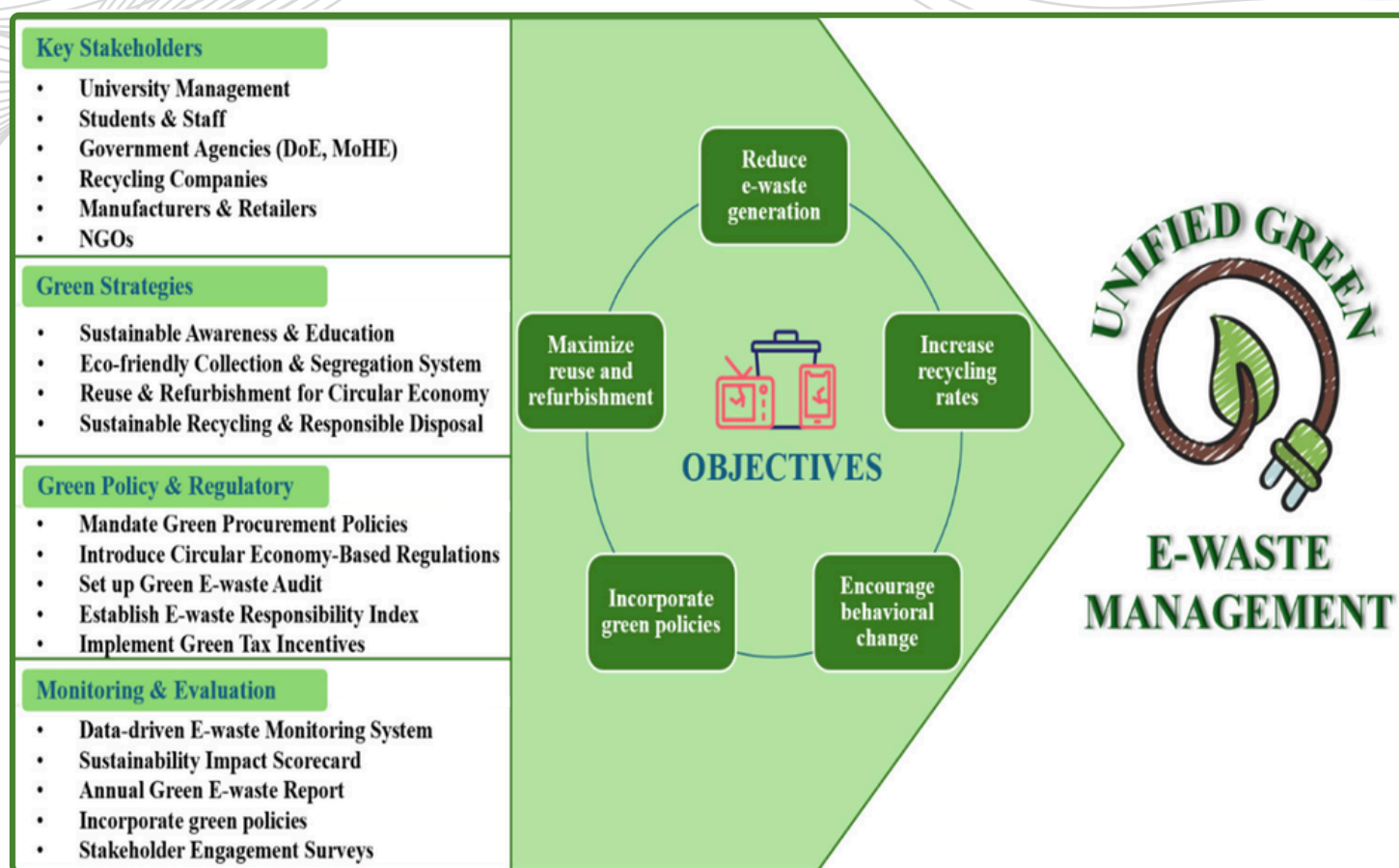




Environment and Natural Resources Journal

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Unified Green E-Waste Management Framework for public universities, highlighting key stakeholders, green strategies, regulatory support, and monitoring mechanisms that collectively drive e-waste reduction, reuse, recycling, and behavioral change. The circular flow emphasizes the transition to a sustainable, circular e-waste management system.

Source: Hashim R, Zahari FM, Salleh NA, and Ibrahim JA. Unified Green E-Waste Management Framework for Sustainable Campus Development: Case Study of Malaysian Public Universities. Environ. Nat. Resour. J. 2026; 24(3): 250-267.



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The scope of the journal covers the integration of multidisciplinary sciences for prevention, control, treatment, environmental clean-up, and restoration. The study of existing or emerging problems related to the environment and natural resources in Southeast Asia and the development of innovative knowledge and/or creative recommendations for mitigation measures and sustainable development are emphasized. The subject areas are diverse, but specific topics of interest include:

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CONTENT

Atmospheric Microplastics in Indoor and Outdoor Air: Abundance and their Potential as Vectors for Heavy Metals <i>Jade Rae B. Ministerio, Najiha B. Amer, Rodolfo A. Romarate II, and Hernando P. Bacosa</i>	268
Attenuation of Organic Matter in Landfill Leachate: Seasonal Characterization and Soil Column Evaluation <i>Lokesh Sapkota, Rajendra Joshi, Bikash Adhikari, Bijay Thapa, Sophie Shrees, Aalekh Bhattarai, and Anish Ghimire</i>	280
Unified Green E-Waste Management Framework for Sustainable Campus Development: Case Study of Malaysian Public Universities <i>Rushanim Hashim, Fadhilah Mohd Zahari, Nurul Azita Salleh, and Jafni Azhan Ibrahim</i>	296
Modeling PM2.5: Temperature Interactions Using Predator-Prey Dynamics <i>Watsapon Saengcharoenthaworn, Itthithep Navarasuchitr, and Siriluk Ruangrungrrote</i>	307
Implementation of the Groundwater Live Observation for Water-Quality (GLOW) in Bojong District, Indonesia <i>Doddi Yudianto, Yong Chan Seo, Stanley Koeswandi Harliman, Stephen Sanjaya, Finna Fitriana, Steven Kent, Albert Wicaksono, Ahmad Taufiq, Nurananda Galuh Syahputri, Steven Reinaldo Rusli, and Obaja Triputera Wijaya</i>	315
Exploring the Relationship between Climate Parameters and Water Salinity Fluctuations: A Case Study in Binh Chanh District, Ho Chi Minh City <i>Phan Thi Ha, Pham Quoc Khanh, Tran Thi Kim Ngan, Le Thanh Hai, and Nguyen Kim Loi</i>	327
A Numerical Investigation of Perforated Inlet Baffle Configurations on Flow Behavior in a Rectangular Oil / Water Separator using CFD <i>Muna S. Resin and Haitham A. Hussein</i>	335
Analyzing the Seasonal Relationship between Vegetation Variation and Land Surface Temperature Dynamics in Eastern Maharashtra <i>Dipti Pawade and Sonali Patil</i>	346
Geological Analysis and Occupational Safety Risks in Traditional Oil Drilling in Ranto Peureulak, East Aceh, Indonesia <i>Muchlis, Nurul Aflah, and Mirna Rahma Lubis</i>	360
Quantifying Decadal Recovery in Small Scale Community-Based Mangrove Management (SSCM) in East Java, Indonesia, using Integrated Remote Sensing and Ecological Assessments <i>Dhira K. Saputra, Sri Sudaryanti, Agus Tjahjono, Hardoko Hardoko, Mulyanto Mulyanto, Umi Zakiyah, Arief Setyanto, Yunita E. Puspitasari, Muhammad Arif Asadi, Ade Yamindago, Seftiawan S. Rijal, M.A.Z. Fuad, and Edi Susilo</i>	371

Atmospheric Microplastics in Indoor and Outdoor Air: Abundance and their Potential as Vectors for Heavy Metals

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ABSTRACT

Microplastics (MPs) have emerged as pervasive atmospheric pollutants, yet their occurrence and characteristics in urban air environments remain poorly characterized. This study quantified the abundance, morphological features, polymer composition, and elemental associations of airborne MPs in indoor and outdoor environments in Marikina, Philippines. Airborne particles were collected using a respirable dust sampler and analyzed through microscopic observation, attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX). Results revealed significantly higher MP concentrations in outdoor air (0.341 ± 0.038 MP/m³) than indoors (0.155 ± 0.106 MP/m³) ($p=0.0454$), with estimated daily intakes ranging from 0.5-3.2 MP/day indoors and 2.1-4.3 MP/day outdoors. Fibers were the predominant morphology in both environments, accounting for 80.0-95.7% indoors and 61.3-84.0% outdoors. Polymer analysis identified indoor MPs mainly as polyvinyl chloride (PVC, 50.0%), polyethylene (PE), and polyurethane (PU), whereas outdoor samples showed a broader diversity, including polyamide (PA), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and high-density polyethylene (HDPE). Elemental analysis revealed the adsorption of toxic metals such as titanium (Ti), chromium (Cr), lead (Pb), mercury (Hg), and cadmium (Cd), with Pb concentrations reaching up to 18.13% in indoor PE fibers and Cr up to 18.29% in outdoor HDPE. These findings demonstrate that outdoor environments harbor higher concentrations and more chemically complex MPs, emphasizing the potential risk of human inhalation exposure. The study underscores the urgent need for monitoring airborne MPs and developing mitigation measures to reduce human and environmental health in urban areas.

HIGHLIGHTS

- Airborne microplastics were detected in indoor and outdoor urban sites.
- Outdoor sites showed higher microplastic levels than indoor areas.
- Black and red synthetic fibers were the dominant microplastic types.
- FTIR identified PU, PE, and PVC in indoor microplastic samples.
- PA, PET, PMMA, and HDPE were present in outdoor microplastics.

1. INTRODUCTION

Plastics have largely replaced traditional materials such as metal, glass, and wood due to their cost-effectiveness, durability, and versatility (Ng et al., 2018; Rehm et al., 2021). Their affordability and widespread applications have made them indispensable across various industries, significantly shaping the global economy (Peña et al., 2023; Ritter,

2022). Much of the research on microplastic (MPs) has focused on marine ecosystems (Bhuyan 2022; Pothiraj et al., 2023; Marcharla et al., 2024; Ellos et al., 2025) while the scale and extent of contamination in other environmental compartments, including the atmosphere, remain poorly understood. Multiple studies have confirmed the presence of MPs across various ecosystems, including river sediments

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(Gabriel and Bacosa, 2024), lakes (Arcadio et al., 2022), beaches (Sajorne et al., 2022) and agricultural soil (Gonzales et al., 2024).

However, research on airborne MPs remains limited despite their potential to pose serious risks to both human health and environmental integrity. Outdoor airborne sources include vehicle tire wear (Brahney et al., 2021; Boakes et al., 2023a), waste disposal, macro-plastic debris and construction works (Salthammer, 2022). Beyond outdoor sources, indoor environments also contribute significantly to MP contamination, as enclosed spaces can facilitate prolonged exposure. Studies have identified textiles as a dominant source, with MPs being released from vented tumbled dryer (Tao et al., 2022), degraded floor finishing materials (Suh et al., 2025), carpets (Yasin et al., 2024), and household fabrics during routine activities such as laundry and mechanized clothes drying (Kapp and Miller, 2020). The distribution of airborne MPs varies depending on location and environmental factors (Perera et al., 2022).

MPs are now ubiquitous, contaminating the human diet (Dimaongon et al., 2024), raising urgent concerns about their potential risks to environmental sustainability and public health (Koelmans et al., 2022). They have been widely reported in various environmental matrices, including atmospheric dust (Xu et al., 2024), personal care products and cosmetics (Gamage and Mahagamage, 2024), food items (Mamun et al., 2023) and water systems (Kye et al., 2023).

In the Philippines, a recent study by Romarate et al. (2023), examined MPs suspended in the atmosphere, estimated that an adult could inhale at least one suspended atmospheric MP (SAMP) after approximately 99 to 132 hours of exposure. This highlights the potential for chronic exposure, particularly in urbanized and industrialized settings. Additionally, Patilan et al. (2024) conducted a preliminary study on mercury (Hg) and lead (Pb) in the ambient air of Metro Manila. Their findings support the reported presence of MPs in the area, providing documented evidence of these toxic metals in the atmosphere of the biggest urban area in the Philippines.

Another study concerning airborne MPs focuses on road dust, which plays a significant role in atmospheric MP pollution. Tejano et al. (2024), confirmed the presence of MPs in road dust samples collected from Iligan City, a rapidly urbanizing area in Mindanao, reinforcing concerns about MP dispersion

in high-traffic environments. Given their widespread presence, human exposure to MPs is inevitable, occurring through ingestion, inhalation, and dermal contact. Studies have suggested that MP exposure may lead to oxidative stress, cytotoxicity, neurotoxicity, immune system disruption, and translocation to other tissues (Bhuyan, 2022).

Despite the increasing evidence of airborne MP contamination, the Philippines still faces a significant research gap in both indoor and outdoor environments. The lack of comprehensive studies limits the ability of policymakers' and public health officials' to assess exposure risks and formulate science-based mitigation strategies. While existing research has identified potential sources of MPs, a critical need remains to establish baseline data on MP levels, sources, and health implications across different settings. Understanding the extent of MP pollution in enclosed indoor spaces, where prolonged exposure may occur, and outdoor environments, where industrial activity, vehicular emissions, and urbanization contribute to dispersion, is essential for developing effective regulatory frameworks. Without such evidence, efforts to curb MP emissions and minimize human exposure remain insufficient.

While studies have been published on airborne MPs in outdoors environments (Discutido et al., 2024), there is a lack of research examining both indoor and outdoor airborne MPs in the Philippines. This study aims to address the knowledge gap regarding airborne suspended MPs in the Philippines by investigating their presence in both indoor and outdoor settings. The specific objectives of the study were as follows: (1) to determine the abundance of MPs in indoor and outdoor environments; (2) to characterize MPs based on shape, color, and polymer composition; and (3) to identify the adsorbed metals associated with MPs. This study provides insights into the current understanding of inhalable MP exposure in indoor and outdoor settings, highlighting the need for further research on the role of MPs as vectors for heavy metals and other pollutants and their potential risks to human health and the environment.

2. METHODOLOGY

2.1 Background of the sampling area

Marikina, is a highly urbanized city located in the eastern part of National Capital Region (NCR) of the Philippines. It serves as the main gateway between Metro Manila and the provinces of Rizal and Quezon. This study was conducted within a two-storey

residential apartment, with indoor sampling taking place on the ground floor (living room). The room had approximate dimensions of 3 m × 5.5 m × 4 m (LWH) (Figure 1). For outdoor sampling, the measurements were taken 5.6 meters from the apartment at ground level (geolocation: 14°39'6.12"N, 121°6'40.68"E. The apartment housed five adult occupants.

2.2 Air sampling and sample preparation

Airborne MP sampling was conducted from July 16 to 18, 2025. In each sampling environment, one-hour sampling sessions were carried out in both the morning and evening using a continuous sampling approach. The morning period, which included both the setup and the sampling process, was conducted between 6:00 am and 8:00 am. Similarly, the evening setup and sampling were performed between 6:00 pm and 8:00 pm.

A respirable dust sampler with an intake flow rate of 1.4 m³/min was used to collect airborne MP

particles. The sampled air volume per session was approximately 84 m³, and the intake rate was monitored every 30 min to ensure a uniform flow rate (Romarate et al., 2023). The sampler's intake was positioned 1.5 meters above the ground to simulate the average height of human breathing. GF/C Whatman filter paper (8.3×11.7 inches) was used to capture suspended atmospheric MPs during each sampling period across different sampling environments. Before sampling, filters were microscopically examined to confirm the absence of MP contaminants. After collection, the filters were transported to a controlled laboratory environment to prevent external contamination and for analysis. Each filter was subjected to microscopy with a magnification power of WF10X/22 (YANA Chemodities Inc.), where potential MP particles were handpicked and embedded in glass slides for further examination.

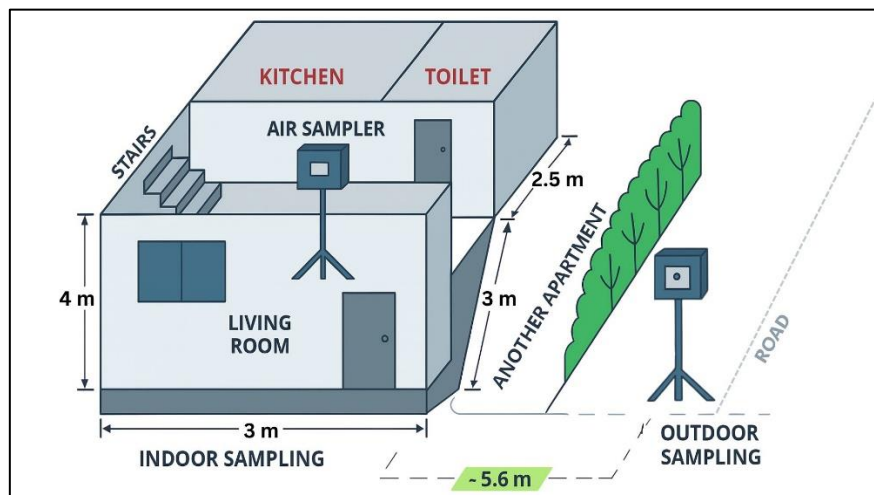


Figure 1. Schematic representation of the sampled area, showing the location of the respirable dust sampler in the indoor and outdoor settings.

2.3 Daily intake of MPs

To estimate the potential daily inhalation of MPs by an individual, a modified version of the equation proposed by Akhbarizadeh et al. (2021), was utilized as shown below:

$$\text{Daily intake } \left(\frac{\text{MP}}{\text{day}} \right) = \text{density} \left(\frac{\text{MP}}{\text{m}^3} \right) \times \text{ventilation rate} \left(\frac{\text{m}^3}{\text{min}} \right) \times \text{exposure time} \left(\frac{\text{min}}{\text{day}} \right) \quad (1)$$

Where; Density is, expressed in MP/m³, refers to the number of airborne MPs per cubic meter of air. Ventilation rate, expressed in m³/min, represents the

average volume of air inhaled per minute, with 5 L/min and 8 L/min used in this study to represent different activity levels. Exposure time was set at 24 hours, assuming continuous daily exposure.

2.4 Morphological characterization and plastic confirmation

Samples mounted on glass slides were examined under a microscope to determine their physical characteristics, such as color and shape. To confirm whether the collected particle was plastic, the "Hot Needle Test" was performed following the study of Beckingham et al. (2023). Plastic particles were

confirmed if they exhibited melting or deformation under the microscope.

2.5 ATR-FTIR analysis

Some MPs confirmed using the “Hot Needle Test” were randomly analyzed using Attenuated Total Reflectance Fourier-Transform Infrared (ATR-FTIR) - Shimadzu (IRTracer 100) to confirm their polymer type. Spectra graphs generated for each MP were automatically matched against a pre-existing standard spectral library. Before each analysis, the ATR crystal was thoroughly cleaned with 70% ethanol, followed by a background scan to ensure accuracy. Additionally, the obtained spectra were cross-referenced with literature-based reference spectra, with a similarity threshold of >70% considered a positive match (Sharaf Din et al., 2024).

