, robust, and integrated energy network is essential. One challenge with EVs is concerns about battery longevity after charging. Today, various charging connectors, interaction procedures, and pricing have emerged among producers, and charging facility suppliers are also present. This work discusses EV charging methods, EV technology, energy sources integrated into EVCS, converter topologies, and optimization techniques, and provides better guidance for selecting an EV power system.

Section II	Types of Energy sources and challenges in integration with EVs.
Section III	EV charging and its related control strategies.
Section IV	Different current EV charging methods.
Section V	EV technologies
Section VI	Optimized techniques.
Section VII	Future Research Scope.
Section VIII	Conclusion

2. Energy Sources for EV

The incorporation of large numbers of EVs will reshape distribution grid operations and structure. The growing number of electric vehicles on the streets is driving increased demand for EV charging infrastructure [6]. Solar- and wind-powered EV charging reduces greenhouse gas emissions and lowers EV life-cycle impact. Hydro, fuel cell, and biogas systems further support sustainable growth [7]. Figure 1 shows the energy resources used in EVCS. Integrating renewable energy-based DERs with EV systems reduces grid demand and carbon emissions while supporting decarbonization goals. Installing solar and wind systems at EVCSs and commercial facilities further alleviates grid stress and offers economically viable investment opportunities.

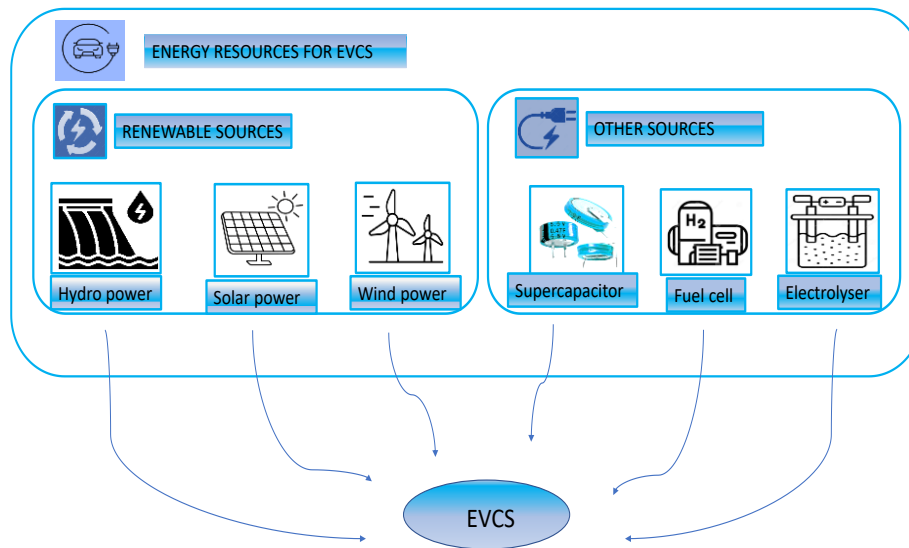


Figure 1. Energy resources for EVCS

2.1 Solar PV-powered EV

Solar-powered EVCSs are flexible and scalable for urban, remote, and off-grid use. Excess solar energy can be stored in EV batteries during peak generation, while smart energy management systems optimize charging by aligning it with periods of high solar availability. Combined with energy storage systems, solar panels enable EVCSs to operate independently as off-grid solutions [8]. Synchronization control between the PV (photovoltaic) system and the BESS is required to sustain power equilibrium [9]. Integrating low-cost robotic technologies into the maintenance routines of solar PV systems, specifically in regions prone to high dust levels, enhances the overall consistency and performance of solar PV power installations [10]. Rooftop solar installations on commercial buildings and car parks are increasingly used to directly control EVCSs in some countries with targets for sustainable energy performance [11].

2.2 Wind energy-powered EV

Wind power is vital for EV infrastructure, especially in regions with consistent wind resources. Both onshore and offshore wind farms can generate large amounts of clean electricity, which can be integrated with EV charging networks. Integrating EVs into power systems, with wind influence, is well-suited to establishing supplementary facilities. In some countries, wind energy contributes meaningfully to regulating EV charging hubs along main highways, and integrating wind energy with smart grids allows real-time adjustments to ensure optimal EV charging without overburdening the grid [12]. The scalability of wind energy makes it a model for large-scale backup EV charging, with supercharging networks for a wide variety of EVs.

2.3 Hydropower in EV setup

Countries with ample water resources have harnessed hydropower to address EV energy challenges efficiently. Hydropower plants provide a constant energy output, making them ideal for baseload EVCSs. In countries like Norway, where nearly 100% of energy comes from hydropower, EVs are almost entirely powered by renewable sources. Additional sources, such as fuel cells, electrolyzers, and supercapacitors, are used to maintain an EV-centered focus on availability and accessibility [13].

2.4 Energy management and challenges in incorporating renewable energy into EV charging stations

Smart charging is the intelligent, data-driven management of EV charging that fully integrates RE resources into EV stations [14]. It uses sophisticated technologies, real-time data, and statistical analytics to optimize EV charging. Smart, data-driven charging systems optimize EV charging by considering renewable availability, grid demand, electricity prices, and user preferences. Using real-time monitoring and analytics, they ensure EVs charge with clean energy whenever possible, reducing carbon emissions and easing grid

stress during peak hours. An EV can serve as an adaptable load or storage resource, with its battery charging and discharging capabilities feeding power to the grid and supporting the V2G concept economically [15]. The growth of wind and solar PV increases grid instability due to their intermittent output, making energy storage systems—particularly lithium-ion batteries—essential for storing excess energy and ensuring reliable EV charging. However, shifting existing EV charging infrastructure to renewable sources requires significant investment [16]. Despite these challenges, advances in energy storage and grid management are gradually addressing them, paving the way for cleaner and more consistent EV arrangements [17]. Table I shows the energy sources used in EVCS and their different modes of operation.

Table 1. Energy sources used in EVCS

Ref No.	Solar PV	Windmill	BESS	Islanded/Grid connected	Other sources	AC bus/DC bus	THD/Metrics	Year
[18]	✓	×	✓	both	×	DC bus	Performance efficiency of 68.90%.	2024
[19]	×	×	✓	Islanded	Super capacitor	DC bus		2024
[20]	✓	✓	×	Grid connected	Diesel generator	AC bus		2024
[21]	✓	×	✓	Grid connected	Fuel cell	DC bus	2.159%	2023
[22]	×	×	×	Grid connected	×	AC bus/DC bus		2020
[23]	✓	×	✓	Islanded	×	DC	Cost effective	2024
[24]	✓	×	×	both	×	DC bus	2.88%	2021
[25]	✓	×	×	both	×	AC /DC bus		2023
[26]	✓	✓	×	islanded	Electrolyzer and fuel cell	×		2023
[27]	✓	×	✓	both	×	DC bus	<5%	2021
[28]	✓	×	✓	both	×	DC bus/AC bus	Standalone-3.83%; Grid-connected-1.54%	2018
[29]	✓	×	✓	both	×	DC bus		2025
[30]	✓	×	✓	both	Diesel Generator	DC bus/AC bus	<5%	2024
[31]	✓	✓	✓	Islanded	Fuel cell	AC /DC bus	Renewable Energy Fraction is 97.95%	2024
[32]	✓	✓	×	Grid connected	Fuel cell	AC bus/DC bus		2025

✓ - used × - Not used

From Table 1 above, the following statements are suggested.

➤ Solar energy is the primary source for EV charging due to its wide availability, followed by wind and hydropower, which can serve as supplementary and base-load sources. Emerging technologies such as fuel cells, supercapacitors, and electrolyzers remain in development. Distributed energy systems may integrate multiple renewable sources with grid and DG support to ensure reliable EV operation during periods of renewable intermittency. Battery energy storage systems are essential for enhancing reliability and preventing supply interruptions, with appropriate sizing of DG, storage, and grid support based on a local renewable resource assessment for EVCS deployment.

➤ Studies indicate that solar PV combined with battery energy storage provides a reliable, cost-effective, and uninterrupted standalone power supply for EVs in regions with high solar irradiance. PV-based charging stations also help reduce grid loading and lower operational costs. When solar and battery resources are insufficient, grid and DG systems help meet EV demand. Without solar input, BES supplies power for charging, reducing grid dependence while exporting excess energy to the grid. Solar-fed EV systems with battery storage can operate in standalone or grid-connected modes [33-37]. Standalone systems use PV and batteries for charging, while grid-connected systems ensure sinusoidal currents to maintain power quality and avoid grid disturbances.

➤ Reliability and financial feasibility are key considerations in designing PV-powered EVCSs. Studies show that integrating BESS improves cost-effectiveness, particularly at higher reliability levels and in islanded (off-grid) operation.

The best approach to EV charging in major areas is grid-centered renewable energy substations. PV-based charging stations with BES have improved power quality for the following reasons.

- Possible to control EVCS in numerous dynamic situations.
- A novel method can be introduced to retain surplus power in the hybrid charging station, switch the energy levels in the energy storage system, and achieve a financial advantage by offering energy to the local grid.
- The grid-connected hybrid system is desired because it reduces the impact of irregularity, as repeatedly monitored through the use of renewable sources.

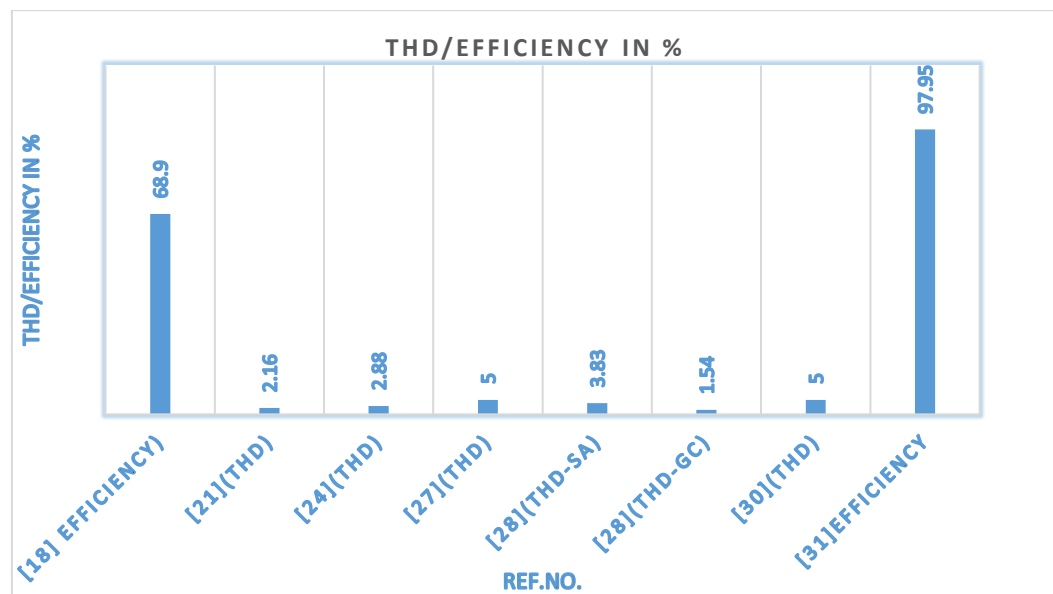


Figure 2. Comparison of THD/Efficiency in Energy Sources of EVCS

Figure 2, derived from Table 1, indicates that grid-connected RES achieves superior power quality, with THD values below 2%. In contrast, islanded systems demonstrate higher efficiency and enable more effective use of available renewable energy. Several important aspects are not included in the research, such as other renewable energy sources, energy management and optimization strategies, smart grid interactions, economic and environmental analyses, reliability under varying conditions, and infrastructure and policy considerations. Future work will be extended to support their effective integration and practical implementation.