2.6 SEM-EDX analysis

Randomly selected MPs from each sample were analyzed using a scanning electron microscope (SEM), JEOL (JSM-IT200) coupled with energy-dispersive X-ray spectroscopy (EDX) for surface elemental composition analysis. SEM utilizes a focused electron beam to scan the sample surface, producing high-resolution images that reveal the fine surface details of the MPs. MPs were carefully picked using metal needles and placed onto stubs. These stubs were then gold-coated before SEM-EDX analysis. Images were captured at various magnifications to examine surface morphology in detail. Surface elemental composition was determined using EDX, with characteristic peaks indicating the presence of specific elements on MP surfaces.

2.7 Quality control

All filter papers were stored in labeled envelopes both before and after exposure. Before use, glass slides were thoroughly cleaned with distilled water and dried. Metal tweezers were used to handle the filter papers to minimize contamination. Exposed

filters were carefully folded and stored in labeled envelopes to prevent contamination. Samples were only opened when required for analysis, ensuring they remained free from the contamination throughout the process.

2.8 Statistical analysis

Microsoft Excel and OriginLab (2025) were used. A paired t-test was conducted to compare the means of the two sampling environments (indoor and outdoor), with statistical significance set at $p < 0.05$. The Shapiro-Wilk test was used to assess the normality of the data. Unless otherwise stated, all statistical results are presented as mean $\pm$ SD.

3. RESULTS

3.1 Microplastic abundance in air samples

Variations in MPs' abundance revealed a distinct contrast between indoor and outdoor environments. Indoor MP concentrations range from 0.071 to 0.274 MP/m³, with the highest recorded on the first day (Table 1). In contrast, outdoor concentrations remained consistently higher, ranging from 0.298 to 0.369 MP/m³. This disparity highlights the significant difference ($p = 0.0454$) in MP presence, with outdoor air containing significantly higher concentrations than indoor spaces. On average, indoor MP levels measured 0.155 ± 0.106 MP/m³, whereas outdoor concentrations were nearly double at 0.341 ± 0.038 MP/m³ (Figure 2).

Assuming that an average person spends a significant portion of their time indoors, indoor MP daily intake ranged from 0.5 to 3.2 MP/day, with the highest intake observed at Indoor 1 (2.0-3.2 MP/day) and the lowest at Indoor 3 (0.5-0.8 MP/day). Outdoor MP daily intake ranges from 2.1 to 4.3 MP/day, with Outdoor 2 recording the highest values (2.7-4.3 MP/day) and Outdoor 1 the lowest (2.1-3.4 MP/day). Outdoor intake values were consistently higher than indoor values, except for Indoor 1, which showed a broader range of intake estimates.

Table 1. MPs concentration and estimated daily intake in indoor and outdoor air samples

Sampling station	No. of MPs observed	MPs concentration (MP/m ³)	MPs daily intake (MP/day)
Indoor 1	23	0.274	2.0-3.2
Indoor 2	10	0.119	0.9-1.4
Indoor 3	6	0.071	0.5-0.8
Outdoor 1	25	0.298	2.1-3.4
Outdoor 2	31	0.369	2.7-4.3
Outdoor 3	30	0.357	2.6-4.1

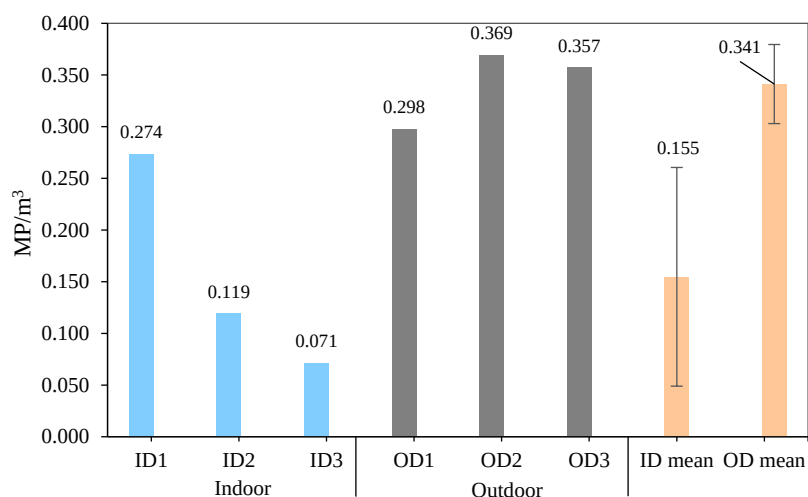


Figure 2. MPs concentration in indoor and outdoor environments

3.2 Shape, color and polymer type of microplastics

MPs in indoor and outdoor environments showed differences in color, polymer type, and shape. Color distribution varied, with indoor samples dominated by blue, transparent, and red MPs. In contrast, outdoor samples have a mix of black, blue, red, and yellow (Figure 3(a)). Shape composition is fiber-dominant indoors (80.0-95.7%) and outdoors (61.3-84.0%), though outdoor samples (Figure 3(b)) showed more fragments. The polymer composition of indoor samples was mainly polyvinyl chloride (PVC) (50.0%), with polyethylene (PE) and polyurethane (PU) at 25.0% each (Figure 3(c)). Outdoor samples have a more diverse composition, including polyamide (PA), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and high-density polyethylene (HDPE), each at 25.0%.

3.3 Elemental mapping associated with microplastics

SEM images (Figure 4) illustrate the surface texture of various atmospheric MPs with different shapes. When analyzing with EDX, different areas of a particle's surface were considered, including the area with potentially adhered foreign material. The results of the SEM-EDX analysis are presented in Table 2. Carbon (C) and oxygen (O) are fundamental elements in all plastic materials, as they are the derivative from the petroleum products. Other metal elements such as titanium (Ti), chromium (Cr), lead (Pb), cadmium (Cd), nickel (Ni), copper (Cu), and zinc (Zn) were present in spots containing foreign materials. Ti concentrations are notably higher in outdoor PET (6.57%) compared to indoor PE (3.05%) and outdoor HDPE (0.14%).

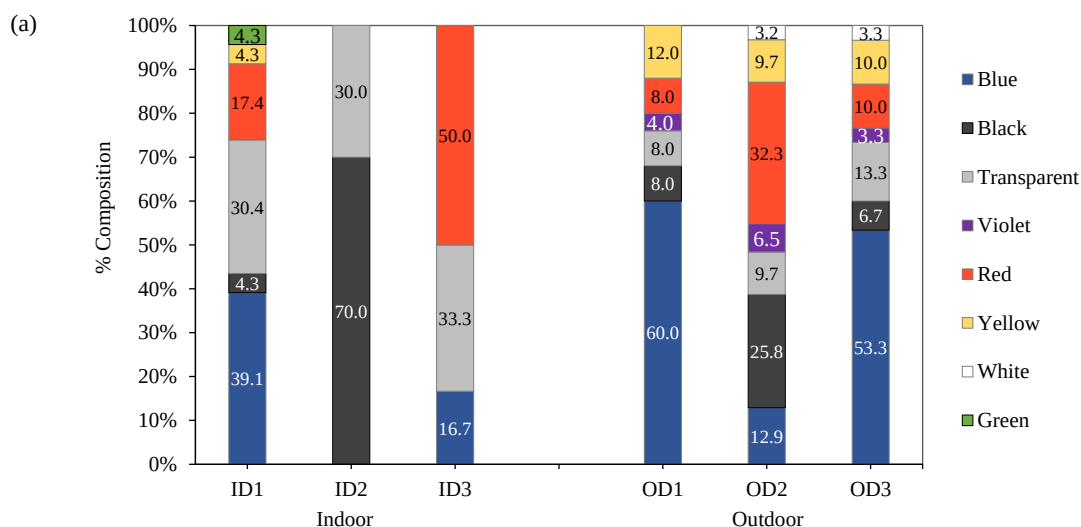


Figure 3. Relative abundance of MPs in indoor (ID) and outdoor (OD) environments (a) color, (b) shape, and (c) polymer type

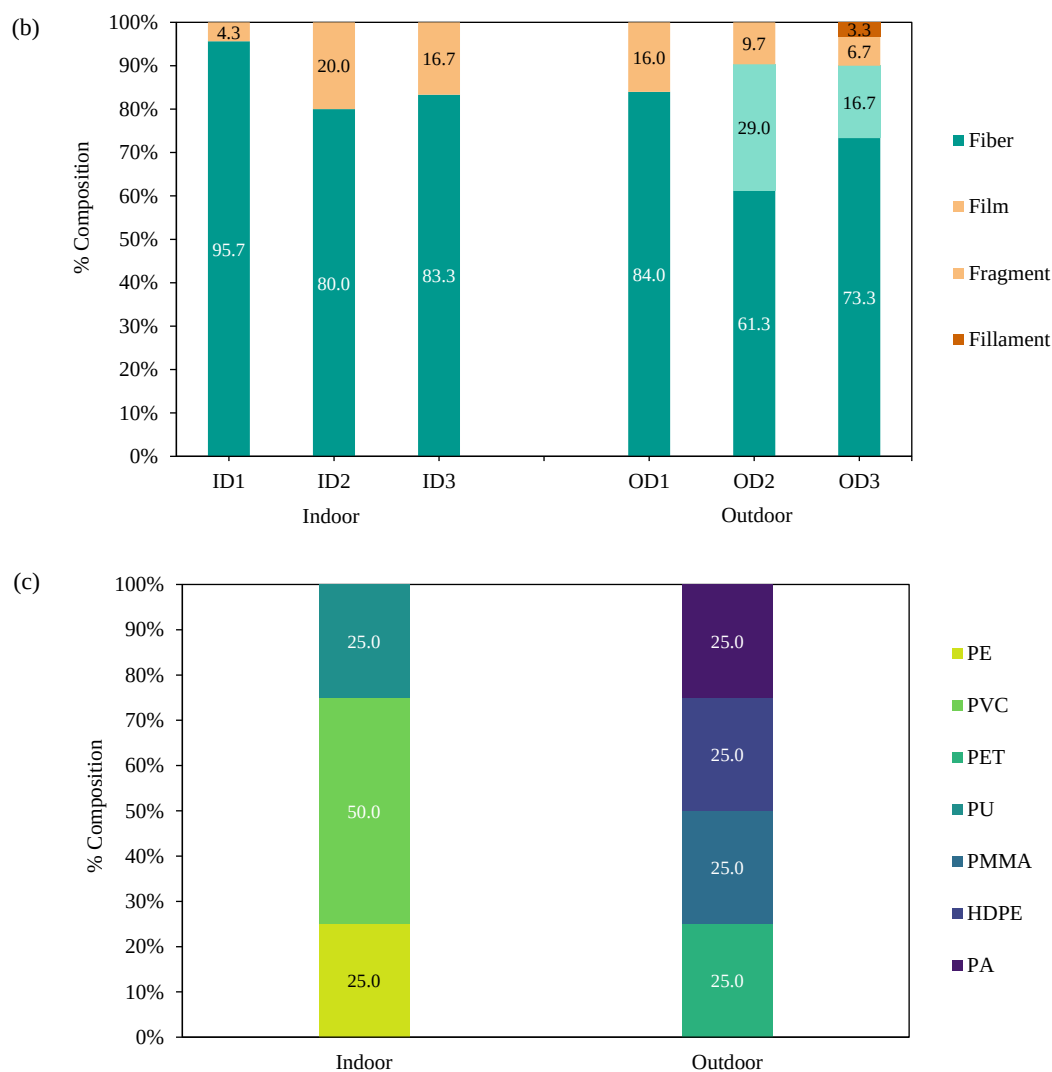


Figure 3. Relative abundance of MPs in indoor (ID) and outdoor (OD) environments (a) color, (b) shape, and (c) polymer type (cont.)

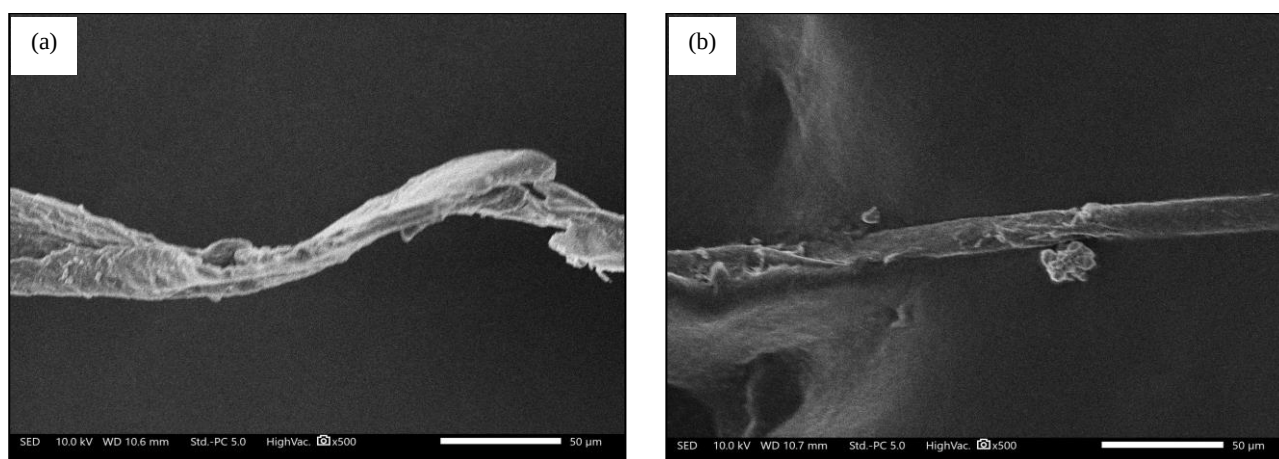


Figure 4. SEM images of MPs (a) frayed indoor PE fiber, (b-c) outdoor MPs with (b) PET fiber and (c) a fragmented HDPE particle

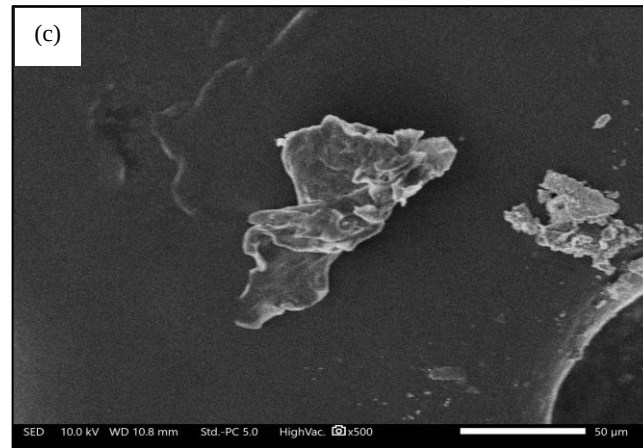


Figure 4. SEM images of MPs (a) frayed indoor PE fiber, (b-c) outdoor MPs with (b) PET fiber and (c) a fragmented HDPE particle (cont.)

Table 2. Summary of adsorbed metals associated with MPs, (a) indoor PE fiber, (b) outdoor PET fiber and (c) fragmented HDPE outdoor.

Element	a. Indoor (Polyethylene)	b. Outdoor (Polyethylene terephthalate)	c. Outdoor (High density polyethylene)
O	51.98 ± 5.24	51.35±6.45	77.42±11.95
Mg	nd	0.96±1.58	0.17±2.59
Al	nd	2.44±2.13	0.14±2.67
Ti	3.05±4.36	6.57±7.34	18.29±17.64
Cr	nd	nd	nd
Ni	0.14±30.62	nd	3.71±113.30
Cu	nd	nd	nd
Zn	16.90±5.29	16.82±5.97	nd
Cd	0.21±3.23	nd	nd
Hg	9.58±7.14	9.35±8.51	nd
Pb	18.13±8.32	12.50±10.50	nd
Total	100.00	100.00	100.00

Cr is only detected only in the outdoor HDPE sample (18.29%), while lead (Pb) and mercury (Hg) are present in both indoor and outdoor fibers, with Pb levels reaching 18.13% in indoor PE and 12.50% in outdoor PET. Cd was recorded in indoor PE (0.21%), while Ni was detected only in indoor PE, with highly variable concentrations. Cu was not found in any of the samples.

4. DISCUSSION

MPs were detected in both indoor and outdoor environments in this study. Outdoor environments may contain higher MPs concentration due to greater exposure to harsh conditions such as heat and mechanical wear. These factors accelerate the breakdown of macroplastics, increasing the likelihood of MP generation compared to the more sheltered indoor setting. Variations in indoor MP abundance may be influenced by differences in human activity

and ventilation efficiency (Sharaf Din et al., 2024), with fibers being the predominant form in both environments.

Contamination in both indoor and outdoor environments arises from multiple sources and is largely driven by poor solid waste management practices (Paler et al., 2022) and varying environmental conditions. While existing studies often focus on quantifying plastic pollution, they fall short in addressing the more pressing concern how rapidly plastics are being released into the environment (Tabañag et al., 2022). Indoor MPs are primarily linked to textiles, household items, and synthetic furnishings, which continuously shed PET and PE fibers into the air. This study found that black (70.0%) and red (50.0%) MPs were predominant indoors, consistent with prior research identifying indoor MP contamination from fabrics and furnishings (Sharaf Din et al., 2024). Similarly, Liao et al. (2021) and

Perera et al. (2022) reported significant indoor PET presence, with PET accounting for 28.4% and 60% of MPs, respectively. This suggests that synthetic textiles, carpets, and household plastics contribute to indoor MP accumulation. The presence of PVC is likely attributed to human activities, while the turbulence created by airflow, aids in the dispersion of MPs. In contrast, outdoor MP composition is more diverse, influenced by environmental exposure, weathering, and industrial or urban waste sources. This study identified blue MPs as the most prevalent outdoors (53.3-60.0%), likely due to the degradation of plastic materials such as tarpaulins and packaging. A similar trend was observed in London, where blue and transparent fibers dominated outdoor samples (Boakes et al., 2023b). The polymeric composition further supports these findings, with indoor MPs being predominantly polyvinyl chloride (PVC) (50.0%), while outdoor MPs exhibited a broader range of polymers, including polyethylene terephthalate (PET), polyamide (PA), high-density polyethylene (HDPE), and polymethyl methacrylate (PMMA). Such variations highlight the influence of regional industrial activities, waste management practices, and atmospheric transport on MP distribution.

Identifying MP sources remains challenging due to the complexity of environmental interactions. However, morphological characteristics, together with polymer composition, provide valuable insights into potential origins. This study found fibrous MPs to be the dominant morphology, comprising 80.0-95.7% of indoor MPs and 61.3-84.0% of outdoor MPs, followed by fragments. These findings align with previous studies, which consistently report fibers and fragments as the most abundant MP types in both indoor and outdoor environments (Liao et al., 2021; Cui et al., 2022; Perera et al., 2022; Romarate et al., 2023; Sharaf Din et al., 2024; Jahanzaib et al., 2025). The predominance of indoor fibers supports the link to the textile shedding, while the presence of diverse polymer types outdoors suggests multiple sources, including urban runoff, industrial emissions, and atmospheric transport. Understanding these patterns is crucial for assessing MP exposure risks and informing mitigation strategies. Given these findings, with MPs densities in this study 0.155 ± 0.106 MP/m³ indoors; 0.341 ± 0.038 MP/m³ outdoors, the implications for an adult person's exposure to MPs are concerning. On average, a person may inhale approximately 1.1 to 1.8 MPs/day indoors and 2.5 to 3.9 MPs/day outdoors, based on normal minute ventilation rates of 5 to 8 liters

of air per minute and an estimated exposure time of 1 hour (Romarate et al., 2023; Levitan, 2015). This study's estimated daily MP inhalation followed a similar trend, with indoor intake ranging from 0.5 to 3.2 MPs per day. The highest recorded indoor intake was observed at Indoor 1, ranging from 2 to 3.2 MPs per day. Outdoor MP inhalation was consistently higher, ranging from 2.1 to 4.3 MPs/day, with the peak intake recorded at outdoor 2 (2.7-4.3 MPs/day).