3. EV charging methods

These are broadly classified into conductive charging, wireless charging, and battery swapping station (BSS) methods. Figure 3 shows the different EV-charging methods available.

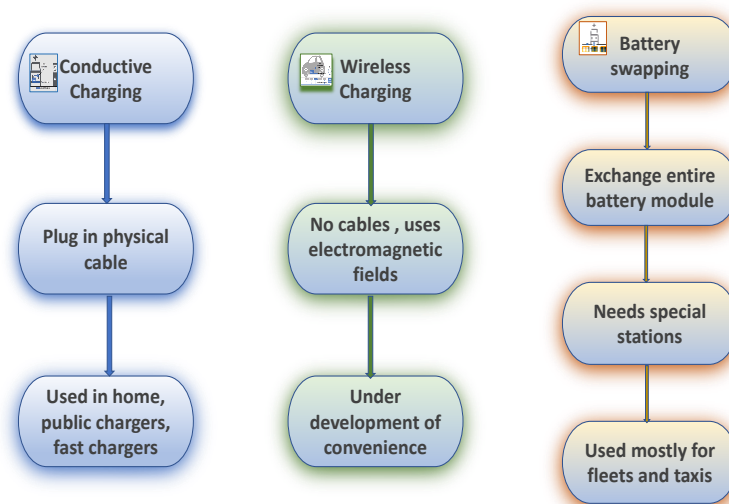


Figure 3. EV charging methods

This section discusses EV charging methods. This section discusses the decisions and recommendations under the strongest circumstances and emphasizes future research directions.

3.1. Conductive charging

EV charging systems are classified as onboard (AC) and offboard (DC) chargers and further categorized by charging speed as Level 1, Level 2, and Level 3. Level 1 charging is slow, typically adding 3.5–6.5 miles of range per hour, and is mainly used as an alternative or backup option. Level 2 chargers operate at 220–240 V and can fully charge an EV with a 300-mile range in approximately 6–8 hours, making them suitable for domestic and commercial applications. Level-3 charging, also known as DC fast or rapid charging, delivers high power and is ideal for locations such as highways, gas stations, and rest stops where quick charging is required.

For rapid charging, the onboard charger can be bypassed, and the energy does not reduce its charging capacity. The onboard charger is suitable for light Plug-in EVs with a small, economical charging system. EV charging occurs via an AC bus supplied by the Grid/DG or by converted AC power from renewable energy sources. Integrating EVs and Energy Storage Systems (ESS) with Renewable Energy Resources (RERs) can mitigate the irregular fluctuations in the electrical power produced by RERs. However, installing charging stations often requires significant investment. If a DC charging station is used and the EV is treated as an ESS, this results in Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) transitions, enabling an economically efficient system. Onboard charging is used when the DG/grid is connected. Offboard charging is used when connected to solar PV/energy storage. If, at a time, the AC and DC ports are used in an EV, it can be charged using the AC grid/DG for the AC port and solar PV/wind/hydro power for the DC port. Off-board EV charging enables fast charging and fast dynamic response. In a grid-connected EVCS, if the grid fails to synchronize, the DC CS

operates autonomously, and the solar PV source also controls the EV battery. Charger selection depends on factors such as potential needs, charging frequency, economic considerations, and whether portability or fast charging is important.

3.2 Wireless charging

In wireless EV charging, the primary coil is placed on the road surface, and the secondary coil is mounted in the vehicle. Charging occurs when the vehicle is parked above the system, enabling high-frequency power transfer. Wireless charging is classified into near-field, medium-field, and far-field methods, including inductive, resonant, capacitive, magnetic gear, and emerging microwave, radio-wave, and laser-based techniques. Wireless inductive and capacitive power transfer is less efficient than wired networks. A hybrid wireless power transfer system improves efficiency and reduces current stress by employing S-LCC/SP compensation with constant-current and constant-voltage control for PV-based EV charging. In dynamic wireless charging methods, EVs are in motion, and the mounted power track beneath the lane poses a substantial concern for financial feasibility. Wireless charging is suitable for locations such as taxi stands and bus stations, where vehicles often wait for passengers.

3.3 Battery Swapping Station

Battery swapping allows EVs to quickly replace depleted batteries with fully charged ones, avoiding the need to wait for recharging. Combined charging and swapping stations help reduce the impact of e-mobility on the power grid [38]. BSS can play a key role in accelerating EV adoption by offering a faster, more consistent, and environmentally friendly alternative. One paper presents an optimization framework for organizing a battery-swapping station to improve efficiency and sustainability in EV infrastructure [39]. Several studies have examined BSS operations, addressing charging scheduling, facility policies, system architecture, communication and control, and power system integration. These works consider perspectives such as BSS types, decision-making strategies, EV categories, battery standardization, V2G capability, clustering, and operational models [40]. Key challenges in future EV systems include optimal battery sizing, system configuration, high BSS investment costs, and battery protection. Integrating optimized charging strategies with PV systems can reduce energy costs by up to 27.63%. Improved battery-swapping schemes further minimize operating costs and enhance usability at electric bus battery-swapping stations [41]. Another study proposes a framework for optimally placing BSS in smart microgrids with distributed energy resources, considering reliability, power quality, and economic factors, including production and operational costs [42].

BSS shows promise as an effective EV charging solution, but challenges such as stability, interoperability, and user acceptance remain. Research insights guide policymakers, industry, and researchers in developing and implementing BSS. Table 2 reviews different EV charging methods and their remarks.

Table 2. EV charging methods

Ref.	Year	Conductive charging (onboard / offboard)	Wireless charging	Battery swapping	Remarks and suggestions	Metrics
[35]	2021	Offboard/onboard	×	×	This system supports both AC and DC charging using solar PV or grid power. The CAPSA algorithm optimizes EV current.	Standalone EV power- 2.01kW Grid connected EV power - 2.359kW

Table 2. EV charging methods (continue)

Ref.	Year	Conductive charging (onboard / offboard)	Wireless charging	Battery swapping	Remarks and suggestions	Metrics
[36]	2022	Onboard	×	×	With an intelligent control management system, optimum EVCS operation is attained.	Optimized battery SOC between 0.3 and 1.
[43]	2024	✓	✓	×	Compared with wired power transmission, standard Wireless power transfer designs typically have lower transfer efficiency but offer greater adaptability.	Transfer efficiency can reach 98% for a given coupling coefficient.
[44]	2023	Offboard	×	×	With supervisory control and a Z-source converter, the fast-charging EV charger proves to be an economically feasible system compared to a grid-based system.	economic benefit for F-SCS is 166.1 € and REF-SCS is -6.65€.
[45]	2023	Onboard	×	×	Robust and single-input adaptive fuzzy logic-tuned Perturb and Observe process and multi-layer, multi-order generalized discrete integrator-based adaptive Control of EV charging takes place through an AC bus supplied by solar PV.	Tracking time is 5 ms. Dynamic efficiency is more than 99%. The dynamic response is faster.
[46]	2023	On board	×	×	This work presents an effective structure for light Plug-in EVs at an economical cost.	The cost of the proposed converter is \$ 178.6.
[47]	2024	Offboard/onboard	×	×	AC and DC ports in an EV can be charged using the AC grid and solar PV, respectively, to reduce charging time.	EV charging time is reduced by 50%.
[48]	2024	Onboard	×	HV and LV battery	This EVCS offers multiple modes, such as V2G, G2V, and HV-to-LV battery, achieving high power density and efficiency.	Maximum efficiency is 98.2% across all modes.
[49]	2024	Offboard	×	×	The dual-control method is used across different operating modes to improve power quality.	THD is 2.008%

Table 2. EV charging methods (continue)

Ref.	Year	Conductive charging (onboard / offboard)	Wireless charging	Battery swapping	Remarks and suggestions	Metrics
[50]	2026	✗	Series-series compensated wireless	✗	It improves energy extraction from solar PV across different modes, such as solar-only, grid-only, and hybrid.	Maintains the 240 V, 32 A output for different modes.
[51]	2025	✗	Dynamic wireless charging (DWC)	✗	A solar PV-integrated DWC system effectively mitigates the highest power demand on the grid.	Peak power demand on the electrical grid is lowered by 18.7 %.

✓ - used ✗ - Not used

Based on Table 2 above, wired charging is more efficient than wireless charging. But wireless chargers are important for dynamic wireless charging systems when the vehicle is in motion. By employing compensation techniques, wireless charging efficiency can be improved. In the wired charging method, the following points are concluded from Table 2:

- a) When DG or grid-connected EVs are used, then onboard charging is preferable. For a solar PV/energy storage facility in a power system, an off-board charger is preferable with optimized converter technologies.
- b) When the EV system rating is high, off-board charging is preferable and also leads to higher installation costs.
- c) The onboard charger provides slower charging than off-board charging.
- d) Onboard chargers are suitable for light plug-in vehicles.
- e) For V2G, G2V technology can be implemented more easily in onboard charging because of recent advancements in converter topologies and intelligent control of power systems.

BSS is an emerging technology, with research focusing on financial models, battery scheduling to meet EV demand, and the standardization of battery size and type. Conductive charging also offers potential to improve supply quality and viability for both users and providers.

Current work is fragmented, focusing on isolated components (e.g., converters, control methods, or efficiency improvements) rather than the end-to-end ecosystem. Integrated planning that combines energy sources, intelligent control, user demand behavior, grid interaction, and long-term sustainability is underemphasized. As a result, real-world deployability, interoperability, and large-scale optimization of EV charging networks remain insufficiently addressed in the above research works.

4. EV Technology

EV technology is rapidly evolving, and these vehicles are becoming more mainstream as governments, automakers, and consumers push for cleaner, greener transportation options. These vehicle technologies are divided into 4 major techniques [52].