Research on airborne MP exposure remains limited these results highlight potential health risks, particularly concerns about MP inhalation and its possible effects on the respiratory system. Table 3 presents a comparative analysis of recent studies on MP contamination. However, direct comparisons are challenging due to variations in sampling methodologies, analytical techniques, environmental conditions, and study parameters. Understanding the sources, behavior, and potential health risks of airborne MPs is essential for informing air quality management policies and reducing plastic pollution. Future studies should explore long-term exposure risks, polymer degradation pathways, and mitigation strategies to address this growing environmental and public health issue. This study presented relatively low airborne MP concentrations (1.65 ± 0.43 MP/m³ indoors; 0.72 ± 0.37 MP/m³ outdoors), comparable to Sri Lanka (Perera et al., 2022) and India (Nandi et al., 2024), but significantly lower than those in highly urbanized areas like China (Liao et al., 2021) and Brazil (Amato-Lourenço et al., 2022). In terms of morphology, both fibers and fragments were observed, consistent with studies from Sri Lanka, India, and New Jersey (Yao et al., 2022), while fragment dominance aligns with studies in China and Brazil. The detected colors - mainly white and transparent - are similar to those reported in India, Sri Lanka, and London (Boakes et al., 2023b), suggesting common sources such as packaging or domestic items.

Polymer analysis revealed PE, PP, PS, and PVC, with PE and PP also reported in China, Sri Lanka, Pakistan (Sharaf Din et al., 2024), and India. The presence of PS and PVC reflects overlap with India, hinting at shared sources such as insulation or consumer goods. Overall, the findings mirror trends observed in developing regions and highlight the influence of local environmental and human factors on airborne MP profiles.

Environmental factors like wind, waves, and sunlight accelerate MP degradation by fragmenting polymers (Lin et al., 2022), increasing their surface

Table 3. Summary of atmospheric MPs

Sampling location	Sampling environment	Average density MP/m ³ ±SD	Dominant MPs characteristics			References	
			Shape	Color	Polymer type		
Wenzhou City, China	Indoor	1.583±1.181	Fragment	84-94%	PET	28%	Liao et al. (2021)
	Outdoor	189±85		90-96%	PE	27%	
Yangzhou, Jiangsu, China	Indoor	34-69%	Fragment	85-89%	PA	31-57%	Cui et al. (2022)
São Paulo, Brazil	Indoor	73±50.52	Fragment	64%	PE	59%	Amato-Lourenço et al. (2022)
	Outdoor	123.20±47.09		74%		67%	
Sri Lanka	Indoor	0.13-0.93	Fiber	-	PET	60%	Perera et al. (2022)
	Outdoor	0.01-0.23	Fragment	Transparent	PET	48%	
Newark, New Jersey	Indoor	(3.57±1.41) ×10 ³	Fiber	(1.09±0.61) ×10 ⁴	PE	-	Yao et al. (2022)
London, England	Indoor	106 - 344	Fiber	Blue/Transparent	-	-	Boakes et al. (2023)
	Outdoor	23		Blue/Transparent			
NUST, Islamabad, Pakistan	Indoor	4.34±1.93	Fiber	66%	PET	52%	Sharaf Din et al. (2024)
	Outdoor	0.93±0.32		58%		42%	
Ranchi, Jharkhand, India	Indoor	0.0166±0.00097	Fiber	-	PE, PP, PS	-	Nandi et al. (2024)
	Outdoor	2.92±0.0688	Fragment	White/Transparent	PVC	-	
Marikina, Metro Manila, Philippines	Indoor	0.155±0.09	Fiber	90%	PVC	50%	This study
Philippines	Outdoor	0.341±0.03	Fiber	Blue	PET, PA, HDPE, PMMA	25%	

area and enhancing their sorption capacity (Wang et al., 2019). SEM-EDX analysis in this study identified additional elements originating from either the natural or virgin plastic composition, suggesting either environmental adsorption. Metals such as Cu, Al, and Ti were detected, consistent with findings from indoor and outdoor air samples in Pakistan (Sharaf Din et al., 2024).

Additionally, Hg, Pb, and Cd are toxic heavy metals that pose serious health risks due to their persistence and bioaccumulation. Mercury, especially as methylmercury, is a potent neurotoxin capable of impairing cognitive function and damaging the kidneys and liver. Lead exposure, particularly in children, causes neurodevelopmental delays, anemia, and cardiovascular issues. Cadmium primarily targets the kidneys, weakens bones, and has carcinogenic potential (Balali-Mood et al., 2021). Although direct causal links between metals adsorbed on MPs and specific health outcomes remains to be established, this study highlights that airborne MPs can act as carriers of hazardous trace elements. Their potential to transport these toxic substances through inhalation pathways emphasizes the possible risks to human health and the environment.

5. CONCLUSION AND RECOMMENDATIONS

This study presents the first characterization of airborne MPs in both indoor and outdoor environments in the Philippines, revealing significant variations in abundance, morphology, and chemical composition. The findings demonstrate that outdoor air harbors nearly double the concentration of MPs compared to indoor environments, emphasizing the influence of traffic emissions, resuspension from road dust, and atmospheric turbulence in enhancing MP dispersion. The dominance of fibrous particles across both environments reflects the extensive shedding of synthetic textiles. The presence of diverse polymer types - PVC indoors and PET, PA, PMMA, and HDPE outdoors - indicates multiple anthropogenic sources, including clothing, packaging materials, and building products.

Beyond physical characterization, elemental analysis through SEM-EDX revealed that MPs serve as potential carriers of toxic metals such as Ti, Cr, Pb, Hg, and Cd, which may originate from industrial emissions, pigments, and fuel combustion. The elevated presence of Pb in indoor PE fibers (18.13%) and Cr in outdoor HDPE fragments (18.29%) highlights potential indoor-outdoor pollution linkages

and the complexity of atmospheric contamination. These findings suggest that MPs not only represent inhalable particulates but also act as vectors of hazardous substances potentially exacerbating human health risks through respiratory exposure.

While the study is limited by its sampling duration and localized scope, it establishes a foundation for understanding atmospheric MP pollution in urban tropical environments. Additionally, the use of GF/C Whatman filters, while effective for general particulate matter, has a nominal pore size and may not efficiently retain smaller MPs or nanoplastics, potentially leading to underestimation of total airborne MP concentrations. Future research should explore seasonal and spatial variability, resuspension dynamics, and human exposure pathways. Integrating toxicological assessments and long-term monitoring will be critical for evaluating the cumulative effects of MPs and their associated contaminants. Ultimately, the study underscores the need for targeted environmental policies, improved waste management, and public awareness campaigns to mitigate airborne MP pollution and safeguard public health.

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AUTHOR CONTRIBUTIONS

Jade Rae Ministerio conceptualized the study, conducted data analysis, and wrote the manuscript. Najiha Amer assisted with sampling and laboratory analysis. Rodolfo Romarate II contributed to manuscript writing and developed the sampling methodology. Hernando Bacosa conceptualized and supervised the research and provided editorial support.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no competing interests relevant to the content of this article.

REFERENCES

- Akhbarizadeh R, Dobaradaran S, Torkmahalleh MA, Saeedi R, Aibaghi R, Faraji Ghasemi F. Suspended fine particulate matter (PM_{2.5}), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: Their possible relationships and health implications. *Environmental Research* 2021;192: Article No. 110339.

- Amato-Lourenço LF, Dos Santos Galvão L, Wiebeck H, Carvalho-Oliveira R, Mauad T. Atmospheric microplastic fallout in outdoor and indoor environments in São Paulo megacity. *Science of the Total Environment* 2022;821:Article No. 153450.
- Arcadio CGLA, Navarro CKP, Similatan KM, Inocente SAT, Ancla SMB, Banda MHT, et al. Microplastics in surface water of Laguna de Bay: First documented evidence on the largest lake in the Philippines. *Environmental Science and Pollution Research* 2022;30(11):29824-33.
- Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic Mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology* 2021;12:Article No. 643972.
- Beckingham B, Apintiloaiei A, Moore C, Brandes J. Hot or not: Systematic review and laboratory evaluation of the hot needle test for microplastic identification. *Microplastics and Nanoplastics* 2023;3(1):Article No. 8.
- Bhuyan MdS. Effects of microplastics on fish and in human health. *Frontiers in Environmental Science* 2022;10:Article No. 827289.
- Boakes LC, Patmore IR, Bancone CEP, Rose NL. High temporal resolution records of outdoor and indoor airborne microplastics. *Environmental Science and Pollution Research* 2023a;30(13):39246-57.
- Boakes LC, Patmore IR, Bancone CEP, Rose NL. High temporal resolution records of outdoor and indoor airborne microplastics. *Environmental Science and Pollution Research* 2023b;30(13):39246-57.
- Brahney J, Mahowald N, Prank M, Cornwell G, Klimont Z, Matsui H, et al. Constraining the atmospheric limb of the plastic cycle. *Proceedings of the National Academy of Sciences of America* 2021;118(16):e2020719118.
- Cui J, Chen C, Gan Q, Wang T, Li W, Zeng W, et al. Indoor microplastics and bacteria in the atmospheric fallout in urban homes. *Science of the Total Environment* 2022;852:Article No. 158233.
- Dimaongon N, Araña KN, Bacosa H. Emerging microplastic contamination in the food industry: The case of commercial table salts in Iligan, Philippines. *The Philippine Journal of Science* 2024;153(1):75-9.
- Discutido CDJ, Sia AALR, Dela Cruz CM. Near-infrared light and openCV as components for low-cost airborne microplastic detection machine. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 2024;X-5-2024:57-62.
- Ellos DMC, Chien MF, Inoue C, Nakano H, Isobe A, Onda DFL, et al. Mesoplastics: A review of contamination status, analytical methods, pollution sources, potential risks, and future perspectives of an emerging global environmental pollutant. *Toxics* 2025;13(3):Article No. 227.
- Gabriel AD, Bacosa HP. Microplastic abundance and distribution in the sediment of Cagayan de Oro River, Philippines. *Soil and Sediment Contamination: An International Journal* 2024;33(8):1252-68.
- Game S, Mahagamage Y. Microplastics in personal care products and cosmetics in Sri Lanka. *Heliyon* 2024;10(8):e29393.
- Gonzales C, Shiu RF, Bacosa HP. Mesoplastic and microplastic pollution in the soil of small-scale agricultural areas in Iligan, Mindanao, Philippines. *Soil and Sediment Contamination: An International Journal* 2024;34(5):905-21.
- Jahanzaib M, Sharma S, Park D. Microplastics comparison of indoor and outdoor air and ventilation rate effect in outskirts of the Seoul metropolitan city. *Emerging Contaminants* 2025;11(1):Article No. 100408.
- Kapp KJ, Miller RZ. Electric clothes dryers: An underestimated source of microfiber pollution. *PLoS ONE* 2020;15(10):e0239165.
- Koelmans AA, Redondo-Hasselerharm PE, Nor NHM, de Ruijter VN, Mintenig SM, Kooi M. Risk assessment of microplastic particles. *Nature Reviews Materials* 2022;7(2):138-52.
- Kye H, Kim J, Ju S, Lee J, Lim C, Yoon Y. Microplastics in water systems: A review of their impacts on the environment and their potential hazards. *Heliyon* 2023;9(3):e14359.
- Levitan R. Avoid Airway Catastrophes on the Extremes of Minute Ventilation. *American College of Emergency Physicians*; 2015.
- Liao Z, Ji X, Ma Y, Lv B, Huang W, Zhu X, et al. Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China. *Journal of Hazardous Materials* 2021;417:Article No. 126007.
- Lin Z, Jin T, Zou T, Xu L, Xi B, Xu D, et al. Current progress on plastic/microplastic degradation: Fact influences and mechanism. *Environmental Pollution* 2022;304:Article No. 119159.
- Mamun AA, Prasetya TAE, Dewi IR, Ahmad M. Microplastics in human food chains: Food becoming a threat to health safety. *Science of the Total Environment* 2023;858:Article No. 159834.
- Marcharla E, Vinayagam S, Gnanasekaran L, Soto-Moscoso M, Chen WH, Thanigaivel S, et al. Microplastics in marine ecosystems: A comprehensive review of biological and ecological implications and its mitigation approach using nanotechnology for the sustainable environment. *Environmental Research* 2024;256:Article No. 119181.
- Nandi S, Kumar RN, Dhandapani A, Iqbal J. Characterization of microplastics in outdoor and indoor air in Ranchi, Jharkhand, India: First insights from the region. *Environmental Pollution* 2024;346:Article No. 123543.
- Ng EL, Huerta Lwanga E, Eldridge SM, Johnston P, Hu HW, Geissen V, et al. An overview of microplastic and nanoplastic pollution in agroecosystems. *Science of the Total Environment* 2018;627:1377-88.
- Paler MKO, Tabañag IDF, Siacor FDC, Geraldino PJL, Walton MEM, Dunn C, et al. Elucidating the surface macroplastic load, types and distribution in mangrove areas around Cebu Island, Philippines and its policy implications. *Science of the Total Environment* 2022;838:Article No. 156408.
- Patilan DM, Romarate Ii R, Bacosa H. Preliminary Study on mercury and lead in the ambient air of metro Manila, the Philippines. *The Philippine Journal of Science* 2024;153(3):1073-6.
- Peña A, Rodríguez-Liébana JA, Delgado-Moreno L. Interactions of microplastics with pesticides in soils and their ecotoxicological implications. *Agronomy* 2023;13(3):Article No. 701.
- Perera K, Ziajahromi S, Bengtson Nash S, Manage PM, Leusch FDL. Airborne Microplastics in Indoor and Outdoor Environments of a Developing Country in South Asia: Abundance, Distribution, Morphology, and Possible Sources. *Environmental Science and Technology* 2022;56(23):16676-85.
- Pothiraj C, Amutha Gokul T, Ramesh Kumar K, Ramasubramanian A, Palanichamy A, Venkatachalam K, et al.

- Vulnerability of microplastics on marine environment: A review. *Ecological Indicators* 2023;155:Article No. 111058.
- Rehm R, Zeyer T, Schmidt A, Fiener P. Soil erosion as transport pathway of microplastic from agriculture soils to aquatic ecosystems. *Science of the Total Environment* 2021;795: Article No. 148774.
- Ritter H. Plastics for people: Benefits and disadvantages (Kunststoffe für die Menschen: Nutzen und Nachteile). *Chemistry in our time (Chemie in unserer Zeit)* 2023;30(18):53662-73.
- Romarate RA, Ancla SMB, Patilan DMM, Inocente SAT, Pacilan CJM, Sinco AL, et al. Breathing plastics in Metro Manila, Philippines: Presence of suspended atmospheric microplastics in ambient air. *Environmental Science and Pollution Research* 2023;30(18):53662-73.
- Sajorne RE, Cayabo GDB, Gajardo LJA, Mabuhay-Omar JA, Creencia LA, Bacosa HP. Disentangling microplastic pollution on beach sand of Puerto Princesa, Palawan Island, Philippines: Abundance and characteristics. *Sustainability* 2022;14(22):Article No. 15303.
- Salthammer T. Microplastics and their Additives in the Indoor Environment. *Angewandte Chemie* 2022;134(32): e202205713
- Sharaf Din K, Khokhar MF, Butt SI, Qadir A, Younas F. Exploration of microplastic concentration in indoor and outdoor air samples: Morphological, polymeric, and elemental analysis. *Science of the Total Environment* 2024;908:Article No. 168398.
- Suh WD, Jo HH, Kim YU, Kim S. Degradation of floor finishing materials owing to continuous gait: A comprehensive study on the generation and impact of microplastics. *Journal of Hazardous Materials* 2025;484:Article No. 136726.
- Tabañag IDF, Mendoza MLG, Samimi AM, Saba MYS, Ignacio PSP, Onda DFL. A Call for Digital Transformation in the Marine Environmental Protection Sector: A case for marine plastic litter pollution monitoring. *Innovatus: A Journal on Computing Technology Innovations* 2022;22(5):1-9.
- Tao D, Zhang K, Xu S, Lin H, Liu Y, Kang J, et al. Microfibers released into the air from a household tumble dryer. *Environmental Science and Technology Letters* 2022;9(2):120-6.
- Tejano JBB, Araña KND, Eleccion EB, Laya-og ME, Palasol CDS, Pimentel CS, et al. Microplastics in the road dust of Iligan City, the Philippines. *Philippine Journal of Science* 2024;153(5):1751-6.
- Wang J, Liu X, Liu G. Sorption behaviors of phenanthrene, nitrobenzene, and naphthalene on mesoplastics and microplastics. *Environmental Science and Pollution Research* 2019;26(12):12563-73.
- Xu L, Bai X, Li K, Zhang G, Zhang M, Wu Z, et al. Sandstorms contribute to the atmospheric microplastic pollution: Transport and accumulation from degraded lands to a megacity. *Journal of Hazardous Materials* 2024;480:Article No. 136427.
- Yao Y, Glamoclija M, Murphy A, Gao Y. Characterization of microplastics in indoor and ambient air in northern New Jersey. *Environmental Research* 2022;207:Article No. 112142.
- Yasin S, Hussain M, Uddin A, Zheng Q, Shi J, Song Y. Recycling of binary polymer (PET/SBR) carpet into microfibrillar composites: A life cycle perspective with microplastics quantification. *Sustainable Materials and Technologies* 2024;40:e00988.

Attenuation of Organic Matter in Landfill Leachate: Seasonal Characterization and Soil Column Evaluation

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ABSTRACT

Landfill leachate (LL) from landfills and open dumpsites poses significant risks to surrounding soils and water bodies. This study investigated seasonal variations in physicochemical and heavy metal characteristics of LL at the newly operational Bancharedada landfill site in Nepal using the Leachate Pollution Index (LPI). It also evaluated the attenuation of organic content, measured as chemical oxygen demand (COD), across different soil textures using fixed-bed column tests. Kinetics analyses employed the Yoon-Nelson model (YNM), Thomas model (TM), and Adam and Bohart model (ABM). The biological oxygen demand (BOD₅)/COD ratio ranged from 0.44 to 0.51, with higher values in the dry seasons and lower values during the monsoon, indicating rainfall-induced dilution of organic pollutants. The bed saturation time for COD removal was longest in clayey soil (35 days) and shortest in sandy soil (4 days). YNM provided the best model fit and was therefore applied for COD breakthrough prediction across soil textures. YNM rate constants (KYN) were lower in clayey soils and higher in sandy soils, thereby increase in breakthrough times (τ) and adsorption capacities (Q_0) in clayey soils whereas the sandy soils shows the opposite trend, highlighting the strong influence of soil texture on COD attenuation potential.

HIGHLIGHTS

- Seasonal LL quality was assessed using the Leachate Pollution Index.
- Fixed-bed column tests evaluated COD attenuation in seven soil textures.
- The Yoon-Nelson model best predicted COD removal across soil types.
- Soil texture strongly influenced COD removal.

1. INTRODUCTION

In 2016, global municipal solid waste generation reached 2.01 billion tonnes and is projected to reach 3.40 billion tonnes by 2050. South Asian cities contributed 334 million tonnes in 2016, with estimates rising to 466 million tonnes by 2030 and 661 million tonnes by 2050 (Kaza et al., 2018). In Nepal, urbanisation has substantially increased waste generation (Pathak et al., 2020), amounting to approximately 1.8 million tonnes annually and requiring 35 hectares of land annually for untreated disposal (Goyal et al., 2020). Current disposal practices

include open dumping (48.6%), burning (32.1%), and river dumping (27.4%) (Central Bureau of Statistics, 2020), leading to significant environmental challenges such as greenhouse gas emissions, land and water contamination, and climate change.

Kathmandu Metropolitan City generated approximately 766 tonnes/day of waste in 2021, a figure projected to reach 1,259 tonnes/day by 2035 (Khanal, 2023). Waste from the Kathmandu Metropolitan City and nearby municipalities is currently managed at the Bancharedada landfill site, located 27 km northwest of Kathmandu. The

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Bancharedada landfill site still lacks a facility for treating leachate. LL is a byproduct of waste decomposition and varies in composition depending on rainfall, landfill age, and waste characteristics (Nayanthika et al., 2018; Nawaz et al., 2020). The Leachate Pollution Index (LPI) can be used to leachate contamination potential and to compare compliance with the regulatory standards (Hussein et al., 2019).

Leachate treatment mechanisms include biological, chemical, and physicochemical processes such as activated sludge, advanced oxidation, adsorption, and membrane filtration (Teng et al., 2021). In landfill sites, the soil cover used for daily waste covering has varying permeability and can function as an in-situ treatment medium for LL (Yidong et al., 2012). This underscores the need to understand the containment and attenuation behaviour of LL across different soil textures. However, research on leachate-soil interactions and natural attenuation of contaminants remains limited (Gonçalves et al., 2019).

Clayey soil is commonly preferred as a daily landfill cover materials due to its low hydraulic conductivity and high sorption capacity, which enhance pollutant retention (Qi et al., 2013; Chetri and Reddy, 2021). Soil texture, particularly the fine content in clayey soil, plays a key role in pollutant attenuation by attracting ions and enhancing adsorption (Regadío et al., 2015; Cronan, 2018). Column experiments are widely used to simulate field conditions and evaluate leachate-soil interactions over time (Naka et al., 2016). This highlights the significant influence, particularly, remain limited. This highlights the significant influence of soil texture on pollutant attenuation and containment. However, studies investigating the attenuation of organic contaminants across localised soil textures, particularly in the South Asian context, remain limited.

This study is the first to investigate the behaviour of COD as an absorbate across different soil textures found in Nepal, focusing on their attenuation capacity to prevent subsoil contamination. Additionally, the study examined seasonal variations in LL physicochemical and heavy metal composition and applied the LPI to identify the key contributing pollutants. Fixed-bed column experiments were conducted to evaluate COD-soil interactions, and the resulting data were analysed using three kinetic models (YNM, TM, and ABM) to quantify COD removal rates. Model performance was evaluated based on R^2 values, and the best-fitting model was used to predict COD attenuation across soil textures,

providing valuable insights to support the design of effective landfill liner materials.

2. METHODOLOGY

2.1 Materials

2.1.1 Leachate and soil sampling

Leachate samples were collected from the Bancharedada landfill site in Nepal, as shown in Figure 1. The site is located 27 km northwest of Kathmandu and 2 km west of the previous Sisdoile landfill site, within the boundaries of Kakani Rural Municipality (Ward number 2) in Nuwakot District and Dhunibesi Municipality (Ward number 1) in Dhading District. Leachate sampling was conducted over 12 months, with a total of 12 samples collected from March 2023 to February 2024, covering the dry, summer, wet, and winter seasons. The samples were collected and preserved according to the Standard Methods for the Examination of Water and Wastewater (Baird et al., 2017).

A purposive sampling technique was used for the first three soil samples (S1, S2, and S3), selected based on clay, sand, and silt content exceeding 50%, as per soil maps prepared by the National Soil Science Research Center (NSSRC), a unit under the Nepal Agricultural Research Council (NARC), Government of Nepal (<https://soil.narc.gov.np/>). Soil samples S4 and S5 were collected from the Sisdoile landfill site, while S6 and S7 were taken from the Bancharedada landfill site. All samples were collected manually at a depth of 0-15 cm after clearing surface debris. The details of the soil sampling sites used in the column experiments are shown in Table 1.

2.1.2 Column tests setup and experimental design

Column tests were conducted using leachate samples applied to seven soil types (clayey, silt loam, sandy, loam, sandy loam, clay loam, and silt loam) under controlled conditions. Polyvinyl chloride pipes (4.5 cm diameter, 30 cm packing height) were used, with 2 mm gravel and sand layers placed at the top and bottom to ensure steady flow. Each day, 250 mL of leachate was applied to each column (25 mL every 30 min for 5 h) over one month. Effluents were collected every 12 h for COD analysis. Bulk densities of the soils ranged from 1.33 to 1.65 g/cm³. The column setup followed the (Organisation for Economic Co-operation and Development (OECD), 2004) and Naka et al. (2016) guidelines. A schematic of the experimental setup is shown in Figure 2.

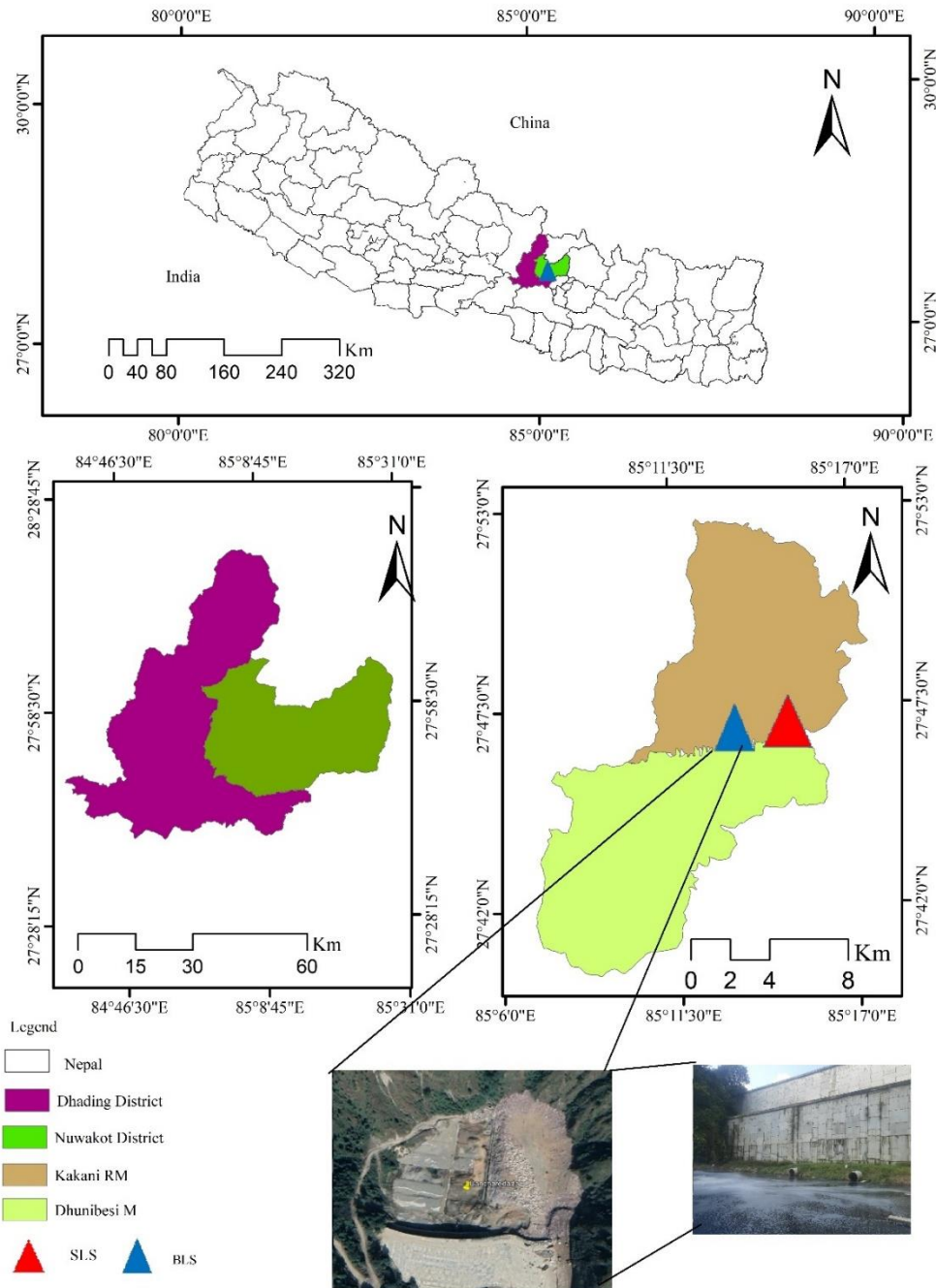


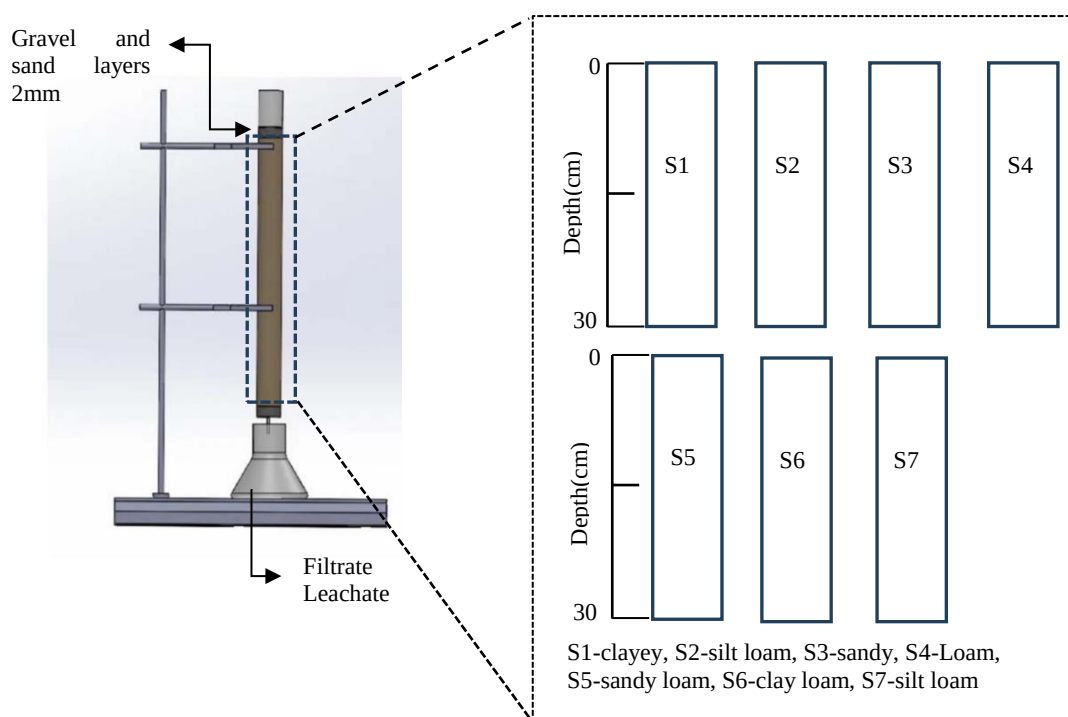
Figure 1. Map of Sisdole landfill site located in Kakani rural municipality (RM), Nuwakot district and Bancharedada landfill site located on the border of Kakani Rural Municipality and Dhunibesi municipality, Dhading district, Bagmati province, Nepal (image from Google Map taken in 2023)

Table 1. Soil sampling sites used in the column experiments

Soil samples	Latitude and longitude	Elevation, above mean sea level (m)	District/RM/Mun	Province
S1 (clayey)	27°39'15.45", 83°02' 10.23"	112	Kapilbastu/ Buddhahumi Municipality-4	Lumbini
S2 (silt loam)	26° 26' 45", 87° 21' 1"	69	Morang/ Jahada Rural Municipality-6	Koshi
S3 (sandy)	27°45' 48.61", 85° 21' 59.80"	1388	Kathmandu/Budhanilkanta Municipality-12	Bagmati
S4 (loam)	27°46' 36.91", 85° 14' 48.81"	1154	Nuwakot/Kakani Rural Municipality-3	Bagmati

Table 1. Soil sampling sites used in the column experiments (cont.)

Soil samples	Latitude and longitude	Elevation, above mean sea level (m)	District/RM/Mun	Province
S5 (Sandy loam)	27°46'32.56", 85° 14' 37.56"	1130	Nuwakot/Kakani Rural Municipality-3	Bagmati
S6 (clay loam)	27° 46' 25.79", 85° 13' 42.20"	1053	Dhading/ Dhunibesi Municipality-1	Bagmati
S7 (silt loam)	27° 46' 31.35", 85° 13' 47.23"	1062	Dhading/ Dhunibesi Municipality-1	Bagmati

**Figure 2.** A schematic of the experimental setup of the column test

2.2 Methods

2.2.1 Analytical methods

The analysis of major physical and chemical properties of raw leachate and effluent obtained from the soil column tests (liquid filtrate) was conducted using standard procedures outlined in the Standard Methods for the Examination of Water and Wastewater, APHA 23rd Edition (Baird et al., 2017). Table 2 presents the parameters, methods, instrumentation, and references used for the analysis of leachate and soil samples.

2.2.2 Calculation of the leachate pollution index

LPI measures the contamination potential of LL (Lothe and Sinha, 2017). It incorporates 18 parameters, including COD, BOD₅, TKN, NH₃-N, pH, TDS, Cr, Pb, Hg, As, cyanide, phenolic compounds, Zn, Ni, Cu, Cl, Fe, and total coliform (Kumar and

Alappat, 2005). Due to analytical limitations, cyanide and phenolic compounds were not analysed in this study. The overall LPI and three sub-indices – LPI Organic (LPI_{or}), LPI inorganic (LPI_{in}), and LPI heavy metals (LPI_{hm}) – were calculated to assess contamination potential of each component. Each sub-index was estimated using the concentration values of the available leachate parameters using equation (1):

$$LPI = \frac{\sum_{i=1}^n W_i P_i}{\sum_{i=1}^n W_i} \quad (1)$$

Then, overall LPI was estimated based on equation (2):

$$\text{Overall LPI} = 0.232 \text{ LPI}_{or} + 0.257 \text{ LPI}_{in} + 0.511 \text{ LPI}_{hm} \quad (2)$$

Where; W_i is the weight for the i^{th} pollutant variable, P_i is the sub-index score of the i^{th} pollutant variable, and n is the number of leachate pollutant variables.

Table 2. Analytical methods for leachate and soil samples

Parameter	Method	Instrumentation	Reference
Leachate samples			
pH	Electrode	pH meter	4500-H ⁺ B. APHA
Conductivity	Electrode	Conductivity meter	2510 B. APHA
Turbidity	Nephelometric	Turbidity meter	2130 B. APHA
Total dissolved solids	Gravimetric	Oven drying at 180°C	2540 C. APHA
BOD ₅	Iodometric titration	BOD Incubator	5210 B. APHA
COD	Closed reflux colorimetric	Colorimeter	5220 D. APHA
Ammoniacal Nitrogen (NH ₃ -N)	Phenate Method	Spectrophotometer	4500- NH ₃ F. APHA
Nitrate-Nitrogen (NO ₃ -N)	Colorimetric	Spectrophotometer	4500-NO ₃ B. APHA
Total Kjeldahl Nitrogen (TKN)	Semi Micro Kjeldahl method	Kjeldahl apparatus	4500-N _{org} C. APHA
Zinc (Zn)	Direct air-acetylene flame	Flame Atomic Absorption	3111 B. APHA
Copper (Cu)	method	Spectrophotometer	
Manganese (Mn)			
Chromium (Cr)			
Cadmium (Cd)			
Lead (Pb)			
Nickel (Ni)			
Mercury (Hg)	Cold Vapour	Atomic Absorption	3112. APHA
Arsenic (As)	Continuous Hydride Generation	Spectrophotometer	311C. APHA
Soil samples			
pH	Electrometric	pH meter	Kueneman et al. (2020)
Moisture	Oven drying at 105°C	Oven	
Soil texture	Hydrometer	Hydrometer analysis	
Bulk density	Core sampler	Core sampler	Allison et al. (1954)
Particle density	Pycnometer	Pycnometer	
Organic matter	Loss on Ignition 400°C	Muffle Furnace	
Exchangeable calcium and magnesium	EDTA titrimetric method	Titration	Carter and Gregorich (2007)
Exchangeable potassium	Flame photometry	Flame photometer	
Cation exchange capacity (CEC)	EDTA Titrimetric method	Titration	
Available phosphorus	Olsen method	Spectrophotometer	Motsara and Roy (2008)

2.2.3 Fixed bed column kinetics modelling using YNM, TM, and ABM

The bed saturation of COD in the fixed-bed column was assessed using breakthrough curves ([Ghosh et al., 2012](#); [Sugashini and Begum, 2013](#)). This study employed YNM, TM, and ABM to analyse the adsorption kinetics of different soil textures, as these models are widely used and have provided a good fit for column experiments with LL and wastewater ([Keerthanan et al., 2021](#); [Nazari, 2017](#)).

YNM assumes that the probability of adsorbate adsorption decreases with time for each molecule ([Patel, 2019](#)). The YNM is given by equation (3):

$$\ln\left(\frac{C_t}{C_0 - C_t}\right) = (K_{YN} * t) - (K_{YN} * \tau) \quad (3)$$

Where; C_0 =influent concentration (mg/L); C_t =outlet concentration at time t (mg/L); K_{YN} =Yoon nelson rate constant (min^{-1}); τ =time required for 50% adsorbate breakthrough.

The adsorption capacity for YNM was determined as a function of M, C_0 , τ and Q using equation (4):

$$q_{YN} = \frac{\tau C_0 Q}{1,000M} \quad (4)$$

Where; M=mass of the adsorbent (gm); C_0 =inlet concentration (mg/L); τ =time required for 50% adsorbate breakthrough (day); Q=flow rate (mL/day).

TM assumes Langmuir kinetics of the adsorption-desorption process to reach equilibrium,

and the maximum adsorption capacity of a bed can be determined using TM (Han et al., 2009). The TM is given by equation (5):

$$\ln\left(\frac{C_o}{C_t} - 1\right) = (K_{TH} * Q_o * \frac{M}{Q}) - (K_{TH} * C_o * t) \quad (5)$$

Where; C_o =Influent concentration (mg/L); C_t =outlet concentration at time t (mg/L); K_{TH} =Thomas rate constant (L/mg·day); Q_o =amount adsorbed at equilibrium (mg/g); Q =Flow rate (mL/day); M =mass of adsorbent (g).

ABM is predicated on the idea that the rate of adsorption is determined by the concentration of the sorbing species and the residual adsorption capacity (Patel, 2019). The ABM is given by equation (6):

$$\ln\left(\frac{C_t}{C_o}\right) = K_{AB} * C_o * t - K_{AB} * N_o * \left(\frac{Z}{U_o}\right) \quad (6)$$

Where; C_o =influent concentration (mg/L); C_t =outlet concentration at time t (mg/L); K_{AB} =Adam and Bohart rate constant (L/mg·day); N_o =adsorption capacity of the bed (mg/L); Z =bed depth (cm); U_o =Superficial velocity (cm/day); t =Time (day).