4.1 Battery Electric Vehicles (BEVs)

As the acceptance of battery EVs rises to the forefront of mainstream transportation systems, their implications for achieving Sustainable Development Goal 13 for climate action become increasingly meaningful [53]. BEVs run solely on electricity stored in onboard batteries, producing near-zero emissions. Powered by large lithium-ion packs, they charge via home or public stations. Examples include the Rivian

R1T, Chevrolet Bolt EV, Nissan Leaf, and Tesla Model 3. Advantages include zero tailpipe emissions, Lower operating costs, Quiet operation, and government incentives for purchasing BEVs [54].

4.2 Hybrid Electric Vehicles(HEVs)

HEVs join an internal combustion engine (ICE) with an electric motor and a small battery. HEVs rely on regenerative braking and ICEs to charge the battery, and are not plug-in. The battery is typically smaller than in BEVs because it is recharged via regenerative braking and engine power. Examples of HEVs include the Toyota Prius, Ford Escape-Hybrid, Honda Insight, and Lexus RX Hybrid. Advantages include better fuel efficiency than conventional gasoline cars, no need for charging infrastructure, and generally lower emissions [55].

4.3 Plug-in Hybrid Electric Vehicles(PHEVs)

PHEVs are hybrids with larger batteries that can be boosted at a charging station or at home. They can drive short distances on electric power alone and switch to the internal combustion engine when the battery is low. With proper energy management techniques, a PHEV can be designed to improve performance [56-57]. Examples include the Toyota Prius Prime, Mitsubishi Outlander PHEV, and Chevrolet Volt. Advantages include a longer electric-only range than standard HEVs, the ability to drive in electric-only mode for short trips, reduced fuel consumption, and greater flexibility.

4.4 Fuel Cell Electric Vehicles (FCEVs)

FCEVs are another type of EV that do not rely on a battery to store electrical energy. FCEVs produce electricity via a chemical reaction in a hydrogen fuel cell, producing water and heat as byproducts. Hydrogen is stored in high-pressure tanks and reacts with oxygen to power the vehicle [58]. FCEVs use electricity from the fuel cell to power the motors and emit only water vapor. They offer zero emissions, fast refueling, and long range, but cost more than BEVs or ICE vehicles because of limited hydrogen refueling stations and complex production processes [59]. Fuel cells are more efficient than ICEs but generally less efficient than BEVs. Examples of FCEVs include the Hyundai Nexo, the Toyota Mirai, and the Honda Clarity Fuel Cell. Table 3 compares components, features, and challenges of various EV technologies.

Table 3. Different EV Technologies with their components, features, problems, and challenges

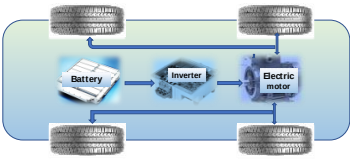
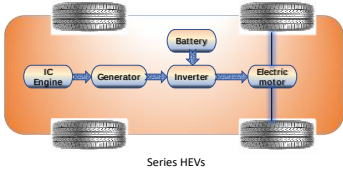
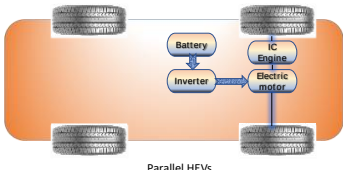
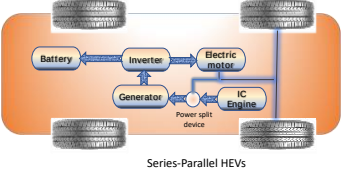
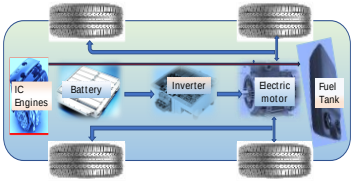
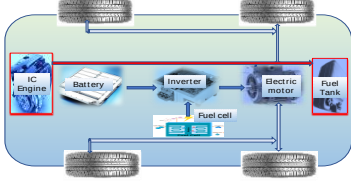
EV Technology	Components	Features	Problems	Challenges
BEVs		Zero emissions. Independent of oil. Economical. Low repairs. Diminished noise pollution. Simple driving.	Limited driving range and speed, long recharge time, and high cost.	Limited range, longer charging times, and uneven availability of charging infrastructure.

Table 3. Different EV Technologies with their components, features, problems, and challenges (continue)

EV Technology	Components	Features	Problems	Challenges
HEVs	 Series HEVs  Parallel HEVs  Series-Parallel HEVs	Environmentally friendly, regenerative braking, electric motor support, smaller engines, and higher resale value.	Less power. Expensive. Poor handling. Battery replacement is costly.	Still relies on gasoline, has complex powertrains that increase maintenance costs, and offers a limited electric-only range.
PHEVs		Zero emissions, efficient in traffic, smooth operation, fewer fuel cells, and tax benefits.	Relatively expensive, complex maintenance, battery life concerns, and uncertain resale value.	Higher upfront cost, still uses gasoline (not fully emissions-free), and depends on charging access for electric range.
FCEVs		Renewable, widely available, supports zero-carbon, zero-emission, efficient operation, and enables rapid refueling.	High costs due to hydrogen production, fuel cell investment, and the challenges of hydrogen storage and transport.	Limited hydrogen refueling stations, costly sustainable hydrogen production, and expensive fuel cell technology.

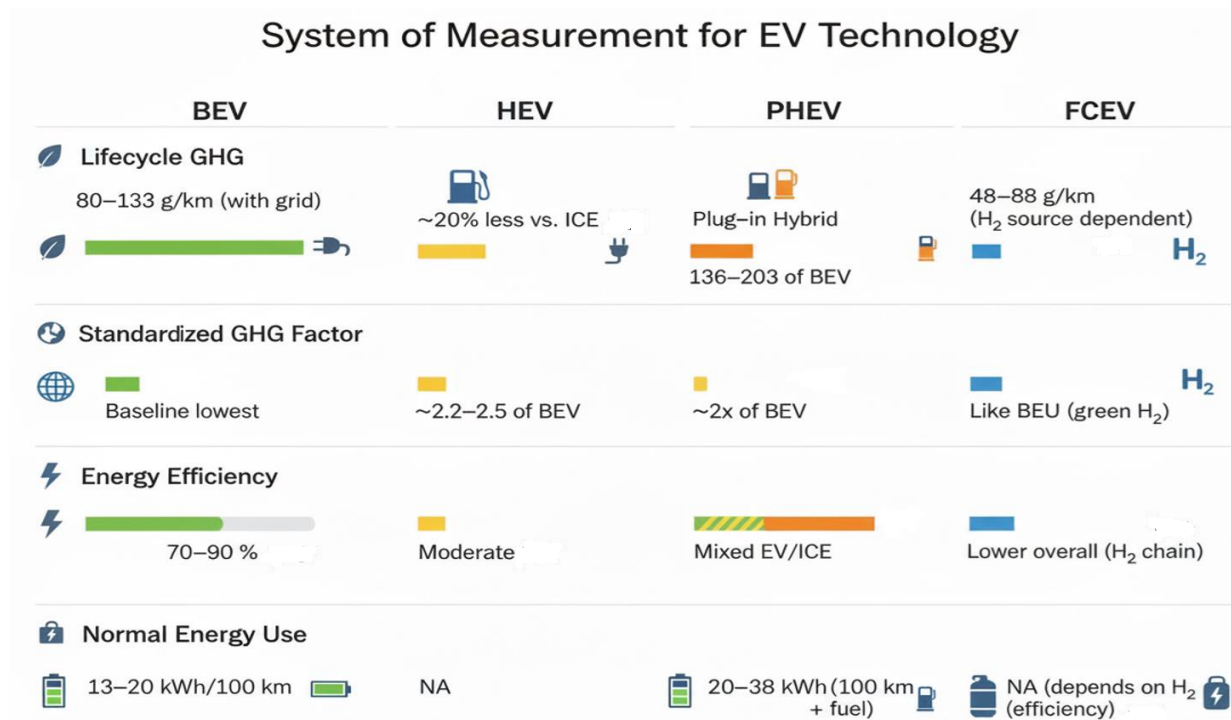


Figure 4. Comparison of different types of EV technology -system of measurement [60-63]

Figure 4. provides a comparative analysis of various EV technologies across key performance parameters. The choice of technology depends on use, infrastructure, cost, and environmental goals. BHEVs suit urban drivers who need daily electric use and combustion backup for long trips. BEVs are ideal for efficient driving in areas with limited charging infrastructure. FCEVs are well-suited to long-distance or heavy-duty applications, offering quick refueling at locations with hydrogen infrastructure. Current studies largely focus on individual technologies in isolation, with limited emphasis on integrated energy systems, interoperability, and cross-platform optimization. Furthermore, issues such as lifecycle sustainability, large-scale deployment feasibility, and dependence on charging or hydrogen infrastructure remain to be addressed.

5. Converters used in EVs

In EVCs, converters are critical components that enable smooth, efficient power transfer from the grid or non-conventional energy sources to the EV battery. These converters transform and regulate electrical power from the power source into the appropriate form for EV charging. Various types of converters are commonly used in EVCs [64].

5.1 AC - DC Converters (Rectifiers)

DC power supplies EV batteries, while charging stations typically supply AC from the grid. For Level-1 and Level-2 charging, an on-board charger is preferable, where converters in the vehicle supply the battery with DC power. In DC fast chargers (Level 3), the AC taken from the grid is first changed to DC outside the vehicle, meaning off-board chargers.

5.2 DC - DC Converters

A DC-to-DC converter regulates DC power flow within the charging system. In some DC fast chargers, a DC-to-DC converter is used to regulate the charging current to the vehicle's battery, ensuring the correct voltage and current are applied for efficient and safe charging [65].

5.3 Bidirectional Converters (V2G/G2V)

Bidirectional converters enable a two-way flow of electricity. While standard chargers only provide electricity to charge the vehicle, bidirectional charging allows the vehicle to send energy back to the grid, creating a V2G system. In bidirectional charging systems, the EV not only receives power but also returns

saved energy to the grid. This helps stabilize the grid and reduce THD, particularly during high-demand periods or when renewable energy sources are intermittent [66].

5.4 AC to AC Converters

AC-to-AC converters are used in charging stations that need to interface with certain industrial or specialized EVs at specific voltages and frequencies. Some AC-AC converters are used in wireless (inductive) charging systems, where AC is converted to a different frequency for wireless power transmission [67]. When wind energy is used to charge EVs, these converters must transfer power at a specified level. Converters play a dynamic role in EVCSs by transforming and regulating electrical energy, ensuring safe and efficient charging, from basic AC-to-DC converters for Level-1 or Level-2 charging to advanced DC-DC converters for fast and bidirectional charging systems. These components are needed to ensure smooth, reliable charging. As the EV market grows, advancements in converter technology will continue to support faster, more efficient, and more versatile charging options [68]. The choice of power electronics converters in popular EVs depends on factors that affect the vehicle's efficiency, performance, compatibility with the power grid, design, charging infrastructure, and energy management requirements. Table 4 lists the converters used on the grid, RES, and battery storage sides, along with their purposes.