2.2.4 Model performance evaluation and COD attenuation prediction

The experimental COD data from fixed-bed column tests and model-predicted (C_t) values from YNM, TM, and ABM for various soil textures were compared using the coefficient of determination (R^2) and root mean square error (RMSE). Observed concentrations ($y_1 \dots y_n$) and model values ($f_1 \dots f_n$) were evaluated, with models showing R^2 near unity and lower RMSE values selected for COD prediction across soil textures. The average of the experimental data is computed by equation (7):

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (7)$$

The total sum of squares SS_{tot} of the data set is given by equation (8):

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \quad (8)$$

The total squared residuals SS_{res} given by equation (9):

$$SS_{res} = \sum_i (y_i - f_i)^2 \quad (9)$$

Then the coefficient of determination (R^2) is calculated using equation (10):

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (10)$$

The Root means square error (RMSE) is calculated using equation (11):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - f_i)^2}{n}} \quad (11)$$

Where; n is the number of observations.

3. RESULTS AND DISCUSSION

3.1 Physicochemical and heavy metal characteristics of LL

The physicochemical and heavy metal characteristics of leachate from the Bancharedada landfill site, averaged over 12 months, are summarised in Table 3 and compared with typical young (acetogenic) leachate. As the Bancharedada landfill site is only 2 years old (<5 years), its leachate can be classified as acetogenic (Bashir et al., 2015). The characteristics of young (acetogenic) leachate reported by Wijekoon et al. (2022) indicate pH values ranging from acidic to alkaline (4.5-7.5), and Electrical Conductivity (EC) ranging from 7,000-30,000 $\mu\text{S}/\text{cm}$, which aligns with the findings of the present study. BOD_5 values in this study ranged from 1,240-2,238 mg/L, with an average of 1,816 mg/L, consistent with the 13.1-6,350 mg/L range reported by Scott et al. (2005) for leachate from large landfills. COD values (2,647-4,650) mg/L fall within the 1,500-7,100 mg/L range observed by Scott et al. (2005) but remain lower than the >10,000 mg/L reported by Foo and Hameed (2009).

The BOD_5/COD ratio (0.44-0.50) in this study is comparable to findings by Bashir et al. (2015). Ammoniacal nitrogen (NH_3-N) ranged from 2.86 to 8.59 mg/L, well below the <400 mg/L limit reported by Foo and Hameed (2009). Total Kjeldahl Nitrogen (TKN) values (638-1,174 mg/L) and chloride concentrations (428-1,094 mg/L) fall within typical ranges reported for young leachate by Mukherjee et al. (2015). Heavy metals were in the low to medium range (Adhikari and Khanal, 2015). Specifically, Fe (4.5-17.87 mg/L), Zn (0.2-2.52 mg/L), and Mn (3.32-9.4) mg/L were all within the expected ranges for acetogenic leachate (Scott et al., 2005).

Table 3. Minimum, maximum, average, standard deviation and median of physicochemical and heavy metals characteristics of raw LL from the Bancharedada landfill site

S.no.	Parameters	Unit	Minimum	Maximum	Average±SD	Median
1	pH	-	6.5	7.8	7±0.42	6.9
2	EC	µs/cm	16,230	18,964	18,274.58±869.88	18,770.5
3	TDS	mg/L	3,654	5,664	4,672.50±691.07	4,754.5
4	BOD ₅	mg/L	1,240	2,238	1,816.00±342.33	1,956
5	COD	mg/L	2,647	4,650	3,853.33±696.22	3,984.5
6	BOD ₅ /COD	-	0.44	0.50	0.48±0.02	0.48
7	TKN	mg/L	638	1174	987.50±143.44	985
8	NH ₃ -N	mg/L	2.86	8.59	5.72±2.18	5.245
9	NO ₃ -N	mg/L	1.35	4.89	4.05±1.00	4.4
10	Cl	mg/L	428	1,094	945.67±186.45	1,002
11	Fe	mg/L	4.5	17.87	15.75±4.03	17.385
12	Cu	mg/L	0.05	0.4	0.17±0.13	0.105
13	Ni	mg/L	0.1	0.94	0.53±0.26	0.5
14	Zn	mg/L	0.2	2.52	1.38±0.91	1.565
15	Pb	mg/L	0.09	0.36	0.21±0.10	0.21
16	Cr	mg/L	0.05	0.35	0.20±0.09	0.2
17	Hg	mg/L	0.001	0.213	0.02±0.06	0.003
18	As	mg/L	0.011	0.105	0.05±0.03	0.037
19	Cd	mg/L	0.01	0.052	0.04±0.02	0.0435
20	Mn	mg/L	3.32	9.4	6.18±1.66	6.31
21	Total Coliform	CFU/100 mL	170,000	241,500	222,067±220,622	230,825

SD: represents the standard deviation

3.2 Seasonal variations of LL

Seasonal variations in Bancharedada landfill site leachate characteristics (Table 4) reflect Nepal's wet (July-August) and dry (December-February) periods. BOD₅ levels were highest in winter (2,086.67) mg/L and lowest in the post-monsoon (1,475.00 mg/L), as shown in Figure 3. This pattern is likely attributed to increased oxygen availability and reduced biodegradation rates at lower temperatures (Ashraf et al., 2022). COD concentrations peaked during the pre-monsoon (4,499.67 mg/L) and were lowest in the post-monsoon (3,083.00 mg/L). Elevated BOD₅ and COD in dry seasons suggest limited dilution, whereas monsoon rainfall increased the leachate volume and diluted pollutant concentrations (Rhout et al., 2019; Hoai et al., 2021).

The BOD₅/COD ratio (0.44-0.51) was higher in the dry season and lower during the monsoon, indicating moderate biodegradability and typical characteristic of young leachate (Bernardo-Bricker et al., 2014). Ratios greater than 0.5 are typical of young landfills (<5 years), whereas ratios close to 0.1 are associated with stabilised landfills (>10 years) as reported by Ghahrchi and Rezaee (2020). With an

operational age of two years (since May 2022) and a BOD₅/COD ratio between 0.44-0.51, the leachate aligns with the characteristics of a young landfill. Seasonal fluctuations are primarily influenced by climate factors (temperature and precipitation) and site-specific conditions: monsoon rainfall dilutes contaminants, while dry periods yield more concentrated leachate (Al-Yaqout and Hamoda, 2020).

3.3 Seasonal fluctuations of LPI

Seasonal variations in overall LPI and its sub-indices (LPIor, LPIin, and LPIhm) are shown in Table 5. Both LPIor and LPIin were consistently higher than LPIhm, indicating dominance of organic and inorganic pollutants in LL from the Bancharedada landfill site. LPIor was lowest during the monsoon (59.52) and highest in winter (64.09), reflecting the trend of the BOD₅/COD ratio shown in Figure 3. LPIin also varied seasonally, from 10.19 in the monsoon to 13.09 in winter. The overall LPI followed the order: winter > pre-monsoon > post-monsoon > monsoon, suggesting higher pollutant concentrations during the dry seasons.

Table 4. Seasonal variations in physicochemical and heavy metals characteristics of raw leachate from the Bancharedada landfill site

S.no.	Parameters	Unit	Pre-monsoon (average±SD)	Monsoon (average±SD)	Post-monsoon (average±SD)	Winter (average±SD)
1	pH	-	6.70±0.26	7.07±0.64	7.40±0.20	6.83±0.12
2	EC	µs/cm	18,917.33±45.09	17,500.00±1,270.00	17,844.00±518.10	18,837.00±78.63
3	TDS	mg/L	5,366.67±412.30	4,584.00±930.00	3,943.67±169.74	4,795.67±94.16
4	BOD ₅	mg/L	2,046.33±133.61	1,657.50±417.50	1,475.00±186.70	2,086.67±183.89
5	COD	mg/L	4,499.67±133.61	3,749.00±901.00	3,083.00±408.16	4,081.67±241.72
6	BOD ₅ /COD	-	0.46±0.02	0.44±0.01	0.48±0.003	0.51±0.015
7	TKN	mg/L	1,116.00±79.02	895.00±257.00	944.67±9.87	994.33±18.50
8	NH ₃ -N	mg/L	8.40±0.20	5.61±2.75	3.78±0.13	5.07±1.25
9	NO ₃ -N	mg/L	4.79±0.14	3.07±1.72	3.89±0.07	4.45±0.14
10	Cl	mg/L	1,063.00±37.03	761.00±333.00	948.00±19.00	1,010.67±20.53
11	Fe	mg/L	17.44±0.25	10.83±6.33	17.29±0.86	17.44±0.10
12	Cu	mg/L	0.07±0.02	0.09±0.03	0.14±0.08	0.36±0.05
13	Ni	mg/L	0.73±0.12	0.49±0.41	0.30±0.18	0.57±0.13
14	Zn	mg/L	2.36±0.20	0.76±0.57	0.41±0.21	1.99±0.35
15	Pb	mg/L	0.31±0.06	0.17±0.10	0.12±0.04	0.25±0.07
16	Cr	mg/L	0.20±0.06	0.10±0.06	0.19±0.08	0.31±0.06
17	Hg	mg/L	0.01±0.01	0.07±0.12	0.004±0.001	0.002±0.001
18	As	mg/L	0.04±0.01	0.04±0.04	0.08±0.05	0.03±0.01
19	Cd	mg/L	0.02±0.01	0.03±0.02	0.05±0.00	0.05±0.00
20	Mn	mg/L	7.07±0.67	6.09±3.08	4.81±0.62	6.74±0.59
21	Total coliform	CFU/100 mL	239,050	205,767	208,950	234,500
Temperature minimum (°C)			10.39	16.77	12.88	5.20
Temperature maximum (°C)			21.16	22.74	20.03	14.00
Precipitation (mm)			192.00	1,799.40	496.00	17.00

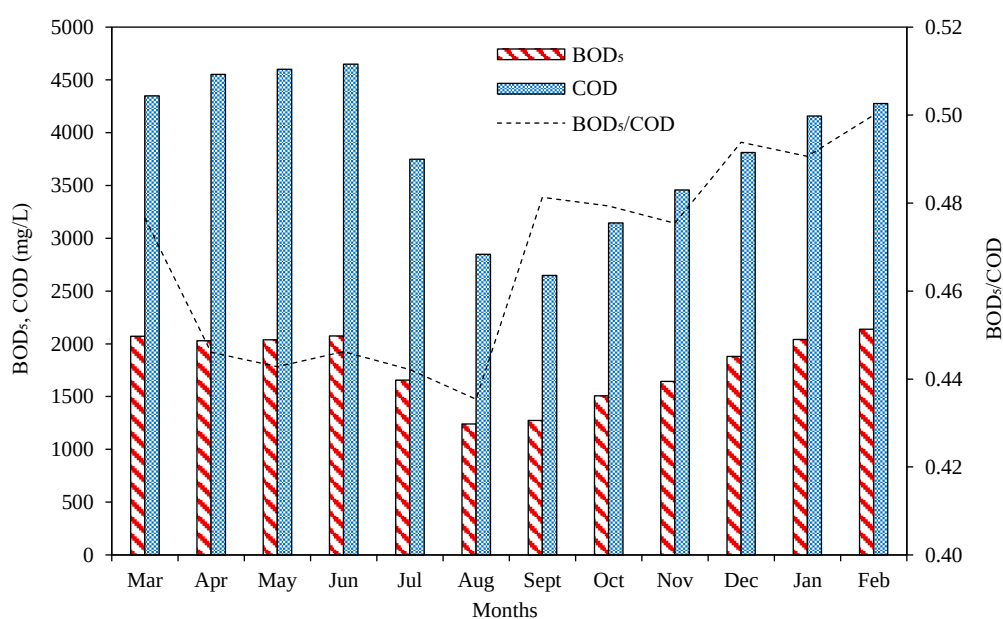
**Figure 3.** Seasonal variation of BOD₅, COD, and BOD₅/COD ratio of leachate from Bancharedada landfill site

Table 5. Seasonal fluctuations of Overall LPI, LPI_{or}, LPI_{in}, LPI_{in}, and LPI_{hm}

Pre-monsoon			Monsoon						Post-monsoon						Winter						
Index	Parameter	Value	Pi	Wi	WiPi	LPI	Value	Pi	Wi	WiPi	LPI	Value	Pi	Wi	WiPi	LPI	Value	Pi	Wi	WiPi	LPI
LPI _{or}	BOD ₅	2,046	35	0.263	9.21	63.16	1,706	30	0.267	8.01	59.52	1,475	30	0.267	8.01	59.52	2,086	40	0.267	9.345	64.09
	COD	4,500	60	0.267	16.02		3,749	55	0.263	14.465		3,083	55	0.263	14.47		4,082	62	0.263	15.78	
	Coliform	239,050	100	0.224	22.4		205,767	100	0.224	22.4		208,950	100	0.224	22.4		234,500	100	0.224	22.4	
LPI _{in}	pH	6.7	5	0.214	1.07	13.09	7.07	5	0.214	1.07	10.19	7.4	5	0.214	1.07	11.05	6.83	5	0.214	1.07	13.09
	NH ₃ -N	8.4	5	0.198	0.99		5.61	5	0.198	0.99		3.78	5	0.198	0.99		5.07	5	0.198	0.99	
	Cl	1,063	10	0.187	1.87		761	5.5	0.187	1.0285		948	9.8	0.187	1.833		1,010.67	10	0.187	1.87	
	TDS	5,367	10	0.195	1.95		4,584	10	0.195	1.95		3,944	5	0.195	0.975		4,796	10	0.195	1.95	
	TKN	1,116	35	0.206	7.21		895	25	0.206	5.15		944.67	30	0.206	6.18		994.33	35	0.206	7.21	
LPI _{hm}	Fe	17.44	5	0.088	0.44	5.00	10.83	5	0.088	0.44	5.00	17.293	5	0.088	0.44	5.00	17.443	5	0.088	0.44	5.00
	Cu	0.07	5	0.098	0.49		0.09	5	0.098	0.49		0.1433	5	0.098	0.49		0.360	5	0.098	0.49	
	Ni	0.73	5	0.102	0.51		0.49	5	0.102	0.51		0.3	5	0.102	0.51		0.573	5	0.102	0.51	
	Zn	2.36	5	0.11	0.55		0.76	5	0.11	0.55		0.41	5	0.11	0.55		1.987	5	0.11	0.55	
	Pb	0.31	5	0.123	0.615		0.17	5	0.123	0.615		0.1233	5	0.123	0.615		0.247	5	0.123	0.615	
	Cr	0.2	5	0.125	0.625		0.10	5	0.125	0.625		0.1933	5	0.125	0.625		0.313	5	0.125	0.625	
	As	0.04	5	0.137	0.685		0.04	5	0.137	0.685		0.0777	5	0.137	0.685		0.035	5	0.137	0.685	
	Hg	0.01	5	0.121	0.605		0.073	5	0.121	0.605		0.004	5	0.121	0.605		0.002	5	0.121	0.605	
Overall LPI						20.57					18.98					19.20				20.79	

3.4 Physicochemical characteristics of soil samples

The physicochemical characteristics of soil samples used in the fixed-bed column tests are summarised in Table 6. Based on the United States Department of Agriculture (USDA) classification, the soils represent seven textures: S1—clayey, S2—silt loam, S3—sandy, S4—loam, S5—sandy loam, S6—clay loam, and S7—silt loam. The characteristics observed across these samples, ranging from clay-rich to sandy textures, demonstrate substantial natural variability consistent with Nepal's heterogeneous soil environment. Sand, silt, and clay content varied

widely (12.68-88%, 9-60%, and 3-56%, respectively), with corresponding differences in porosity (31-48%) and cation exchange capacity (CEC) (7.63-11.68 cmol/kg). These variations align with the diverse soil types reported across Nepal's physiographic regions, which are shaped by pronounced altitudinal gradients and differences in parent material (Nepal et al., 2023). Fine-textured soils (clayey, silt loam and clay loam) exhibited higher moisture content, organic matter, and CEC values consistent with those found in Nepal's Terai and hill regions (Shrestha et al., 2017).

Table 6. Physicochemical characteristics of soil samples

Parameters	Unit	S1	S2	S3	S4	S5	S6	S7
Moisture content	%	7.92	8.3	4.52	6.95	3.46	5.68	4.16
pH	-	6.3	5.9	6.2	7.3	6.6	6.65	6.22
Soil texture	Sand (%)	12.68	14.00	88.00	37.65	63.99	25.92	32.88
	Silt (%)	31.32	60.00	9.00	46.34	21.00	46.07	59.11
	Clay (%)	56.00	26.00	3.00	16	15.00	28.00	8.00
USDA classification of soil textures		Clayey	Silt loam	Sandy	Loam	Sandy loam	Clay loam	Silt loam
Bulk density	g/cm ³	1.35	1.42	1.65	1.5	1.45	1.45	1.33
Particle density	g/cm ³	2.32	2.42	2.45	2.32	2.28	2.52	2.38
Porosity	%	31	37	48	42	36	42	38
Organic matter	%	7.62	7.40	2.53	4.46	0.53	5.86	6.88
Carbon	%	4.28	2.48	0.5	2.58	0.3	3.4	3.99
Total nitrogen	%	0.38	1.26	1.12	1.67	1.96	1.21	2.69
Phosphorus	mg/kg	4.42	2.48	1.56	2.896	3.84	1.496	2.304
Potassium	mg/kg	1,243	1,037	1,068	1,444	1,245	1,156	1,356
Calcium	mg/kg	518	487	309	319	348	412	559
Magnesium	mg/kg	253	143	98	168	102	118	327
CEC	cmol/kg	11.68	8.02	7.89	7.95	7.63	10.81	9.17

3.5 Breakthrough curve analysis for different soil textures

The breakthrough curves for S1-S7 soil samples, classified per USDA soil textures are presented in Figure 4. The results show that lower soil porosity shortens the bed saturation time by reducing the contact time between adsorbate molecules and adsorbent pore surfaces. During the first 12 h, no filtrate was observed for S1, S2, S3, S4, S5, S6, and S7 whereas S3 (sandy) exhibited a breakthrough at 1 h. Bed saturation times were 35, 22, 4, 15, 11, 18, and 12 days for S1-S7 soils, respectively. The shape of the breakthrough curve is affected by the porosity and clay percentage of soils. Lower porosity and clay percentages result in longer contact times due to reduced hydraulic conductivity, allowing the

adsorbate molecules more time to diffuse into the adsorbent's pores and thereby increasing the bed's adsorption efficiency (Foo, 2020; Yahya et al., 2021). Clayey soil (31% porosity) reached 99% influent concentration of day 35, whereas sandy soil (48% porosity) reached saturation by day 4. Consequently, fine-textured soils with higher organic matter and CEC offer greater potential for COD adsorption and microbial activity, while sandy soils exhibit faster leachate breakthrough and reduced attenuation (Koirala et al., 2019). These findings suggest that leachate attenuation capacity in Nepal cannot be generalized; rather, it is strongly influenced by the combined effects of soil texture, mineralogy, and seasonal rainfall patterns.

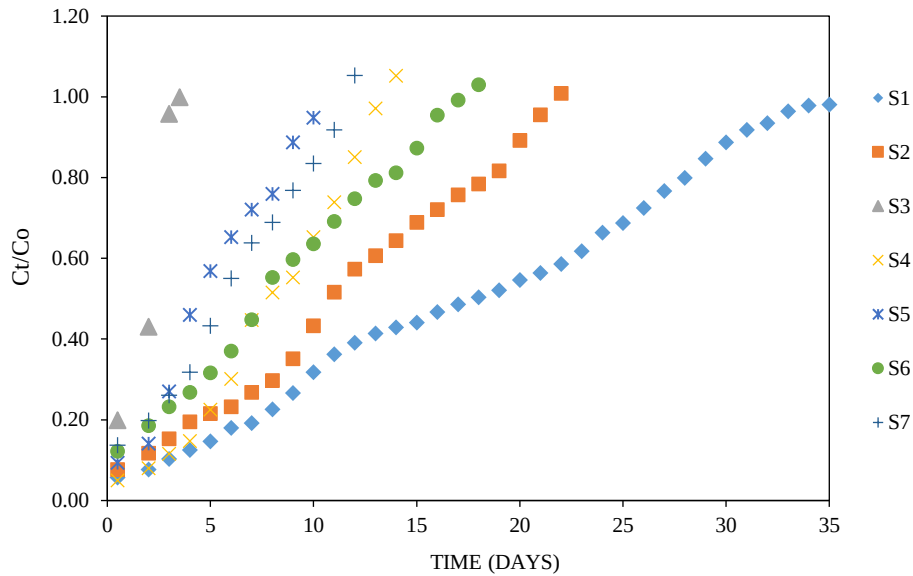


Figure 4. Breakthrough curves from column tests done in S1-S7 soil samples with LL for COD

3.6 Column kinetics for COD adsorption using three models

3.6.1 YNM, TM, and ABM models

The parameters obtained from fitting experimental data with YNM, TM, and ABM are shown in Table 7. Plotting $\ln\left(\frac{C_t}{C_0 - C_t}\right)$ against time yielded the YN rate constant K_{YN} of 0.16, 0.23, 2.39, 0.42, 0.52, 0.31, and 0.39 L/day, with corresponding τ (50% adsorbate breakthrough) values of 16.76, 11.06, 1.56, 7.84, 4.90, 7.43, and 5.66 days for S1, S2, S3, S4, S5, S6, and S7 soil samples, respectively. The corresponding adsorption capacities (q_{YN}) were 22.77, 14.82, 1.92, 10.76, 6.59, 10.24, and 7.72 mg/g, respectively.

Plotting $\ln\left(\frac{C_0}{C_t} - 1\right)$ against time yielded the TM rate constant K_{th} of 0.6, 0.9, 3.8, 1.6, 2.0, 1.2 and 1.5 (L/mg·day)* 10^{-4} , and the adsorption capacities (Q_0) of 22.78, 14.82, 2.42, 10.76, 6.59, and 10.24 mg/g for S1, S2, S3, S4, S5, S6, and S7 soil samples, respectively.

Plotting $\ln\left(\frac{C_t}{C_0}\right)$ against time yielded ABM rate constants K_{AB} of 0.3, 0.4, 2.1, 0.8, 0.9, 0.4, and 0.7 (L/mg·day)* 10^{-4} and adsorption capacity N_0 values of 41,957, 26,934, 4,575, 17,222, 12,417, 21,447, and 14,700 mg/L for S1, S2, S3, S4, S5, S6, and S7 soil samples, respectively.

The model parameters showed that soils with higher clay content have lower adsorption

rate constants and substantially higher adsorption capacities. S1 (clayey, 56%) showed lower adsorption rate constants with greater adsorption capacity, whereas S3 (sandy, 3% clay) exhibited the opposite trend. The high surface charge and low hydraulic conductivity of clay minerals enhance contaminant removal via ion exchange and adsorption (Foo, 2020), while their strong affinity for contaminants delays rather than removes the pollutants (Khan et al., 2023). Further, in the adsorption mechanism of LL treatment, molecularly imprinted polymers have shown significantly higher adsorption capacity (42.55 mg/g) compared to 7 mg/g for a non-imprinted polymer, demonstrating nearly a sixfold improvement in dye removal from wastewater (Khan et al., 2024). Mxenes-based materials also exhibit strong adsorption performance for heavy metals due to their high surface area and metal ion trapping ability (Zahoor et al., 2024).

The results indicate that clay-rich soils are suitable for landfill cover materials because of their high adsorption capacity and retention of organic pollutants, thereby protecting underlying soils and groundwater. Better adsorption in clay covers decreases the concentration of contaminants entering the leachate collection system, which lowers the operational load on leachate treatment facilities and reduces long-term costs.

Table 7. Obtained parameters from fitting the experimental data with YNM, TM, and ABM for the adsorption of COD in different soil textures

Soil textures	(Co) mg/L	Mass (gm)	YNM			TM			ABM		
			K_{YN} (L/day)	τ (days)	q_{YN} (mg/g)	R^2	K_{th} (L/mg·day)* 10^{-4}	Q_0 (mg/g)	R^2	K_{AB} (L/mg·day)* 10^{-4}	N_0 (mg/L)
S1	2,647	487	0.16	16.76	22.77	0.95	0.6	22.78	0.95	0.3	41,957
S2	2,647	494	0.23	11.06	14.82	0.96	0.9	14.82	0.96	0.4	26,934
S3	2,647	537	1.01	1.98	2.44	0.90	3.8	2.42	0.90	2.1	4,575
S4	2,647	482	0.42	7.84	10.76	0.96	1.6	10.76	0.96	0.8	17,222
S5	2,647	492	0.52	4.90	6.59	0.98	2.0	6.59	0.98	0.9	12,417
S6	2,647	480	0.31	7.43	10.24	0.92	1.2	10.24	0.92	0.4	21,447
S7	2,647	485	0.39	5.66	7.72	0.99	1.5	7.73	0.99	0.7	14,700

Table 8. SS_{tot} , SS_{res} , R^2 , and RMSE obtained from model evaluation

Soil textures	YNM			TM			ABM		
	SS_{tot} (* 10^6)	SS_{res} (* 10^5)	R^2	RMSE	SS_{tot} (* 10^6)	SS_{res} (* 10^5)	R^2	RMSE	SS_{tot} (* 10^6)
S1	39	16	0.959	151.88	39	806	-1.07	1,073.55	39
S2	24	2	0.989	78.95	24	517	-1.08	1,083.98	24
S3	557	6	0.999	307.06	557	60	0.70	931.96	557
S4	22	6	0.972	147.01	22	460	-1.09	1,260.20	22
S5	13	2	0.983	102.85	13	211	0.65	1,002.48	13
S6	19	4	0.978	109.18	19	304	-0.53	919.40	19
S7	13	2	0.981	103.32	13	218	-0.60	954.50	13

3.7 Model evaluation and prediction

Three models (YNM, TM, and ABM) were evaluated for predicting COD concentrations in leachate through soil columns. Table 8 compares their performance using the total sum of squares (SS_{tot}), residual sum of squares (SS_{res}), coefficient of determination (R^2), and RMSE. A higher R^2 value (closer to 1) indicates better predictive accuracy and reliability (Yousefi Kebria et al., 2018; Patel, 2019).

The R^2 and RMSE values across different soil textures indicate that YNM and ABM better predict COD concentrations than TM, with YNM performing the best due to consistently higher R^2 (closer to 1) and

lower RMSE. The TM produced negative R^2 values across most soil textures, indicating that its residual variance exceeded the total variance, which means this model demonstrates poor predictive capability for the adsorption breakthrough behaviour in all soil textures. Therefore, Figure 5 shows the fit between observed COD values and those predicted by YNM. Similar findings were reported by Kovo et al. (2023), where YNM effectively predicted COD in a column study using magnetite-zeolite composites. Zhang et al. (2022) also found YNM to be reliable in modelling Cr (VI) adsorption in red mud leachate onto clay layers.

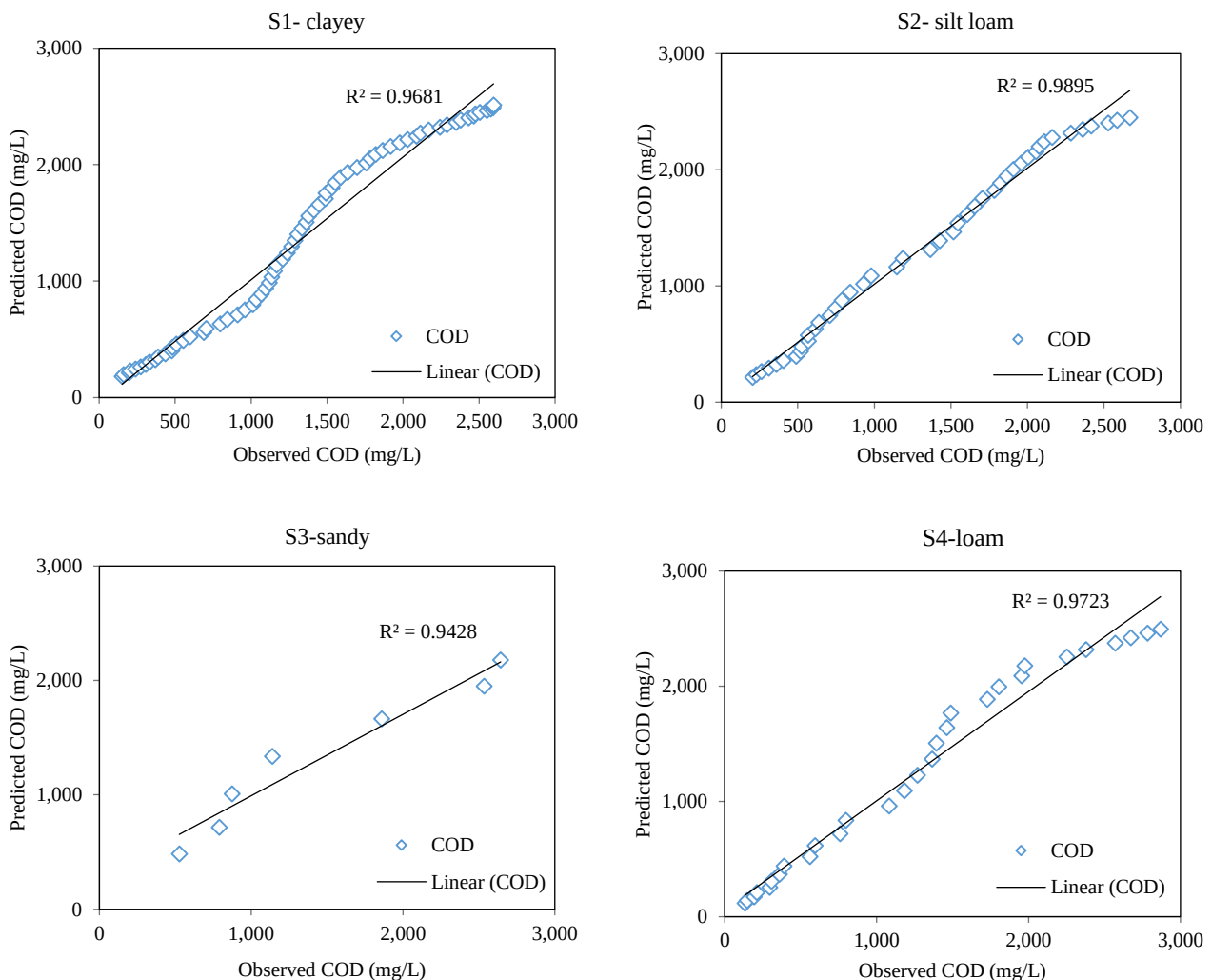


Figure 5. Regression line for all of the S1-S7 soil textures of the for observed and predicted values using YNM

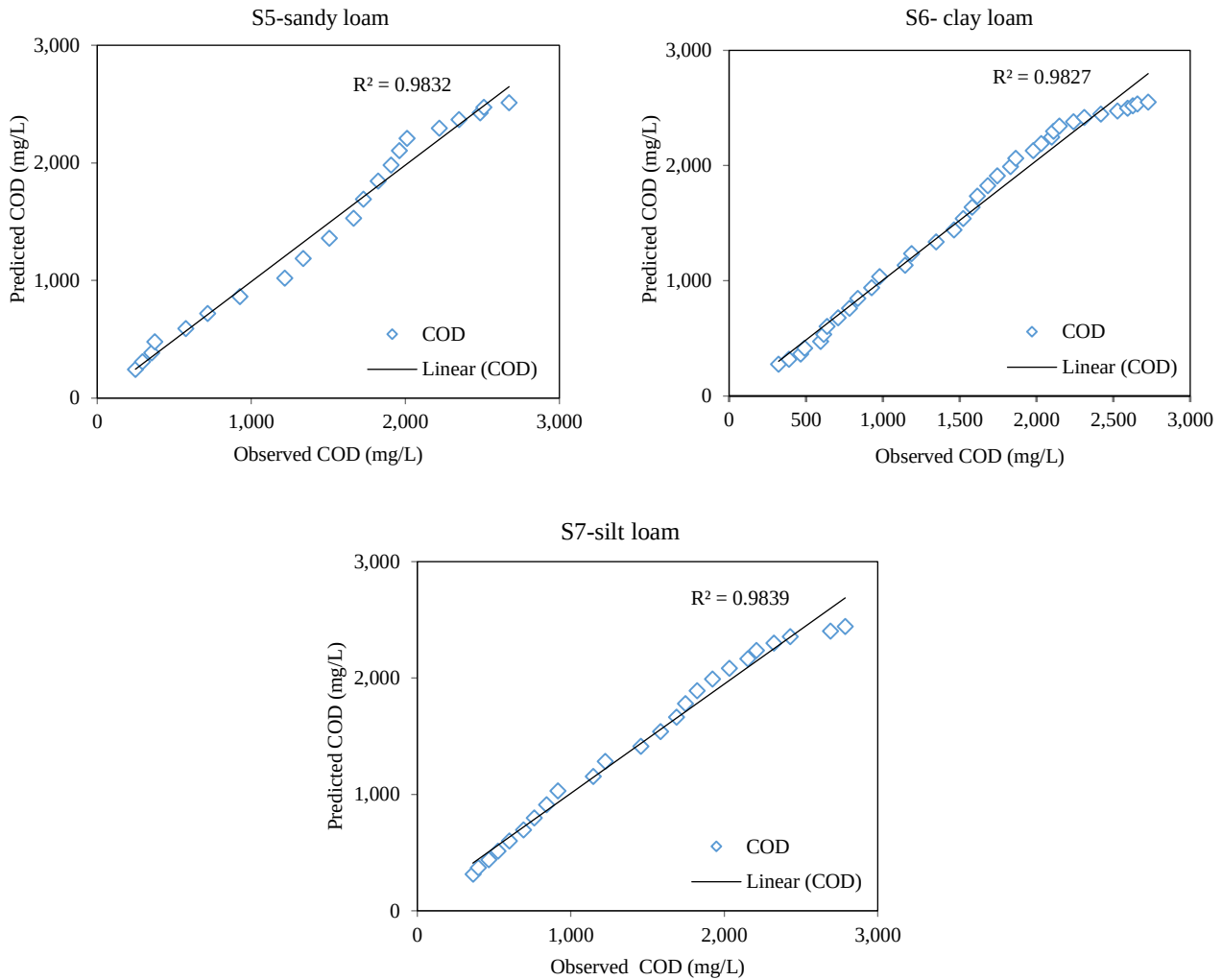


Figure 5. Regression line for all of the S1-S7 soil textures of the observed and predicted values using YNM (cont.)

4. CONCLUSION

Seasonal LPI fluctuations indicated that organic content significantly influences leachate pollution at the Bancharedada landfill site. Experimental results showed that clay-rich soils effectively delay the transport of organic contaminants, highlighting their suitability as landfill cover materials in landfill design. Among the three kinetic models (YNM, TM, and ABM) tested, YNM achieved the highest predictive accuracy (lowest RMSE), followed by ABM, which also performed acceptably based on RMSE and R^2 metrics. YNM parameters (K_{YN}) showed strong correlations with soil texture, confirming its reliability for predicting COD attenuation. Future studies should examine soils with higher clay fractions and consider factors such as adsorbent dosage, loading rate, and contact time for on-site leachate remediation. Additional experiments incorporating locally

available amendments such as biochar or compost would also help assess their potential to enhance soil sorption capacity for other pollutants.

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DECLARATION OF CONFLICT OF INTEREST

Dr. Anish Ghimire serves as a member of the editorial board for the Environment and Natural Resources Journal. He has not participated in any peer review processes. The authors declare that there are no competing interests.

REFERENCES

- Adhikari B, Khanal SN. Qualitative study of landfill leachate from different ages of landfill sites of various countries including Nepal. *IOSR Journal of Environmental Science, Toxicology and Food Technology* 2015;9:23-36.
- Al-Yaqout A, Hamoda MF. Long-term temporal variations in characteristics of leachates from a closed landfill in an arid region. *Water, Air, and Soil Pollution* 2020;231:Article No. 319.
- Allison L, Bernstein L, Bower CA, Brown JW, Fireman M, Hatcher JT, et al. *Diagnosis and Improvement of Saline and Alkaline Soils*. Vol. 18. Washington, DC: United States Department of Agriculture; 1954.
- Ashraf M, Zeshan M, Hafeez S, Hussain R, Qadir A, Majid M, et al. Temporal variation in leachate composition of a newly constructed landfill site in Lahore in context to environmental pollution and risks. *Environmental Science and Pollution Research* 2022;29:37129-43.
- Baird RB, Eaton AD, Rice EW. *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association. 23rd ed. Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation; 2017.
- Bashir MJK, Aziz HA, Amr SSA, Sethupathi S, Ng CA, Lim JW. The competency of various applied strategies in treating tropical municipal landfill leachate. *Desalination and Water Treatment* 2015;54:2382-95.
- Bernardo-Bricker AR, Singh SK, Trovó AG, Tang WZ, Tachiev G. Biodegradability enhancement of mature landfill leachate using fenton process under different COD loading factors. *Environmental Processes* 2014;1:207-19.
- Carter MR, Gregorich EG. *Soil Sampling and Methods of Analysis*. Ottawa: Canadian Society of Soil Science; 2007.
- Central Bureau of Statistics. *Waste Management Baseline Survey of Nepal 2020*. Kathmandu: National Planning Commission, Government of Nepal; 2020.
- Chetri JK, Reddy KR. Advancements in municipal solid waste landfill cover system: A review. *Journal of the Indian Institute of Science* 2021;101:557-88.
- Cronan CS. *Ecosystem Biogeochemistry*. Textbooks in Earth Sciences, Geography and Environment. Springer International Publishing; 2018, p. 11-29.
- Foo KY. Potential of natural clay derived functionalized adsorbent for the effective remediation of sanitary landfill leachate. *Desalination and Water Treatment* 2020;175:164-73.
- Foo KY, Hameed BH. An overview of landfill leachate treatment via activated carbon adsorption process. *Journal of Hazardous Materials* 2009;171:54-60.
- Ghahrchai M, Rezaee A. Electro-catalytic ozonation for improving the biodegradability of mature landfill leachate. *Journal of Environmental Management* 2020;254:Article No. 109811.
- Ghosh S, Kumar S, Mukherjee S, Tarafder DD, Hettiaratchi P. Adsorptive chromium removal by some clayey soil for abatement of tannery waste pollution. *Journal of Hazardous, Toxic, and Radioactive Waste* 2012;16:243-9.
- Gonçalves F, Correa CZ, Lopes DD, Vendrame PRS, Teixeira RS. Monitoring of the process of waste landfill leachate diffusion in clay and sandy soil. *Environmental Monitoring and Assessment* 2019;191:Article No. 577.
- Goyal H, Parby JI, Lypiridis C, Lal MK, Soni P, Mondal P, et al. *Strategic Assessment of Solid Waste Management Services and Systems in Nepal: City-Level Assessment and Draft Service Improvement Plan for Solid Waste Management For Pokhara Metropolitan City*. Washington, DC: World Bank; 2020.
- Han R, Wang Yu, Zhao X, Yuanfeng W, Xie F, Cheng J, et al. Adsorption of methylene blue by phoenix tree leaf powder in a fixed-bed column: Experiments and prediction of breakthrough curves. *Desalination* 2009;245:284-97.
- Hoai ST, Lan HN, Viet NTT, Hoang GN, Kawamoto K. Characterizing seasonal variation in landfill leachate using leachate pollution index (LPI) at nam son solid waste landfill in Hanoi, Vietnam. *Environments* 2021;8(3):Article No. 17.
- Hussein M, Yoneda K, Zaki ZM, Othman NA, Amir A. Leachate characterizations and pollution indices of active and closed unlined landfills in Malaysia. *Environmental Nanotechnology, Monitoring and Management* 2019;12:Article No. 100232.
- Kaza S, Lisa Y, Bhada TP, Frank VW. *What a Waste 2.0, A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank; 2018.
- Keerthanam S, Gunawardane C, Somasundaram T, Jayampathi T, Jayasinghe C, Vithanage M. Immobilization and retention of caffeine in soil amended with *Ulva reticulata* biochar. *Journal of Environmental Management* 2021;281:Article No. 111852.
- Khan M, Ahmad I, Khan S, Zeb A, Elsadek MF, Patel S. Molecularly imprinted polymer for the selective removal of direct violet 51 from wastewater: synthesis, characterization, and environmental applications. *Journal of Polymer Engineering* 2024;44(10):761-75.
- Khan S, Ajmal S, Hussain T, Rahman MU. Clay-based materials for enhanced water treatment: Adsorption mechanisms, challenges, and future directions. *Journal of Umm Al-Qura University for Applied Sciences* 2023;11:219-34.
- Khanal A. Forecasting municipal solid waste generation using linear regression analysis: A case of Kathmandu Metropolitan City, Nepal. *Multidisciplinary Science Journal* 2023;5(2): Article No. 19.
- Koirala P, Thakuri S, Joshi S, Chauhan R. Estimation of soil erosion in Nepal using a RUSLE modeling and geospatial tool. *Geosciences* 2019;9:Article No. 147.
- Kovo AS, Alaya-Ibrahim S, Abdulkareem AS, Adeniyi OD, Egbosiuba TC, Tijani JO, et al. Column adsorption of biological oxygen demand, chemical oxygen demand and total organic carbon from wastewater by magnetite nanoparticles-zeolite A composite. *Heliyon* 2023;9:e13095.
- Kueneman E, Hopmans JW, Raser E, Martin CCGS, Fisher J. *Water-Smart Agriculture A Biophysical Focused Introduction: Addressing Needs and Opportunities in Developing Nations*. San José: Inter-American Institute for Cooperation on Agriculture; 2020.
- Kumar D, Alappat BJ. Evaluating leachate contamination potential of landfill sites using leachate pollution index. *Clean Technologies and Environmental Policy* 2005;7:190-7.