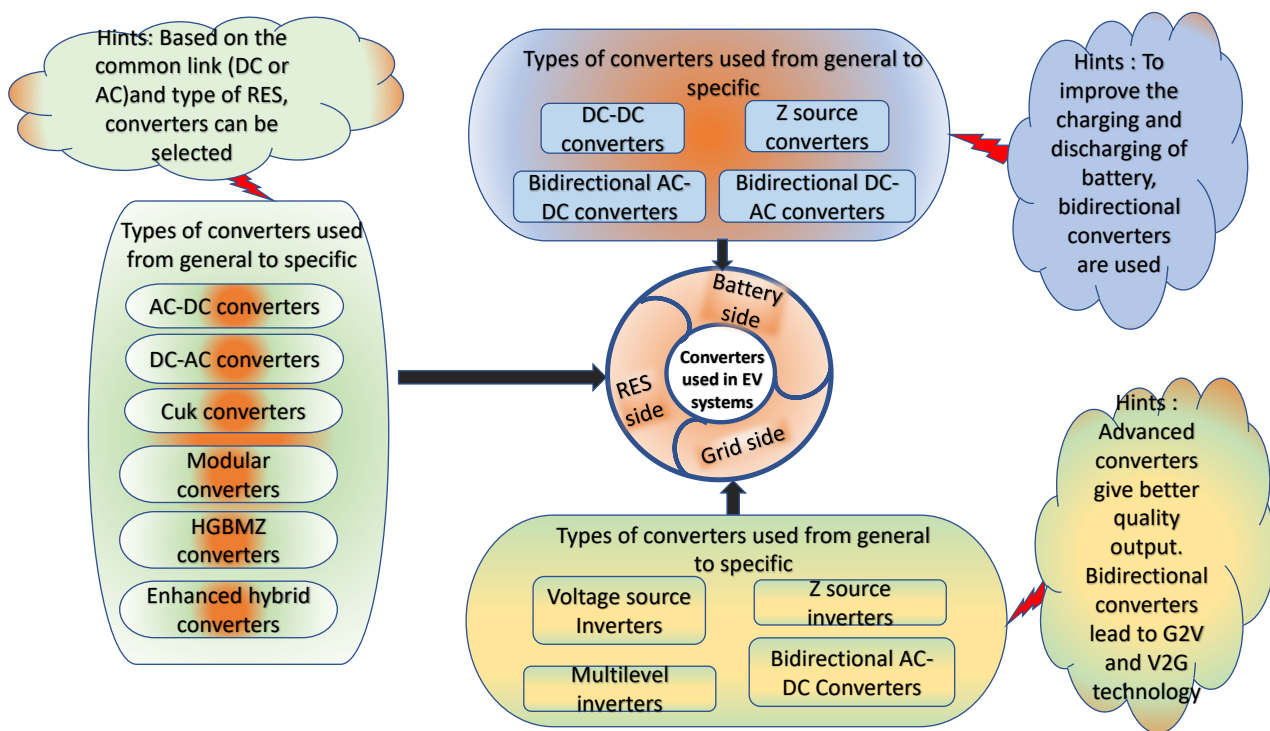


Figure 5. Converters used in EV systems [from Table 4]

Figure 5 summarizes the types of converters used on the grid, RES, and battery sides, and also suggests selecting a better converter from Table 4 below. Current research has limited capability for seamless multi-port, bidirectional power flow among renewables, storage, EVs, and the grid under dynamic conditions. In addition, long-term reliability, thermal management, switching losses, real-time adaptive control, and interoperability standards need improvement for large-scale deployment.

Table 4. Converters used in the Grid, RES, and Batteries side

Ref	Year	Converters used in the grid	Converters used in RES/hybrid sources	Converters used in a battery storage system	Purpose of the converter	Metrics
[33]	2023	VSC (Bi-directional)	DC-to-DC converter	DC-DC converter	Power exchange among the solar PV array, BES, EV, and grid is achieved.	The DC link voltage is maintained at 500 V.
[37]	2020	Bidirectional AC-DC converter	Bidirectional AC-DC converter	Bidirectional AC-DC converter	Solar PV, a boost converter, and battery storage are coupled to the DC side of the AC-DC converter that supplies EV2, while the DG and grid are connected to the AC side of the VSC that supplies EV1.	In GCM mode, the current THD is 4.1%, and in DG mode, it is 1.7%.
[69]	2021	VSC	Boost converter	-	VSC output is well balanced with respect to grid voltage.	Grid voltages at balanced conditions are 213.37V, 217.31V, and 215V, and grid currents are 5.512A, 5.692A, and 5.609A.
[70]	2022	Seven-level CHBDC MLI	Diode-based converter	Bidirectional DC-DC converter	To improve voltage quality, reduce converter dimensions, and control the charging and discharging of both the storage capacity and EV batteries.	Power from PV is 4.86 kW; EV takes 1.6801 kW; storage is 1.052 kW; 1.9298 kW to the grid. THD is less than 5%.

Ref	Year	Converters used in the grid	Converters used in RES/hybrid sources	Converters used in a battery storage system	Purpose of the converter	Metrics
[71]	2022	Open DC modular multilevel converter	Open DC modular multilevel converter	-	To prefer fewer devices and greater reliability.	The total number of devices has decreased to half. (=36 devices)
[72]	2023	VSC converter	Bidirectional converter	-	Used for EV charging or discharging.	THD is 3.3%, and settling time is 20ms, compared to the papers discussed.
[73]	2024	-	DC -DC converter	DC -DC converter	A high-frequency inverter is used after the DC bus on the transmitting side of wireless power transfer, and a diode rectifier is used on the receiving side.	Power is transferred across a 100-200 mm air gap.
[74]	2021	VSC	modular converters	DC/DC stage converter	To achieve maximum power levels and obtain a fixed DC link voltage.	Stack efficiency is above 50 %.
[75]	2023	VSI	HGBMZ converter	-	It is designed to enhance PV system efficiency by boosting voltage levels and enabling V2G.	Converter efficiency is 93.04%
[76]	2025	Bidirectional converter	Bidirectional converter	Bidirectional converter	Best converter choices and designs for EV applications.	Voltage stress, current stress, voltage-gain range, conversion efficiency, power density, and switching frequency are improved.

6. Optimization methods in EV

Optimization in Electrical systems is essential for improving the efficiency, sustainability, and consistency of energy generation, storage, and consumption [66]. Advanced algorithms and supervised methods optimize power flow between the grid, renewables, storage, and EVs efficiently and cost-effectively, using optimization techniques across RES, EVCS, V2G integration, smart grids, and controllers.

6.1 Essentials of optimization in Energy sources of EV systems:

Some key areas of optimization in Renewables-connected EV applications include maximizing energy efficiency, enhancing grid stability, minimizing costs, increasing the lifetime of energy systems, and supporting V2G operations based on the grid's actual time requirements and the battery's SoC. Battery Storage Regulator optimization in both EVs and the energy system can store excess renewable energy and release it when renewable generation is low or grid demand is elevated [77-78]. In most works, solar PV output is optimized using various methods to extract more energy. ANFIS-based control supports grid management, while fuzzy optimization minimizes EV charging costs under power and renewable constraints. In DES-based EV systems, mixed-integer quadratic optimization and Markov Decision Processes optimize energy flow among the DES, battery, load, and grid. In contrast, battery-side optimization enhances DWC revenue and reduces grid impact.

6.2 Essentials of Optimization in EVCS:

In the EVCS, optimization techniques control charging infrastructure and charging management, such as dynamic pricing and load balancing. Accurate forecasting of solar and wind generation, charging demand, and electricity prices enables optimal evaluation and achieves the energy remit [79-80]. The proposed design algorithm determines the required number of EVCSs, thereby increasing the system's operator reward. The PSO Optimization method used here fully estimates the modifying interdependencies and the values of financial and dependability indicators for the standalone hybrid energy power systems.

6.3 Multi-Objective Optimization and Advanced Optimization Techniques in EVs:

Multi-objective optimization simultaneously achieves goals such as reducing costs, maximizing renewable energy use, minimizing battery degradation, and enhancing grid stability, for optimal siting and sizing of EVCSs with PV and energy storage systems. Multi-objective optimization is used to reduce electricity costs and radiation contamination [81]. Advanced optimization techniques, including energy management strategies, smart grid integration, multi-objective optimization, and AI-based algorithms, enhance the efficiency, reliability, and sustainability of DES. Comparative studies show that optimally designed standalone hybrid charging stations offer a cost-effective, eco-friendly alternative to grid extension. Moreover, decentralized optimization and IoT-enabled real-time data collection enable dynamic energy management across smart grids and EVCSs [82].

6.4 Different optimization algorithms and models:

Mathematical models and optimization algorithms include linear programming, Dynamic Programming, mixed-integer linear programming, Stochastic Optimization, Genetic Algorithms (GA), and Artificial Intelligence. Optimization in distributed energy systems for EVs improves energy efficiency, reduces costs, and enhances overall performance and sustainability [83]. The CAPSA algorithm optimizes EV current and power quality, while ANC-based control enhances power exchange, DG loading, and power factor. A fuzzy-tuned P&O and MMGDI AC controller regulates the boost converter and grid-tied inverter, whereas the Whale Optimization Algorithm improves renewable integration. Additionally, a two-stage robust optimization model minimizes 24-hour operational costs associated with energy losses, power transactions, DG control, and battery/EV operations. All system factors can be optimized to improve overall performance. Table 5 summarizes the objectives of different optimization techniques and control algorithms, as well as their applicability.

Table 5. Different optimization techniques and control algorithms with the objective.

Ref.	Optimization / special control algorithm	Applied in/among	Objective of optimization or control algorithm.	Year	Metrics
[8]	A planning algorithm is employed	EVCSs	To obtain the needed number of EVCSs, which increase the system's operator reward.	2023	1355 EVs for 100% of SOC
[34]	MPPT algorithm	Solar PV	Harvesting more energy from solar PV.	2018	Power to EV is 421W, and to BES is 35W.
[84]	The merged integer Quadratic.	DES, load, and grid	Confirms managing energy, which minimizes the cost function.	2024	--
[85]	SSOA assisted the fuzzy controller.	Solar PV	Harvesting more energy from solar PV.	2024	MPPT efficiency of 97.12%
[86]	Whale optimization algorithm(WOA)	RES	Raising the deployment of RE and lowering reliance on non-renewable energy sources	2023	COE is nearly 0.25\$/KWhr.
[87]	Optimization policy	EV-charging	Helps in dynamic wireless charging, earnings, and reduces the grid effect by altering charging and electricity purchasing at each prospect.	2023	Charging costs cut by 50%.
[88]	Fuzzy-based optimization algorithm.	Pricing based on RES availability	Increases the charging fee based on power convenience, EV power load, charging period, and prevailing tariff, with renewable use serving as an upper limit.	2023	Reduces energy cost by 74.67%.
[89]	Optimization and comparative consideration.	Standalone hybrid charging station	Showing that choosing an optimum is a reasonable, environmentally friendly alternative to grid extension.	2023	The system's capacity shortage is 0.09%.
[90]	Two stage robust day-ahead optimization model	Pricing based on DG and battery	To reduce many costs connected with energy losses, power gains, and load restrictions.	2024	Efficiency is improved by at least 5% over other methods.
[91]	Multi-objective optimization, Fuzzy inference system-based planning framework.	EVCSs	Optimal siting and sizing of EVCSs are used to reduce electricity costs and radiation contamination.	2025	Net energy cost reduced by 42%.
[92]	BBO algorithm	EMS	Optimizes the production and consumption of comparable hydrogen in the microgrid.	2021	-
[93]	Energy management algorithm	PV, EV, BESS, and grid	Balance the power flow among all DES and EVs.	2024	Maximum 1 % and 1.25% voltage deviation.
[94]	Grid topology optimization framework	Solar PV	Optimal placement of feeders, substations, and interconnections to minimize overall price and technical losses.	2026	Voltage and current THD are less than 2%.

Ref.	Category	Efficiency	Cost Reduction	System Capacity	Power Quality
[8]	EVCS	—	—	High	—
[34]	RES	Medium	—	Low	—
[84]	RES	—	—	—	—
[85]	RES	High	—	—	—
[86]	RES	Medium	Medium	—	—
[87]	EVCS	—	High	—	—
[88]	Pricing	—	Very High	—	—
[89]	EVCS	—	—	High	High
[90]	Pricing	Medium	—	—	—
[91]	EVCS	—	High	—	—
[94]	RES	High	—	—	High

Figure 6. Comparison of efficiency, cost reduction, system capacity, and power quality [from Table 5]

Cost optimization in EV charging systems (EVCS) focuses on reducing energy costs while also enhancing scalability and capacity. In Figure 6, renewable energy systems (RES) focus primarily on efficiency and power quality. Most studies emphasize these aspects, but pay limited attention to maintaining stable system parameters. In practice, faults and disturbances can cause voltage instability, highlighting the need for robust control strategies to ensure reliable operation.

7. Future Recommendations

Based on a survey of EV charging research, the following are recommended as future research thrust areas.

7.1 Energy sources for EV

Solar energy is ideal for home and public EV charging, while wind supports grid-level supply in windy areas. Hydropower provides a reliable base load, and biomass/biogas serve remote or hybrid stations. Green hydrogen powers fuel-cell EVs in heavy transport. Used EV batteries store excess renewable energy, and AI and IoT optimize charging and system monitoring. Smart infrastructure, policies, and storage accelerate EV adoption as key components of a decentralized, renewable energy ecosystem.

7.2 EV charging methods

Optimal EV charging integrates Level-2 AC for daily use, DC fast charging for long trips, and battery swapping for commercial fleets. Wireless charging supports autonomous vehicles. Future EV charging should prioritize faster, smarter, safer, and greener systems that leverage AI, wireless technologies, V2G, and renewables to enable sustainable growth.

7.3 EV Technology

Future research should focus on BEVs for their scalability, zero-emission operation, and compatibility with renewable energy, making them ideal for personal and urban use. FCEVs are well-suited to heavy-duty and long-range applications and support the development of green hydrogen. PHEVs offer a temporary solution in areas with limited EV infrastructure, while HEVs are becoming less relevant.

7.4 Converters used in EVs

Future research on EV converters should focus on efficiency, power density, thermal management, and bidirectional energy flow. Multilevel converters (e.g., neutral-point-clamped and flying-capacitor) reduce switching losses and improve output quality in high-voltage applications. Soft-switching techniques, such as resonant converters and zero-voltage switching, minimize EMI and improve system efficiency. Bidirectional converters support V2G and regenerative braking. Advancing wide-bandgap semiconductors (SiC, GaN) enhances switching speed, thermal performance, and compactness. Modular and integrated designs reduce size, weight, and cost while improving reliability, enabling smarter, high-performance, and sustainable EV power management.

7.5 Optimization methods in EV

Future research in EV optimization should focus on battery management, powertrain efficiency, energy use, and route planning. Advanced algorithms such as genetic algorithms, particle swarm optimization, and model predictive control can maximize battery life and minimize degradation. Optimizing power distribution among motors, converters, and regenerative braking improves overall efficiency. In charging infrastructure, load forecasting and dynamic pricing reduce grid strain and costs. AI-based route and driving optimization lowers energy use and enhances vehicle range. Multi-objective optimization can ensure safe, energy-efficient thermal management of batteries and electronics. Integrated frameworks that combine vehicle dynamics, energy flow, thermal control, and charging policies, along with real-time, adaptive, AI-driven solutions, will be key to connected and autonomous EVs.

8. Conclusions

This review paper on electric vehicle systems highlights the rapid growth and multidisciplinary nature of this developing field. Non-conventional energy resources such as solar PV and wind are increasingly integrated into EV charging infrastructure, promoting sustainability and reducing reliance on fossil fuels. Conductive charging, particularly on-board charging, offers higher efficiency than other methods and supports the implementation of V2G and G2V technologies through converter topologies and intelligent controllers in power systems. Dynamic wireless charging systems are the most sought-after technology for vehicles in motion and are the leading technique in some countries for consumers' convenience zones. BSS is a flourishing technique, driving the application of economic principles, the planning of battery-based EVs, and the standardization of battery sizes. Among various charging methods, Level 2 AC charging for regular use and DC fast charging for long-distance travel are emerging as the most practical solutions. In terms of EV technologies, BEVs currently offer the best balance among performance, scalability, and environmental impact, although FCEVs show potential to meet EV demand and support long-term applications. Power converter topologies are undergoing substantial modernization, with trends favoring multilevel, soft-switching, and bidirectional designs, enhanced by wide-bandgap semiconductors that enable superior efficiency and compactness. Optimization techniques for energy management, cost minimization, grid stabilization, and power quality improvements enhance EV system-level performance, and artificial intelligence is playing an increasingly prominent role in real-time decision-making and predictive control. Ongoing research and development across these domains will be essential to overcome current constraints and accelerate the transition to cleaner, smarter transportation.

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Enhanced Germination and Early Growth of Tacunan Dwarf Coconut (*Cocos nucifera* L.) through Coconut Water and Auxin Injection

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Abstract: Coconut (*Cocos nucifera* L.) propagation via seednuts is limited by slow and inconsistent germination restricts uniform seedling production in coconut. This study evaluated the effectiveness of coconut water, a natural source of phytohormones, compared with synthetic auxin (NAA) on the germination and early seedling growth of Tacunan Dwarf coconuts under nursery conditions. The experiment was arranged in a randomized complete block design with four treatments: control (no injection), 200 mL NAA + 200 mL distilled water, 200 mL coconut water + 200 mL distilled water, and a combination of NAA + coconut water (100 mL each) + 200 mL distilled water, with four replications. Treatments were applied by injecting the solution near the soft eye at 10 ml/seednut, and germination and growth parameters were recorded over 120 days. Coconut water significantly reduced the time to plumule emergence (61.00 days), produced the longest shoots (142.62 cm), shortened mean germination time (49.52 days), and increased both germination index (0.1527) and seedling vigor index (22,120.44), outperforming both NAA alone and the combined treatment, with a germination rate of 72%. In contrast, NAA resulted in the highest germination percentage (90.67%) but lower seedling vigor, while the combined treatment produced intermediate responses, suggesting no clear synergistic effect between the two stimulants. These findings demonstrate that coconut water can serve as an effective natural alternative for enhancing germination speed and early seedling growth of coconut seedlings.

Keywords: *Cocos nucifera* L., coconut water, auxin (NAA), germination, biostimulant

1. Introduction

Coconut (*Cocos nucifera* L.) is a monoecious, perennial palm belonging to the family Arecaceae. Globally, coconut is cultivated on approximately 12 million hectares of land across more than 90 countries [1], with over 80% of production concentrated in the Asia-Pacific region [2]. This makes coconut a vital source of income for many nations in the region, contributing significantly to export earnings, local economies, and cultural traditions [3]. Often referred to as the "tree of life," the coconut is valued for its versatility, as every part of the plant serves a purpose [3, 4]. It provides food, household materials, and income for an estimated 11 million smallholder farmers worldwide. Traditionally, coconut farming has focused on copra production for crude endosperm oil and dried kernel. However, recent trends show a shift toward more profitable products with nutritional and medicinal value [5], such as shell charcoal, husk fiber, virgin

coconut oil, and coconut wood used in furniture, construction, veneer, and handicrafts [6]. This wide array of products underscores coconut's importance in tropical agriculture, with an annual global output of approximately 61,165 million nuts, equivalent to 13.59 million tonnes of copra [4].

Coconut cultivation remains a cornerstone of the Philippine economy. However, Crisostomo [7] reports that the three million Filipino farmers and workers dependent on coconut face challenges such as low yields and poor productivity, largely due to the use of genetically inferior varieties. As Lee [8] points out, limited access to high-quality planting materials and low adoption of modern technologies have contributed to a decline in the total coconut-growing area. Beveridge [1] also highlights the limitations of conventional seedling production methods. Farmers must contend with climate change and extreme weather events, which further complicate cultivation [9]. Studies on seedling survival highlight that high germination capacity (the 90%) is an unreliable metric for field success compared to seed vigor [10]. Seedlings are highly vulnerable to early drought, transplant shock, or micro-climate stress within their first six months of development [11]. Domingues [12] observes that traditional seed-based propagation is hindered by slow and inconsistent germination, which delays seedling development.

In response to these challenges, this study aims to investigate the use of stimulants to enhance germination in the Tacunan Dwarf Coconut. This study seeks to understand how synthetic and organic stimulants affect the germination and early growth of coconut palms in Barili, Central Visayas, Philippines, after four (4) months.

According to Rosa [13], stimulants, whether organic or synthetic, are substances that promote germination, enhance root and shoot development, and improve seedling vigor and establishment. For example, fermented seaweed as organic stimulant could promote vegetative growth of lettuce [14] and enhanced the assimilation rate of rice bean [15]. This study will utilize two types of stimulants: coconut water as the organic treatment and auxin as the synthetic one. Auxins play a crucial role in initiating root formation, promoting shoot elongation, and suppressing lateral bud growth. Coconut water, rich in plant growth regulators, exhibits properties similar to root hormones. It naturally contains compounds such as indole acetic acid (IAA), cytokinins, abscisic acid, and salicylic acid, making it a potent supplement for plant propagation. Aishwarya [16] notes that coconut water, due to its natural auxin content, supports adventitious root formation in vegetative propagation and serves as an effective medium in micropropagation. Similarly, Setyowati [17] emphasizes that coconut water's hormonal composition can accelerate root development in plants.