- Lothe AG, Sinha A. Development of model for prediction of Leachate Pollution Index (LPI) in absence of leachate parameters. *Waste Management* 2017;63:327-36.
- Motsara MR, Roy RN. Guide to Laboratory Establishment for Plant Nutrient Analysis. Rome: Food and Agriculture Organization of the United Nations (FAO); 2008.
- Mukherjee S, Mukhopadhyay S, Hashim MA, Gupta BS. Contemporary environmental issues of landfill leachate: Assessment and remedies. *Critical Reviews in Environmental Science and Technology* 2015;45:472-590.
- Naka A, Yasutaka T, Sakanakura H, Kalbe U, Watanabe Y, Inoba S, et al. Column percolation test for contaminated soils: Key factors for standardization. *Journal of Hazardous Materials* 2016;320:326-40.
- Nawaz T, Rahman A, Pan S, Dixon K, Petri B, Selvaratnam T. A review of landfill leachate treatment by microalgae: Current status and future directions. *Processes* 2020;8:Article No. 384.
- Nayanthika IVK, Jayawardana DT, Bandara NJGJ, Manage PM, Madushanka RMTD. Effective use of iron-aluminum rich laterite based soil mixture for treatment of landfill leachate. *Waste Management* 2018;74:347-61.
- Nazari M. The Use of Brown Coal for the Removal of Nutrients from Wastewater [dissertation]. Melbourne, RMIT University, 2017.
- Nepal S, K.C. M, Pudasainia N, Adhikari H. Divergent Effects of Topography on Soil Properties and Above-Ground Biomass in Nepal's Mid-Hill Forests. *Resources* 2023;12:Article No. 136.
- Organisation for Economic Co-operation and Development (OECD). OECD Guidelines for the Testing of Chemicals, Section 3. Paris: OECD Publishing; 2004.
- Patel H. Fixed-bed column adsorption study: A comprehensive review. *Applied Water Science* 2019;9:Article No. 45.
- Pathak DR, Mainali B, Abuel-Naga H, Angove M, Kong I. Quantification and characterization of the municipal solid waste for sustainable waste management in newly formed municipalities of Nepal. *Waste Management and Research* 2020;38:1007-18.
- Qi G, Yue D, Liu J, Li R, Shi X, He L, et al. Impact assessment of intermediate soil cover on landfill stabilization by characterizing landfilled municipal solid waste. *Journal of Environmental Management* 2013;128:259-65.
- Regadío M, Ruiz AI, Rodríguez-Rastrero M, Cuevas J. Containment and attenuating layers: An affordable strategy that preserves soil and water from landfill pollution. *Waste Management* 2015;46:408-19.
- Rhouat S, El Youbi MS, Dimane F. Physico-chemical characterization of Meknes municipal landfill leachate and assessment of the seasonal effects using PCA. *Environmental Engineering and Management Journal* 2019;18:2405-15.
- Scott J, Beydoun D, Amal R, Low G, Cattle J. Landfill management, leachate generation, and leach testing of solid wastes in Australia and overseas. *Critical Reviews in Environmental Science and Technology* 2005;35:239-332.
- Shrestha HL, Bhandari TS, Karky BS, Kotru R. Linking soil properties to climate change mitigation and food security in Nepal. *Environments* 2017;4:Article No. 29.
- Sugashini S, Begum KMMS. Performance of ozone treated rice husk carbon (OTRHC) for continuous adsorption of Cr (VI) ions from synthetic effluent. *Journal of Environmental Chemical Engineering* 2013;1:79-85.
- Teng C, Zhou K, Peng C, Chen W. Characterization and treatment of landfill leachate: A review. *Water Research* 2021;203:Article No. 117525.
- Wijekoon P, Koliyabandara PA, Cooray AT, Lam SS, Athapattu BCL, Vithanage M. Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges. *Journal of Hazardous Materials* 2022;421:Article No. 126627.
- Yahya MD, Imam IA, Abdulkareem SA. Column adsorption studies for the removal of chemical oxygen demand from fish pond wastewater using waste alum sludge. In: *Advances in Remediation Techniques for Polluted Soils and Groundwater*. Elsevier; 2021. p. 21-48.
- Yidong G, Xin C, Shuai Z, Ancheng L. Performance of multi-soil-layering system (MSL) treating leachate from rural unsanitary landfills. *Science of the Total Environment* 2012;420:183-90.
- Yousefi Kebria D, Ghavami M, Javadi S, Goharimanesh M. Combining an experimental study and ANFIS modeling to predict landfill leachate transport in underlying soil: A case study in north of Iran. *Environmental Monitoring and Assessment* 2018;190:Article No. 26.
- Zahoor M, Ikram M, Khan S, Ali S. Mxene a versatile hybrid inorganic nanomaterial: A useful adsorbent for the removal of toxic heavy metals and its other applications. *Inorganic Chemistry Communications* 2024;170:Article No. 113157.
- Zhang Y, Yu Y, Qin H, Peng D, Chen X. Dynamic adsorption characteristics of Cr (VI) in red-mud leachate onto a red clay anti-seepage layer. *Toxics* 2022;10:Article No. 606.

Unified Green E-Waste Management Framework for Sustainable Campus Development: Case Study of Malaysian Public Universities

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ABSTRACT

Electronic waste (e-waste) has become the fastest-growing waste stream globally, presenting complex environmental and regulatory challenges that are particularly evident in higher education institutions. In Malaysia, public universities are significant contributors to e-waste generation due to their extensive reliance on information and communication technologies, laboratory equipment, and administrative devices. Although regulatory frameworks, such as the Environmental Quality (Scheduled Wastes) Regulations 2005, exist, current practices in universities remain fragmented, focusing largely on asset disposal under Ministry of Finance guidelines and neglecting gaps in behavioral, infrastructural, and policy integration. This study introduces the Unified Green E-waste Management Framework (UGEMF), a holistic model specifically designed for Malaysian public universities. The framework was developed through qualitative methods, including document analysis, in-depth interviews with key stakeholders, and a review of institutional practices, regulatory documents, and best-practice case studies. The findings highlight barriers, including limited awareness, bureaucratic constraints, and the absence of institutionalized policies, while also identifying emerging best practices, such as refurbishment initiatives, decentralized collection points, and cross-sector collaborations. By operationalizing circular economy principles within the higher education context, UGEMF contributes theoretically to sustainability and waste management literature, while offering practical guidance for policymakers and administrators. Its adoption can transform e-waste management in Malaysian public universities from fragmented compliance processes into comprehensive, integrated sustainability strategies. This approach supports national green growth targets and sustainable campus development.

HIGHLIGHTS

This study highlights a Unified Green E-waste Management Framework (UGEMF) that integrates four core components: stakeholder engagement, green strategies, policy and regulatory alignment, and monitoring and evaluation. Anchored in circular economy principles, it emphasizes prevention, reuse, repair, and refurbishment alongside responsible disposal. Furthermore, the framework incorporates behavioral change initiatives, green procurement practices, and data-driven monitoring to build a transparent, accountable, and sustainable system at public universities in Malaysia.

1. INTRODUCTION

Electronic waste (e-waste) is the fastest-growing solid waste stream globally. The Global E-waste Monitor 2024 reports that 62 million tonnes were generated in 2022, an 82% increase since 2010, with projections exceeding 82 million tonnes by 2030 if current trends persist (ITU and UNITAR, 2024). This rapid growth, driven by shorter product lifecycles and continuous technological innovation, is not

matched by formal recycling, which remains at only 22.3%. Consistent with the global rise, Malaysia's e-waste stream is also substantial. Recent reports estimate that approximately 280,000 tonnes of e-waste are generated nationally, equivalent to roughly 8.8 kilograms per person. In 2023, documented collection reached 65,280 tonnes, with 13,760 tonnes recovered, resulting in a recovery rate of about 21.1% (The Edge Malaysia, 2024). As a result, large volumes of e-waste

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are unmanaged or processed informally, posing risks to resource recovery and environmental sustainability.

Unmanaged e-waste releases hazardous substances such as lead and mercury, thereby contaminating ecosystems and threatening biodiversity (Mlelwa and Rother, 2024; Okeke et al., 2024). Valuable materials such as gold and copper are lost outside formal recycling systems, undermining circular economy efforts. The WHO (2021) warns that informal recycling also endangers human health, especially among vulnerable groups (Andeobu et al., 2023). These concerns have prompted the global expansion of e-waste regulations, with extended producer responsibility (EPR) emerging as a central strategy (Ramasubramanian et al., 2023; Grandhi et al., 2024). Countries such as Japan, South Korea, and EU members have implemented mandatory EPR schemes involving take-back obligations, eco-design standards, and recycling targets (Noranarttakun and Pharino, 2021), which have significantly improved recovery rates and reduced hazardous components.

In Malaysia, e-waste management is governed by the Environmental Quality Act 1974 and the Environmental Quality (Scheduled Wastes) Regulations 2005, which classify e-waste as SW110 and require documentation, secure storage, and disposal through licensed facilities (DOE, 2005; DOE, 2022). While these regulation ensures traceability and compliance with the Basel Convention (DOE, 2021), these regulations focus primarily on downstream control. Recent initiatives such as Government Green Procurement (GGP) and the MyHIJAU eco-label encourage the purchase of certified green and durable products (MGTC, 2018), while the Circular Economy Policy Framework emphasizes the gradual adoption of mandatory EPR schemes in Malaysia (MITI, 2024). These developments create opportunities for universities to strengthen e-waste governance and sustainability strategies (KPMG Malaysia, 2023).

Higher education institutions (HEIs) consume large volumes of electronic equipment and are expected to demonstrate sustainability leadership (Molina-Motos et al., 2023). The UI GreenMetric includes waste, hazardous waste, and recycling indicators (UI GreenMetric, 2024), motivating universities to adopt sustainability initiatives. However, global evidence shows that campus e-waste management remains fragmented, with institutions focusing more on energy and water conservation while overlooking e-waste despite its toxicity and resource recovery potential (Oliveira and Proença, 2025;

Dawodu et al., 2022). Many efforts, such as refurbishment programs and awareness campaigns, remain ad hoc and lack policy-level integration (Dayaday and Galleto, 2022).

Recent Malaysian studies reveal similar issues. Hashim et al. (2025) highlight bureaucratic hurdles and limited centralized guidance for public universities. Student surveys indicate inconsistent awareness and disposal practices (Yaacob et al., 2025; Yee et al., 2024; Barcelo et al., 2024). Although promising practices exist, such as refurbishment for student use, decentralized collection points, and partnerships with certified recyclers, these initiatives remain fragmented and lack a unified strategy.

E-waste is also recognized globally as hazardous waste due to toxic components such as lead, mercury, cadmium, and brominated flame retardants, which pose significant risks to human health and the environment if improperly managed. (WHO, 2021; WHO, 2024; Mlelwa and Rother, 2024). In Malaysia, e-waste is formally classified as Scheduled Waste SW110 under the Environmental Quality (Scheduled Wastes) Regulations 2005, requiring strict handling, storage, and disposal procedures (DOE, 2005; DOE, 2022). This hazardous classification underscores the urgency for universities to adopt structured and legally compliant e-waste management approaches.

The circular economy (CE) framework provides a powerful conceptual lens for rethinking e-waste management in universities. By emphasizing prevention, reuse, refurbishment, repair, and recycling, CE framework shifts the focus from linear disposal models to systems that maximize resource efficiency (Korhonen et al., 2018; Stankevičienė et al., 2020). In higher education, this involves embedding principles of circularity into procurement, IT asset management, and end-of-life practices, while fostering awareness among students and staff (Rodríguez-Guerreiro et al., 2024). Universities, as living laboratories, are uniquely positioned to demonstrate circular practices while integrating them into teaching and research (Sugiarto et al., 2022; Giurea et al., 2024).

Digital technologies such as IoT sensors, RFID tagging, and blockchain tracking can enhance transparency in waste systems by improving inventory control, ensuring secure data wiping, and providing auditable chains of custody (Ahmed et al., 2024; Borges et al., 2024). However, technological solutions alone are insufficient. Effective governance, policy alignment, and community engagement remain critical

for achieving durable impacts (Ermayendri et al., 2025; Molina-Motos et al., 2023).

Additional insights can be drawn from community-based e-waste bank models in Indonesia, where decentralized collection points, transparent valuation mechanisms, and formal partnerships with recyclers encourage participation (Rimantho et al., 2022). Such principles can be adapted to university settings.

The Unified Green E-waste Management Framework (UGEMF) integrates governance, infrastructure, and engagement to address fragmented campus practices. It promotes regulatory alignment, efficient collection and processing systems, and behavioral change through participation. UGEMF has also informed broader municipal and industrial applications (Andeobu et al., 2023; Barcelo et al., 2024), demonstrating its adaptability. Compared to other frameworks, such as the Circular Campus Framework (Sugiarto et al., 2022), the Sustainable Campus Framework (Oliveira and Proença, 2025), and extended producer responsibility or EPR-based models (Noranartakun and Pharino, 2021), UGEMF provides an integrated, context-specific approach suited to Malaysian HEIs.

This paper proposes UGEMF, developed through qualitative research involving document analysis and stakeholder interviews. Its contributions are threefold: advancing circular economy scholarship in Malaysian higher education, offering practical pathways for universities to shift from compliance-based disposal to integrated sustainability strategies, and supporting national aspirations for circular economy and sustainable development.

Despite existing regulations and emerging initiatives, Malaysian public universities still lack a unified and systematic approach to e-waste management. Therefore, this study addresses the problem of fragmented governance, inconsistent practices, and limited engagement by proposing UGEMF as a structured solution for Malaysian HEIs.

2. METHODOLOGY

2.1 Research design

This study employed a qualitative research design to develop the Unified Green E-waste Management Framework (UGEMF) for Malaysian public universities. Qualitative inquiry was considered appropriate because the objective was not to quantify e-waste generation or statistically measure behavioral patterns statistically, but rather to explore processes,

institutional practices, and stakeholder perceptions that underpin e-waste management. As Creswell and Poth (2018) argue, qualitative methods are particularly useful when the goal is to understand complex social phenomena and to generate models or frameworks grounded in stakeholder experiences.

The study followed an exploratory multiple-case study approach, with several Malaysian public universities serving as embedded units of analysis. This approach enabled the researcher to examine similarities and differences across institutions, thereby identifying both common barriers and context-specific unique practices in e-waste management. Such a design is aligned with Yin's (2018) proposition that multiple case studies provide stronger theoretical grounding by permitting cross-case comparisons and replication logic.

In terms of research setting and context, Malaysia currently hosts more than 20 public universities, all of which play a significant role in advancing the country's sustainability agenda. These institutions are major consumers of electronic devices due to their dependence on information and communication technologies (ICT), laboratory equipment, and digital services. At the same time, public universities are subject to national regulations such as the Environmental Quality (Scheduled Wastes) Regulations 2005 (SW110) and Government Green Procurement (GGP) guidelines. However, past studies suggest that universities often face difficulties in translating these national frameworks into coherent institutional strategies (Hashim et al., 2025; Yaacob et al., 2025). This study, therefore, situates its exploration within public universities as both significant e-waste generators and critical agents of change for sustainable campus development.

A purposive sampling strategy was adopted to identify participants who possessed direct knowledge of and responsibility for e-waste management. Stakeholders included university administrators responsible for asset management, procurement, and sustainability policies; IT department staff managing the lifecycle of ICT equipment; and facilities and estate managers overseeing campus waste management practices. In total, six respondents participated in the study, one from each university. Table 1 presents their institutional background and positions. This selection ensured that findings were not overly context-specific but captured a broad range of operational realities in Malaysian higher education.