2. Materials and Methods

2.1 Experimental Design and Treatments

A Randomized Complete Block Design (RCBD) was utilized to account for potential variability within the experimental area. The experiment consisted of four blocks, with each block containing all four treatments randomly assigned. Each treatment contained 10 seed nuts and was replicated four times within each block. The different treatments used in the study were as follows: T0- control (no injection), T1- Injection with 200 ml NAA + 200 ml distilled water (1:1) as stock solution, 10 ml of which is applied via syringe, T2- Injection with 200 ml coconut water + 200 ml distilled water (1:1) as stock solution, 10 ml of which is applied via syringe, T3- Injection with 100 ml coconut water + 100 ml NAA + 200 ml distilled water (1:1:2) as stock solution, 10 ml of which is applied via syringe.

2.2 Cultural Management and Practices

Proper sourcing and selection of quality seed nuts were done to ensure palm productivity. Seed nuts were sourced from the selected mother palm (Tacunan Dwarf Coconut) located in the CTU-Barili Campus. Seed nuts were disease-free, undamaged by insects and rodents, physiologically mature, without deep punctures or cuts, with water manifested by "sloshing sound" when shaken, ungerminated, and resembled the distinct appearance of the specific variety of the mother palm. Seed nuts were appropriately watered, weeded, and inspected for disease and pest incidence. Fresh coconut water from mature Tacunan Dwarf Coconut was extracted from fully developed coconut fruits by first manually removing the husk using a dehusking tool. The hard endocarp was then cracked carefully to expose the liquid endosperm. The coconut

water was immediately poured and aseptically collected into a clean, sterilized container to prevent contamination and preserve its chemical integrity prior to use with distilled water at 1:1 (v/v) coconut water solution. The auxin solution was prepared using a commercially available liquid formulation of Alpha-Naphthalene Acetic Acid (1 gm/liter Naphthalene Acetic Acid). A measured volume of 200 mL ANAA was mixed with an equal volume (200 mL) of distilled water, resulting in a 1:1 (v/v) auxin solution. The solution was thoroughly mixed to ensure uniformity and used immediately for the experiment.

2.3 Treatment Application and Seed-nut Germination

Plant growth regulators (PGRs) were administered via vertical injection near the germ pore (soft eye) [1] of each hybrid seednut at a fixed volume of 10 mL per seednut. Following the injection of these stimulants, a preventative fungicide treatment was applied directly to the wound sites to suppress fungal pathogens and ensure optimal, disease-free growth conditions. The fungicide treatment was prepared using a 0.1% v/v concentration of azoxystrobin (Amistar 25 SC), calculated in accordance with the manufacturer's specification. This standard agricultural dilution was achieved by homogenizing 0.6 mL of the commercial liquid fungicide with 599.4 mL of distilled water, 5 ml of which is applied via pressurized sprayer to the injected part. This specific concentration effectively mitigates fungal risks while eliminating the potential for phytotoxicity, thereby establishing a safe chemical baseline for sprouting. To safeguard against excessive heat and desiccation, the treated seednuts were then maintained in a shaded nursery environment, minimizing microclimatic stress and promoting uniform early seedling development.

2.4 Data Gathered

Percent Germination. The final germination percentage was evaluated four months after treatment initiation. Calculations were performed according to the method described by [18] using the following equation:

$$GP(\%) = \left(\frac{G}{S}\right) \times 100\%$$

Where:

GP is a germination percentage

G is a number of normal germinated seeds

S is a number of total seeds

Days to Plumule Emergence. The timeline for initial sprouting was determined by tracking the day of visible plumule emergence through the fibrous outer husk for each individual seed nut. This parameter was quantified by calculating the exact number of days elapsed from the date of initial treatment application to the day of first visible emergence.

Shoot Length (cm). Four months post-treatment, seedling shoot length was measured using a standardized flexible measuring tape. Measurements were taken from the visible structural base of the seedling (at the apical surface of the nut) to the tip of the longest, fully unfurled leaf blade. To ensure measurement accuracy, curved leaves were gently straightened without applying force that could stretch or damage the plant tissue.

Mean Germination Time. The velocity and uniformity of sprout emergence were quantified using the Mean Germination Time index adapted from [19], expressed through the following equation:

$$MGT = \frac{\sum(n \times d)}{N}$$

Where:

MGT is a mean germination time

n is the exact number of individual seednuts that germinated on a specific observation day

d is the specific day number from the start of the experiment when the observation was made

N is the cumulative number of seednuts that successfully germinated

Germination Index. To evaluate the combined speed and complete success rate of sprout establishment, the Germination Index was calculated following the mathematical criteria established by [20]:

$$GI = \sum \left(\frac{G_t}{Tt} \right) = \frac{G_1}{1} + \frac{G_2}{2} + \frac{G_3}{3} + \dots + \frac{G_x}{x}$$

Where:

GI is a germination index

G_t is the number of seeds germinated on a specific day t

Tt the specific day number from the start of the experiment

X is the final day of the germination monitoring period.

Seedling Vigor Index. The overall physiological quality and seedling establishment potential were evaluated four months post-planting. The calculation followed the integrated framework established by [21]:

$$SVI = \text{Germination \%} \times \text{Average Seedling Length}$$

Statistical Tool and Analysis

Analysis of variance (ANOVA) for a randomized complete block design (RCBD) was used to analyze any significant difference in all the parameters gathered. Comparisons among means were done using Least Significant Difference (LSD) to determine the specific significant differences among treatments.

3. Results and Discussion

3.1 Germination Percentage of Seed nuts at 120 days after Injection

Figure 1 showed that coconut seed responses were treatment-specific and stage-dependent, strongly reflecting underlying hormonal regulation. Injection with 200 ml NAA + 200 ml distilled water (T_1) produced the highest germination percentage at 90.67%, which was significantly superior to all other treatments. This response highlights the critical role of auxin in stimulating seed germination by enhancing reserve mobilization, cell elongation, and early embryo growth. Similar findings have been reported by Xing [22], who demonstrated that α -naphthaleneacetic acid markedly improved seed germination and early seedling establishment through improved metabolic activity and antioxidant capacity. Auxin has also been shown to interact with abscisic acid signaling to regulate dormancy release and germination, suggesting that optimal auxin levels can shift seeds toward active growth [23].

In contrast, the control exhibited the lowest germination (33.33%), indicating that the absence of growth regulators limits physiological activation necessary for uniform germination. Treatments involving 100 ml coconut water + 100 ml NAA + 200 ml distilled water (T_3) resulted in moderate germination and similar germination percentages (72%) to using only coconut water (T_2). Coconut water is known to contain natural growth-promoting substances, including cytokinins and small amounts of auxins and gibberellins, which can stimulate cell division and metabolic activity [24]. However, its comparatively lower effectiveness during germination may be attributed to variability in hormone concentration and composition, as documented by Ge [25], who reported fluctuating cytokinin levels in coconut water. This is also attributed to lower concentrations of hormones in natural organic sources like coconut water. The intermediate response observed in the combined treatment suggests possible hormonal interaction effects rather than additive benefits, consistent with reports that mixed growth regulators can alter hormonal balance and influence early developmental responses [26]. Overall, the results indicate that synthetic auxin at an optimal concentration is more effective than coconut water, at the same concentration, in enhancing germination, emphasizing the importance of treatment specificity during the early stages of seedling development.

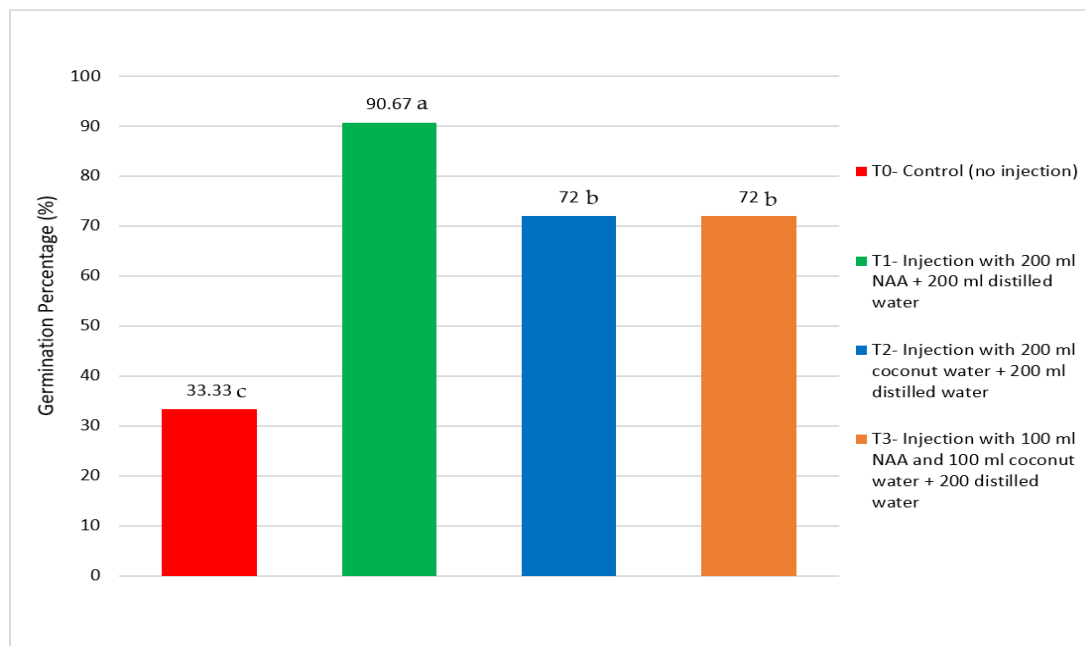


Figure 1. Germination Percentage of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 1. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	244.5000	81.5000	1.42	0.2985
Treatment	3	6974.6044	2324.8681	40.64	0.0000
Error	9	514.8334	57.2037		
Total	15	7733.9378			
CV (%)	11.29				
% Germination Mean	67				

Table 1.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	57.2037
Critical Value	2.2622
Test Statistics	12.0982

3.2 Plumule Emergence of Seed nuts at 120 days after Injection

Figure 2 shows the emergence of shoots where that seed nuts treated with 200 ml coconut water + 200 ml distilled water (T₂) and with the combined application of 100 ml coconut water + 100 ml NAA + 200 ml distilled water (T₃) exhibited the shortest number of days to plumule emergence, indicating significantly earlier shoot development compared with the control and the NAA-only treatment (Figure 3). The rapid plumule emergence observed under coconut water-based treatments can be attributed to the presence of naturally occurring cytokinins, auxins, gibberellins, sugars, amino acids, and vitamins, which collectively stimulate cell division, enhance metabolic activity, and promote meristematic growth during early seed development [24]. Coconut water has been widely reported as an effective natural biostimulant capable of accelerating germination and shoot initiation by improving embryo physiological readiness and hormonal balance [24,27]. In contrast, the 200 ml NAA + 200 ml distilled water (T₁) did not significantly reduce the number of days to plumule emergence and performed similar to the untreated control, suggesting that a higher concentration of synthetic auxin applied alone may not favor early shoot differentiation. This response is consistent with plant physiological principles, indicating that auxins must be applied within optimal concentration ranges, as excessive auxin can suppress or delay shoot initiation by disrupting hormonal

equilibrium [28]. Furthermore, the comparable performance of coconut water alone and its combination with low-dose NAA suggests that naturally balanced hormone sources may be more effective than single synthetic regulators in controlling early growth processes, a trend also documented in plant propagation and embryo development studies [27, 29]. Overall, the figure highlights the strong potential of coconut water-based treatments in significantly shortening the time to plumule emergence, thereby improving early seed nut establishment and seedling vigor.



Figure 2. Morphological growth stages of Tacunan Dwarf Coconut (*Cocos nucifera*) seednuts (clockwise) during germination: **(a)** first sign of sprout emergence at day 8; **(b)** clear emergence of the shoot tip “button stage” at day 15; **(c)** development of a visible, upright spear at day 31; **(d)** early opening of the blade at day 56; **(e)** unfurling and elongation of the young leaves at day 78; and **(f)** distinct separation of leaf sheets with fully visible midribs at day 93.

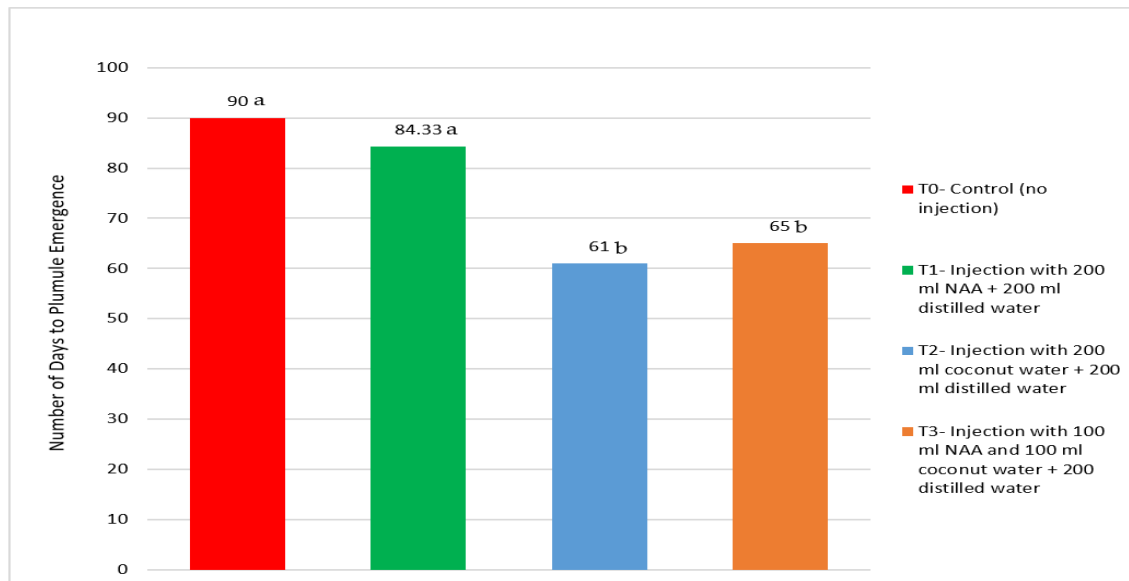


Figure 3. Plumule Emergence of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 2. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	21.667	7.0556	0.35	0.7877
Treatment	3	2432.2717	810.7572	40.65	0.0000
Error	9	179.5000	19.9444		
Total	15	2632.9383			
CV (%)	5.95				
Plumule Emergence Mean	75.08				

Table 2.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	19.9444
Critical Value	2.2622
Test Statistics	7.1436

3.3 Shoot Length of Seed nuts 120 days after Injection

Average shoot length of seed nuts at 120 days after injection was significantly affected by the different treatments, as shown in Figure 4. Injection with 200 ml coconut water + 200 ml distilled water (T₂) produced the longest shoots (142.62 cm) and was significantly superior to all other treatments. This is approximately three times longer than without injection (40 cm), underscoring the beneficial effects of coconut water on shoot development. This pronounced elongation response can be attributed to the presence of naturally occurring growth regulators, particularly cytokinins, along with detectable levels of auxins and gibberellins, which collectively stimulate cell division and cell elongation in shoot tissues [24]. Coconut water has been widely reported to enhance vegetative growth due to its complex hormonal composition and nutrient content, providing a strong physiological basis for the observed shoot elongation [25]. The combined treatment of 100 ml NAA and 100 ml coconut water + 200 ml distilled water (T₃) resulted in intermediate shoot length (94.40 cm), which was significantly lower than coconut water alone but higher than NAA alone. This suggests that the combined application did not produce additive effects, likely due to hormonal interactions that altered the balance between auxin-mediated elongation and cytokinin-regulated cell division. Similar non-additive responses have been documented when coconut water is applied together with synthetic growth regulators, indicating that optimal shoot growth depends on precise hormonal balance rather than multiple hormone

sources [26]. Injection with 200 ml NAA + 200 ml distilled water (T_1) produced moderate shoot elongation (88.67 cm), which was significantly higher than the control. Although auxin is known to promote cell elongation, its effect is often concentration- and stage-dependent, and excessive auxin may limit sustained shoot elongation during later growth stages [23]. The control treatment (T_0) recorded the shortest shoots (40 cm), reflecting the absence of external growth stimulation. Overall, these findings indicate that coconut water is the most effective treatment for promoting shoot elongation, whereas auxin application alone primarily supports early growth stages rather than sustained vegetative expansion [30].

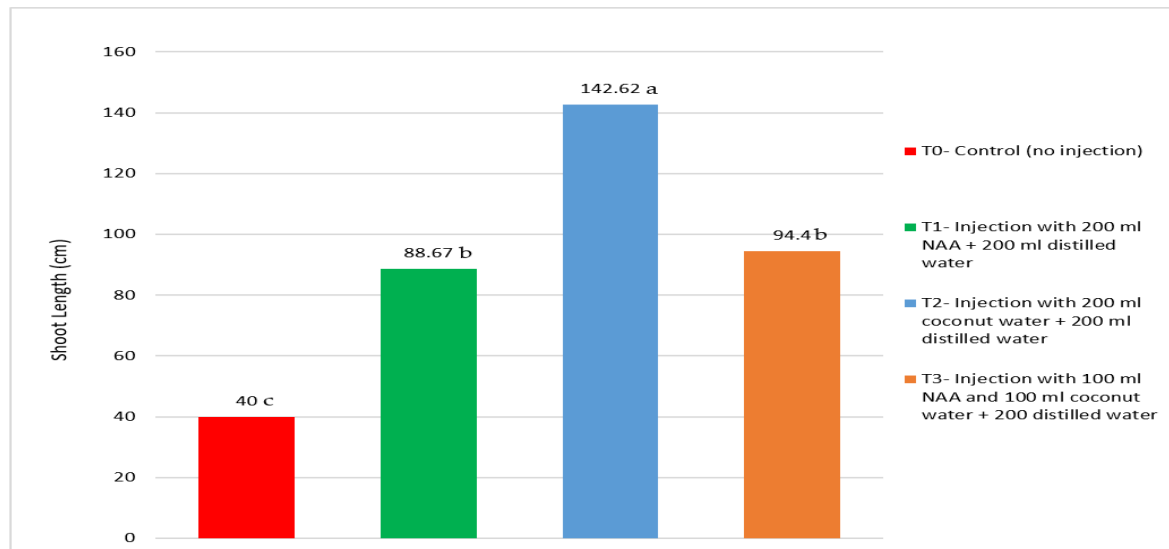


Figure 4. Shoot Length of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 3. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	119.7254	39.9085	0.40	0.7563
Treatment	3	21126.6282	7042.2094	70.61	0.0000
Error	9	897.5829	99.7314		
Total	15	22143.9366			
CV (%)	10.92				
Shoot Length Mean	91.42				

Table 3.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	99.7314
Critical Value	2.2622
Test Statistics	15.9744

3.4 Mean Germination Time at 120 days after Injection

Figure 5 indicates that the mean germination time (MGT) of Tacunan Dwarf seednuts was significantly reduced by all injection treatments compared to the control group (T_0), which recorded the longest MGT at 103.38 days. Notably, the injection of 200 mL coconut water combined with distilled water (T_2) achieved the most rapid germination with an MGT of 49.52 days, outperforming both the 200 mL NAA treatment (T_1 ; 53.66 days) and the combined injection (T_3 ; 59.90 days). This pronounced acceleration of MGT serves as a vital indicator of increased germination speed and enhanced seed vigor [10], demonstrating that coconut water drives the physiological processes leading to radicle protrusion more effectively than synthetic hormones alone or in combination. This superior performance aligns with findings by [31], who reported that

coconut water priming reduces germination time by enhancing metabolic activity and reserve mobilization. As a natural biostimulant, coconut water contains essential endogenous growth regulators such as auxins, cytokinins, and gibberellins that work synergistically to break seed dormancy and stimulate embryo emergence by facilitating hydrolytic enzyme synthesis and cell elongation [32-35]. Concurrently, while the application of NAA (T₁) provides a synthetic auxin source that promotes cell division and elongation to accelerate germination physiology [36], its combination with coconut water (T₃) proved less effective than the pure organic treatment. This response suggests a possible hormonal antagonism or receptor saturation when synthetic and natural auxins are applied simultaneously, ultimately emphasizing that coconut water provides a highly efficient, more natural stimulus that bridges traditional agricultural practices with modern plant physiology.

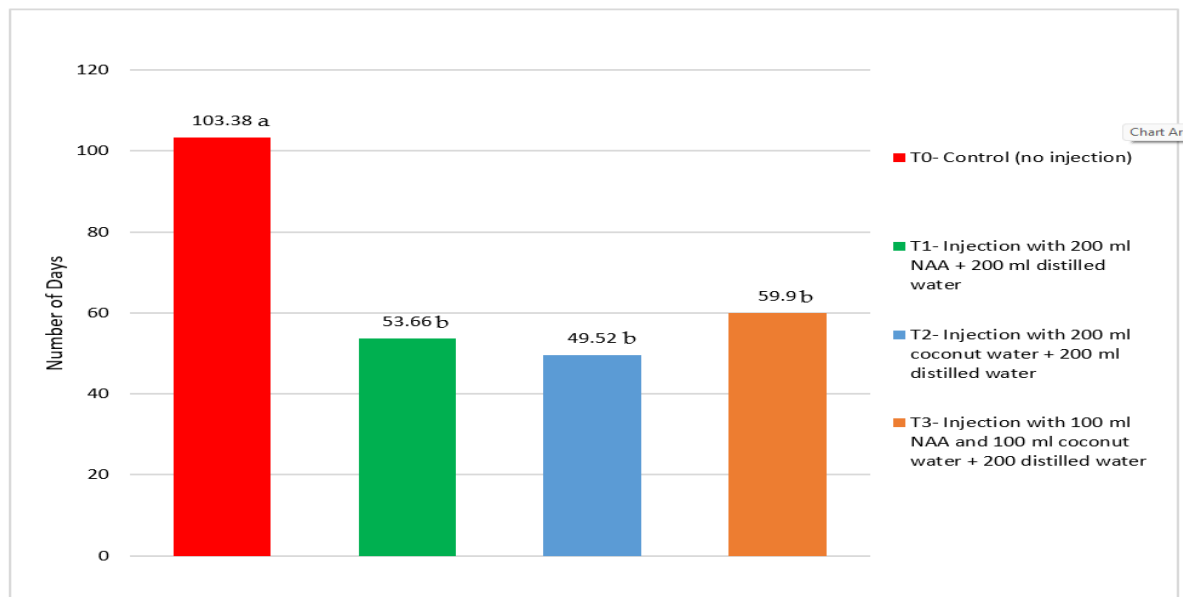


Figure 5. Mean Germination Time of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 4. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	438.4821	146.1607	1.59	0.2592
Treatment	3	7428.2625	2476.0875	26.91	0.0001
Error	9	827.9761	91.9973		
Total	15	8694.7207			
CV (%)	14.40				
MGT Mean	66.62				

Table 4.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	91.9973
Critical Value	2.2622
Test Statistics	15.3425

3.5 Germination Index of Seed-nuts at 120 days after Injection

Figure 6 revealed that seed-nuts injected with coconut water (T₂) exhibited the highest germination index (0.1527), outperforming both NAA alone (T₁) and the combined NAA + coconut water treatment (T₃). This finding underscores the efficacy of coconut water as a natural biostimulant, likely due to its rich composition of cytokinins, gibberellins, and auxins that collectively stimulate enzymatic activity and cell division during germination. Previous studies have reported similar outcomes; [37] demonstrated that

coconut water supplementation enhanced orchid seed germination, while [33] confirmed its role in accelerating rice seed germination. These results suggest that coconut water provides a more balanced hormonal environment compared to synthetic auxin alone, thereby promoting uniform and vigorous germination. The superior performance of T₂ highlights the potential of coconut water as a sustainable alternative to synthetic stimulants in coconut propagation.

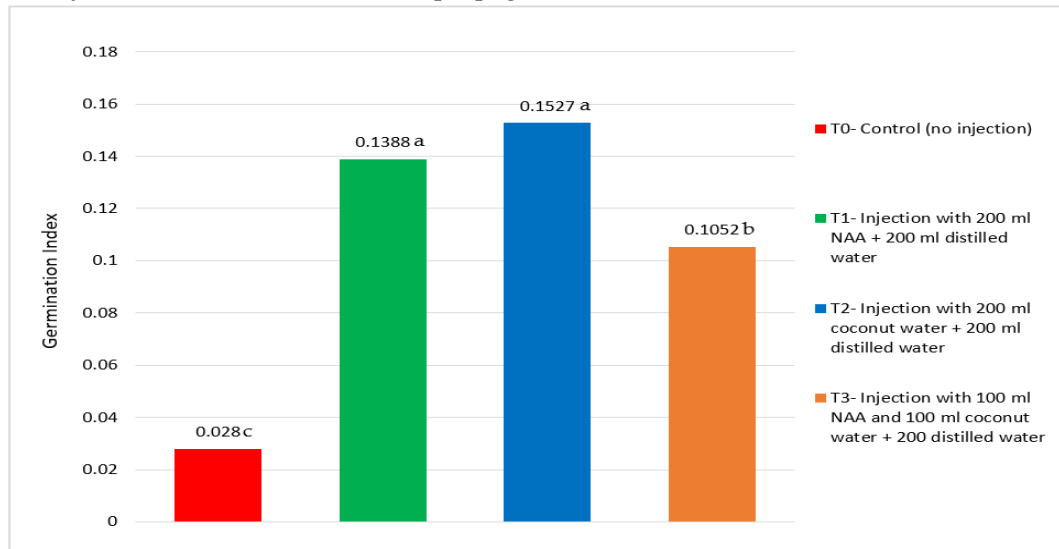


Figure 6. Germination Index of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 5. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	0.0017	0.0006	1.28	0.3391
Treatment	3	0.0374	0.0125	28.97	0.0001
Error	9	0.0039	0.0004		
Total	15	0.0429			
CV (%)	19.53				
Germination Index Mean	0.1062				

Table 5.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	0.0004
Critical Value	2.2622
Test Statistics	0.0332

3.6 Seedling Vigor Index at 120 days after Injection

Figure 7 shows that with T₂ (Injection with 200 ml coconut water + 200 ml distilled water) achieving a value of 22,120.44 substantially higher than T₁ (Injection with 200 ml NAA + 200 ml distilled water) with 8,540.41 and the control (T₀; 1,320.8). This demonstrates that coconut water not only accelerates germination but also sustains robust seedling growth. Coconut water's diverse phytohormone profile, coupled with essential minerals and sugars, likely contributed to enhanced shoot development. [38] reported similar improvements in coconut micropropagation when auxin-rich treatments were optimized, while [31] highlighted coconut water's ability to promote balanced seedling growth in coconut seedlings. The exceptionally high vigor index in T₂ underscores coconut water's holistic role in promoting seedling establishment, making it a promising eco-friendly biostimulant for coconut cultivation.

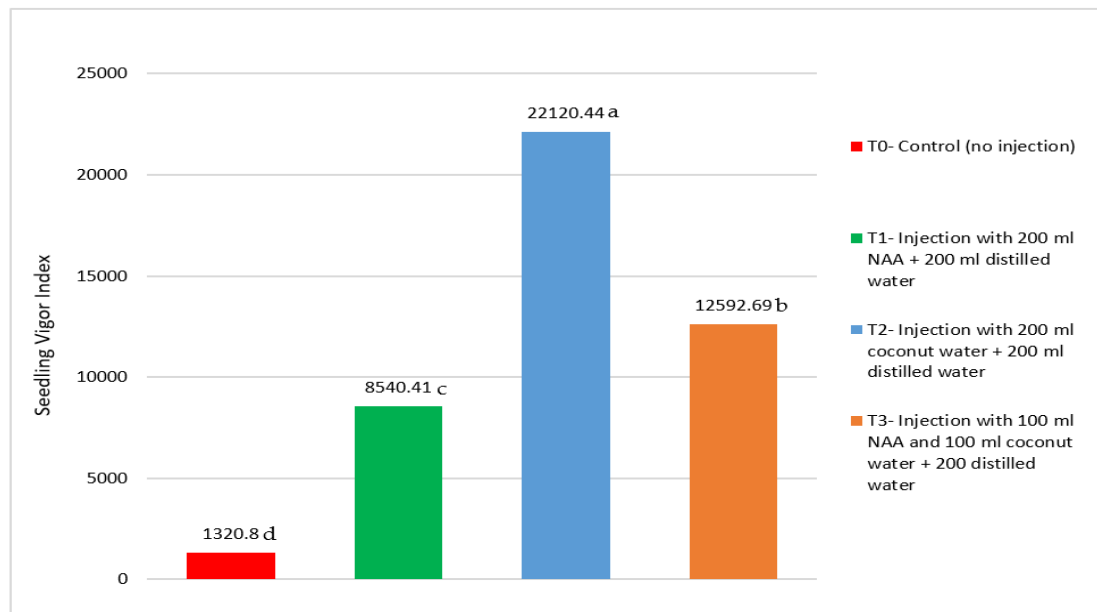


Figure 7. Seedling Vigor Index of Seed-nuts at 120 days as Affected by Coconut Water and Auxin Injection

Table 6. Analysis of Variance (ANOVA)

Source	DF	Sum of Square	Mean Square	F Value	Pr (> F)
Block	3	10835548.6229	3611849.5410	1.14	0.3851
Treatment	3	903419463.2648	301139821.0883	94.84	0.0000
Error	9	28575895.2680	3175099.4742		
Total	15	942830907.1557			
CV (%)	15.99				
SVI Mean	11143.59				

Table 6.1 Least Significant Difference (LSD) Test

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	3175099.4742
Critical Value	2.2622
Test Statistics	2850.2729

4. Conclusions

This study demonstrated that the application of organic and synthetic plant growth stimulants significantly enhanced the germination and early seedling development of Tacunan Dwarf Coconut. Among the treatments, injection with 200 ml coconut water + 200 ml distilled water proved most effective in promoting overall seedling vigor, producing the longest shoots, achieving the earliest plumule emergence, reducing mean germination time, and increasing both germination index and seedling vigor index, highlighting its strong potential as a natural biostimulant. On the other hand, injection with 200 ml NAA + 200 ml distilled water yielded the highest germination percentage, confirming its effectiveness in stimulating embryo activation and early metabolic processes. The combined treatment (100 ml NAA + 100 ml coconut water + 200 ml distilled water) produced intermediate effects across all parameters, suggesting partial but not synergistic hormonal interactions.

Overall, the findings confirm that coconut water is a sustainable, accessible, and efficient alternative to synthetic plant growth regulators for enhancing early coconut seedling performance, especially under climate-stressed nursery conditions in Cebu, Philippines. Its use can support local coconut farmers by improving germination uniformity and accelerating early growth, thereby strengthening propagation systems for Tacunan Dwarf and other coconut varieties.

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The introduction should briefly place the study in a broad context and highlight why it is crucial. It should define the purpose of the work and its significance. The current state of the research field should be carefully reviewed and critical publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work. References should be numbered in order of appearance and indicated by a numeral or numerals in square brackets—e.g., [1] or [2, 3], or [4-6]. See the end of the document for further details on references.

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3.1. Subsection
 3.1.1. Subsubsection

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entry 1	data	data
entry 2	data	data ¹

¹ Table may have a footer.

3.3. Formatting of Mathematical Components

This is example 1 of an equation:

$$a = 1, \tag{1}$$

The text following an equation need not be a new paragraph. Please punctuate equations as regular text. This is example 2 of an equation:

$$a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u \tag{2}$$

The text following an equation need not be a new paragraph. Please punctuate equations as regular text. The text continues here.

4. Conclusions

Concisely restate the hypothesis and most important findings. Summarize the significant findings, contributions to existing knowledge, and limitations. What are the future directions? Conclusions MUST be well stated, linked to original research question & limited to supporting results.

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