Table 1. Interview participants

Respondent	Region	Position	Unit/Department
R1	North	Director	Dept. of Development and Asset Management
R2	North	Administrative Assistant	IT Department
R3	Central	Head of Operation and Service Section	Occupational Safety and Health Management Office
R4	Central	Director	Department of Development and Infrastructure
R5	Central	Evaluation Officer	Department of Development and Estate Maintenance
R6	South	Deputy Director	Campus Sustainability Office

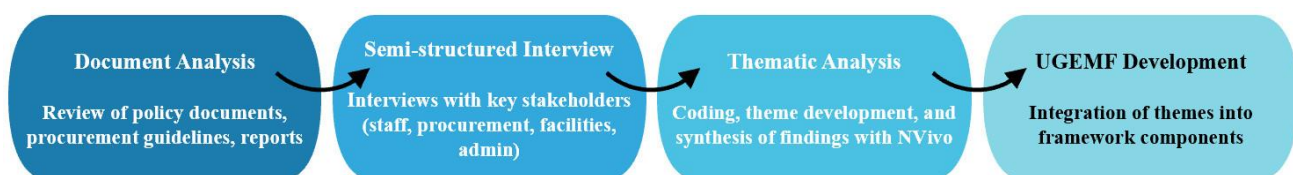
2.2 Data collection methods and analysis

Policy documents, procurement guidelines, e-waste management reports, and sustainability strategies were systematically collected and reviewed. These included internal university policies and standard operating procedures (SOPs) as well as national-level instruments (e.g., the DOE's Scheduled Wastes Regulations, the Government Green Procurement/MyHIJAU programme, and the Circular Economy Policy Framework) that shape e-waste governance in public universities. Document analysis served to map the existing institutional and regulatory frameworks shaping e-waste practices. It also provided triangulation to validate data obtained through interviews (Bowen, 2009). In addition, the semi-structured interviews were conducted with key informants across the six universities. An interview protocol was designed to cover themes such as institutional policies on e-waste management, challenges and barriers encountered in practice, existing practices of reuse, refurbishment, and recycling, awareness and training initiatives targeting students and staff, and partnerships with recyclers, government agencies, and suppliers. Each interview lasted between 45-90 minutes and was conducted in either English or Malay, depending on the participant's preference. All interviews were audio-recorded with consent and later transcribed verbatim for analysis.

Data were then analysed following a thematic analysis approach as outlined by Braun and Clarke

(2021). This involved six stages: familiarization with the data through repeated reading of transcripts and documents, initial coding of meaningful units relevant to the research questions, searching for themes by grouping codes into broader categories, reviewing themes to ensure coherence and distinction, defining and naming themes to align them with conceptual elements of e-waste management, and producing the report by linking themes to theoretical and policy frameworks. NVivo 12 software was employed to manage and organize data, enabling systematic coding and retrieval of excerpts. To enhance validity, peer debriefing was conducted with two qualitative research experts who reviewed a subset of codes to ensure coding consistency. Discrepancies were discussed and reconciled through consensus, thus improving analytical reliability.

The thematic analysis produced four major thematic categories, namely stakeholder engagement, green strategies, policy and regulatory alignment, and monitoring and evaluation, which became the foundation of the proposed UGEMF. Figure 1 summarizes the research design process, starting with document analysis, followed by semi-structured interviews across six universities, and concluding with thematic analysis. It highlights the triangulation of methods, the purposive sampling of key stakeholders, and the iterative process of coding and theme development that led to the formulation of UGEMF.

**Figure 1.** Research design of the study

2.3 Trustworthiness of the study and ethical considerations

To ensure rigor, the study adhered to Lincoln and Guba's (1985) criteria for trustworthiness. Credibility was achieved through data triangulation (documents and interviews) and member checking, where preliminary findings were shared with selected participants for validation. Transferability was supported through a thick description of institutional contexts, allowing readers to assess applicability to other HEIs. Dependability was ensured by maintaining a detailed audit trail documenting research decisions, coding procedures, and analytic steps. Confirmability was reinforced through reflexivity, with the researcher maintaining a reflective journal to bracket personal assumptions. Moreover, ethical approval was obtained from the relevant university research ethics committee prior to data collection. Participation was voluntary, with informed consent obtained from all interviewees. Anonymity and confidentiality were assured, and sensitive data were handled in accordance with research ethics guidelines. Data were stored securely with restricted access to ensure participant privacy.

2.4 Methodological limitations

As with most qualitative studies, several limitations apply. First, the reliance on interviews introduces the possibility of subjectivity bias, as responses may reflect personal interpretations or institutional sensitivities. Second, the small number of respondents, which is appropriate for an exploratory case study design, limits the generalizability to all

Malaysian HEIs. However, the purpose was depth rather than breadth, and the multiple-case approach enhanced analytical richness. Finally, while triangulation and peer checking were employed, interpretation remains influenced by the researcher's perspective despite the use of reflexive measures.

3. RESULTS

3.1 Development of the unified green e-waste management framework (UGEMF)

The findings of this study led to the development of the Unified Green E-waste Management Framework (UGEMF). The findings were analyzed comparatively across the six universities, highlighting both similarities and variations in e-waste management practices that informed the formulation of the UGEMF. This framework brings together people, policies, and practices to improve the management of electronic waste within Malaysian public universities. It is designed to move universities away from fragmented, disposal-based approaches and toward a more sustainable, circular system. The framework is illustrated in Figure 2: the Unified Green E-waste Management Framework, which shows the four main components: stakeholder engagement, green strategies, policy and regulatory alignment, and monitoring and evaluation. Together, these components ensure that e-waste is not only disposed of safely but also prevented, reused, refurbished, and tracked in a way that benefits the environment, the institution, and the wider community.

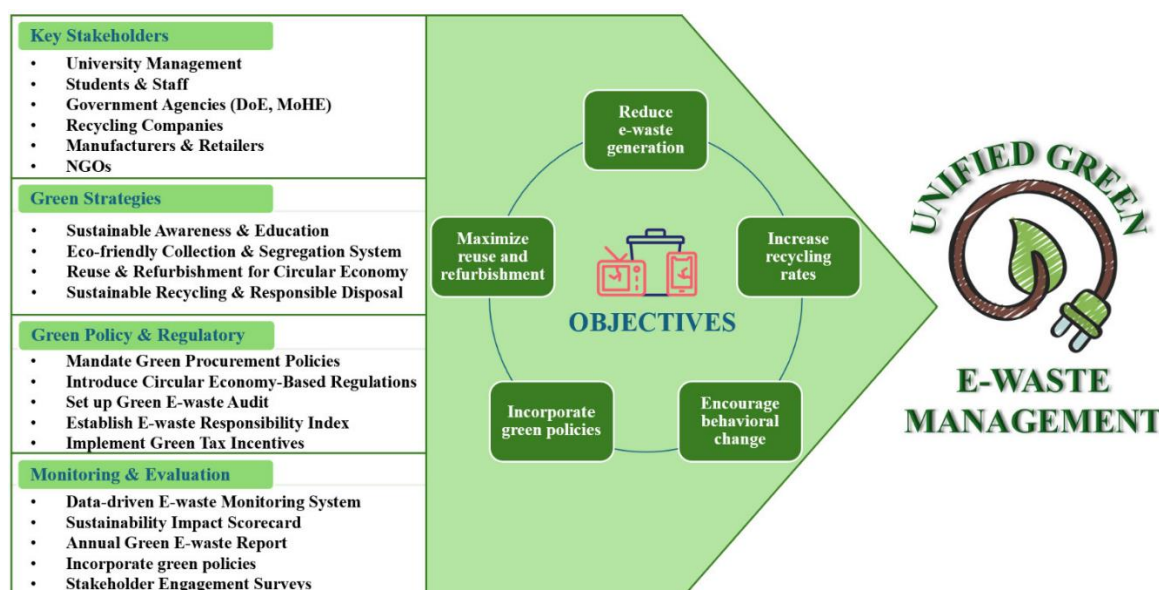


Figure 2. The Unified Green E-waste Management Framework

UGEMF functions as a holistic model to strengthen e-waste management across universities by embedding sustainability at every stage of the electronic device lifecycle. Details of the four main components are as follows:

3.1.1 Stakeholder engagement

The first component of the UGEMF stresses that e-waste management cannot be successful without the involvement of multiple stakeholders. Stakeholder engagement emerged as the central foundation of effective e-waste governance. The analysis showed that responsibilities were frequently distributed across multiple departments, including IT services, procurement, facilities management, and sustainability units, without formal mechanisms for coordination. As a result, universities often experienced inconsistent data sanitization processes, duplicated storage arrangements, delayed disposal, and limited participation from students and staff.

UGEMF addresses these issues through a clearly defined governance structure, as illustrated in [Table 2](#), which outlines the roles of various stakeholders, ranging from university leadership to external recyclers. The framework positions university management as the strategic decision-makers responsible for policy approval and resource allocation. Technical units such as IT and facilities management serve as operational coordinators by managing asset tracking, data sanitization, and storage compliance. Students and staff play a complementary role by supporting awareness activities and participating in collection initiatives. External recyclers, manufacturers, and government agencies operate as compliance and recovery partners, providing certified treatment services and ensuring alignment with national policies. This shared responsibility ensures that e-waste management is not just a technical exercise but a collective effort.

Table 2. Key stakeholders and their responsibilities in UGEMF

Stakeholder group	Core responsibilities
University Top Management	Strategic leadership, policy approval, resource allocation
IT Department	Data sanitization, asset tracking, device cascading
Procurement Unit	Green procurement clauses, after-sales/take-back agreements
Facilities/Asset Management	Storage, scheduled waste compliance, recycler coordination
Students and Staff	Participation in collection campaigns and reuse initiatives
External Recyclers	Licensed treatment, reporting, recovery documentation
Government Agencies	Regulatory oversight, compliance support

3.1.2 Green strategies

The second component focuses on adopting strategies that reduce the amount of e-waste and make better use of what already existing resources. Findings from the study showed that universities often emphasize disposal, with little effort devoted into prevention or reuse. UGEMF offers a different approach by encouraging actions across the entire lifecycle of electronic devices.

Before devices are purchased, universities can apply green procurement policies that require suppliers to provide equipment that is durable, repairable, and supported by after-sales services such as maintenance and take-back programs. This reduces the chances of devices becoming waste too quickly. During the use phase, UGEMF encourages refurbishment and reuse. For example, when computers are no longer suitable for high-performance tasks such as those in research labs, they can be

reassigned to administrative offices or student labs where performance demands are lower. Slightly outdated devices can be refurbished and upgraded rather than discarded.

UGEMF also supports the establishment of campus-wide segregation and collection efforts. These include the placement of colour-coded or category-specific collection points to ensure that ICT devices, batteries, lamps, laboratory electronics, and other equipment are separated correctly before processing. This ensures that materials are easier to recycle and prevents hazardous components from mixing with general waste. Although the qualitative methodology did not produce precise numerical data, several interviewees shared indicative trends, such as low student awareness, which was often reflected in estimated participation rates of between 20 and 40 percent during collection programs, and increasing annual volumes of ICT disposals, which ranged from

800 to 1,500 units in larger institutions. These examples do not represent the formal collection of quantitative data but serve to illustrate the scale of the challenges faced and the importance of structured interventions.

3.1.3 Policy and regulatory alignment

The third component links university practices with national laws and internal policies. Malaysia already has regulations such as the Environmental Quality (Scheduled Wastes) Regulations 2005 (SW110), which classify e-waste as a scheduled waste that must be handled with care. However, the findings revealed that many universities treat these requirements as largely administrative rather than operational.

UGEMF bridges this gap by embedding policy into routine processes. Universities can develop their own e-waste policy that sets out responsibilities, procedures, and compliance requirements. Procurement rules can be updated to include green clauses, such as requiring vendors to handle end-of-life equipment responsibly. Regular e-waste audits can identify weak areas and ensure that reporting requirements are met. Incentives such as tax benefits or recognition schemes can encourage departments to follow the rules more closely. By aligning campus practices with both national regulations and university-level policies, UGEMF reduces the risk of non-compliance and builds a stronger culture of accountability. This alignment also supports national goals for the circular economy and sustainability, making universities role models for other institutions.

3.1.4 Monitoring and evaluation

The fourth component focuses on tracking progress and learning from experience. One of the main problems identified in the study was the lack of reliable data on how much e-waste is generated, reused, or recycled by universities. Without such data, it is difficult to plan or improve management practices.

UGEMF introduces a structured monitoring and evaluation system. Universities can use tracking tools to record the number and type of devices collected, refurbished, or recycled. Dashboards and sustainability scorecards make this information visible to administrators and the wider campus community. Annual reports can summarize achievements, highlight areas for improvement, and set new targets for the following year. Surveys can also be used to measure awareness and satisfaction among staff and

students. Regular monitoring helps universities identify problems early. For example, if one faculty shows very low collection rates, additional awareness campaigns or collection points can be introduced. Over time, the data also allows universities to demonstrate their contribution to environmental goals, both at the institutional and national levels.

Together, these four interrelated functions; engagement, strategies, policy alignment, and monitoring, form a comprehensive system that transforms e-waste management from a reactive task into a proactive and sustainable practice. Through the UGEMF, universities are positioned not only as compliant institutions but also as leaders in sustainable campus development, offering a replicable model that can inspire similar transitions across the higher education sector.

3.2 Comparative positioning of UGEMF with prior e-waste frameworks

Although UGEMF is newly introduced in the context of Malaysian public universities, its principles resonate with global best practices and prior frameworks applied in both academic and non-academic contexts. For instance, [Cristi \(2024\)](#) assessed the e-waste management framework at the University of Leeds, emphasizing policy-practice alignment, stakeholder roles, and performance monitoring, which are elements that mirror the functions of UGEMF. Similarly, [Hashim et al. \(2025\)](#) highlighted how fragmented departmental responsibilities in Malaysian universities hinder systematic e-waste strategies, underscoring the need for unified approaches such as UGEMF.

Beyond university contexts, national and community-based initiatives demonstrate comparable strategies. [Rimantho et al. \(2022\)](#) introduced an electronic waste bank model in Indonesia, which integrated decentralized collection, transparent valuation, and partnerships with recyclers. This approach parallels UGEMF's emphasis on stakeholder engagement and principles of circularity. In Malaysia, [Yusof et al. \(2023\)](#) analyzed e-waste sustainability efforts, revealing the importance of integrating green procurement, regulatory alignment, and behavioral change, which are key elements of UGEMF. Additionally, [Shad \(2020\)](#) discussed sustainable e-waste management from a legal and policy perspective, highlighting governance and enforcement mechanisms that reinforce the regulatory component of UGEMF.

These studies demonstrate that while UGEMF is unique in its unified design for Malaysian public universities, its functions align with broader international and community-based practices. Integrating such lessons ensures that UGEMF is not only contextually relevant but also consistent with the evolving global standards in e-waste management.

To situate UGEMF within the broader scholarly literature, [Table 3](#) compares UGEMF with several existing e-waste management models. The comparison shows that while previous frameworks emphasize elements such as circularity, stakeholder roles, or regulatory compliance, UGEMF uniquely combines all three within a single governance model tailored to the needs of Malaysian HEIs.

Table 3. Comparison of UGEMF with existing e-waste frameworks

Framework/study	Scope	Key features	Alignment with UGEMF
Cristi (2024) , Univ. of Leeds	HEI	Policy alignment, stakeholder roles	High-mirrors governance and monitoring emphasis
Rimantho et al. (2022) , Indonesia	Community	Waste bank, decentralized collection	Medium-similar on engagement, different in scale
Yusof et al. (2023) , Malaysia	National	Green procurement, behavior change	High-supports green purchasing and awareness
Shad (2020)	Legal/policy	Governance, strict enforcement	High-reinforces regulatory alignment
UGEMF (This Study)	Malaysian HEIs	Unified governance, lifecycle strategies, MEL	Unique integration of all components in HEI context

In the context of Malaysian public universities, the main advantage of UGEMF is its ability to unify governance structures. It translates national regulations and circular economy goals into practical campus actions by clearly defining responsibilities, implementation steps, and reporting mechanisms. This helps overcome common problems such as weak coordination and superficial regulatory compliance. The framework also supports device reuse and refurbishment, which can reduce costs and extend product lifecycles. In addition, its monitoring, evaluation, and learning (MEL) component improves transparency and allows universities to track progress and make continuous improvements. This aligns with global recommendations that higher education institutions should report clear and consistent sustainability metrics to maintain stakeholder trust and participation.

However, the main challenges of implementing UGEMF involve the complex coordination and capacity requirements. Successful adoption requires close collaboration between units handling data sanitization, procurement, storage, and licensed recycling, and many universities may initially struggle with these cross-departmental processes. There are also liability and market issues, such as ensuring data security, finding reliable recyclers, and managing inconsistent participation across faculties. As of 31 July 2025, Malaysia’s Department of Environment reported 128 licensed e-waste recovery facilities nationwide ([Bernama, 2025](#)), reflecting growing

formal capacity, while public registries (eSWIS) also list licensed transporters and recovery premises for SW110. Despite this expanding infrastructure, reliance on external recyclers and market conditions may still limit reuse opportunities when vendor capacity or incentives are weak. To address these risks, universities should consider a phased implementation, clear vendor agreements that include take-back and data-wiping requirements, and transparent dashboards to keep stakeholders informed and engaged.

4. DISCUSSION

The Global E-waste Monitor 2024 indicates that e-waste generation continues to grow rapidly worldwide, with projections suggesting a significant increase if current trends persist ([ITU and UNITAR, 2024](#)). This trend emphasizes the urgent need for structured institutional responses. UGEMF contributes to this agenda by operationalizing circular economy principles through coordinated governance, targeted procurement practices, comprehensive lifecycle strategies, and systematic monitoring and evaluation. Despite these strengths, the findings also highlight critical implementation challenges that universities will need to anticipate and manage.

The first major challenge concerns the hidden and indirect costs associated with implementing UGEMF. Although the model does not require significant capital expenditure, institutions may need

to allocate additional labour for data wiping, invest in secure storage infrastructure to ensure compliance with SW110 requirements, and provide regular training for staff involved in green procurement and monitoring. The introduction of digital systems for asset tracking, such as QR codes or RFID tagging, may also require careful financial planning.

A second challenge arises from bureaucratic resistance and the siloed organizational culture that is common in many public universities. Departments may be reluctant to collaborate due to unclear jurisdictional boundaries, concerns about assuming new responsibilities, or a preference for maintaining familiar, informal practices. Strong leadership commitment, clear SOPs, and regular communication channels are therefore essential for overcoming these barriers.

A third challenge relates to the variability in recycler reliability and the influence of market conditions. Several universities reported inconsistent pickup schedules, limited refurbishment capacity, and fluctuating market prices for recovered materials, all of which may weaken incentives for reuse and discourage sustained participation in collection initiatives.

A final challenge concerns the uneven levels of awareness and participation among students and staff. Although not measured quantitatively in this study, interview themes consistently suggested that many individuals were unsure about the proper channels for disposal or were unaware of institutional initiatives. Frequent turnover among students further complicates sustained behavioural change, making ongoing awareness campaigns and MEL feedback mechanisms essential.

Overall, UGEMF offers a structured and replicable approach that links circular economy principles, regulatory requirements, and institutional practices. By translating policy directives, such as extended producer responsibility, green procurement, and scheduled waste management, into practical campus-level actions, the framework addresses long-standing coordination problems and strengthens e-waste governance across Malaysian HEIs. Its comprehensive scope positions universities as key contributors to the nation's transition toward a circular and environmentally responsible future.

5. CONCLUSION

The Unified Green E-waste Management Framework (UGEMF) provides Malaysian public universities with a comprehensive approach to transition from fragmented, disposal-focused practices to an integrated, circular model that emphasizes prevention, reuse, refurbishment, and responsible recycling. By clearly defining stakeholder roles, embedding green procurement and extended producer responsibility (EPR) principles, and introducing structured monitoring and evaluation mechanisms, UGEMF strengthens institutional accountability while aligning campus practices with national regulations.

For practical implementation, universities can adopt a gradual, phased approach. Initially, institutions can focus on establishing governance structures and clarifying responsibilities across departments. The second phase may involve integrating green procurement requirements into tenders and promoting refurbishment and cascading of devices. Subsequently, universities can implement systematic monitoring and evaluation using dashboards and periodic reporting, coupled with awareness campaigns to engage students, staff, and external partners. Priority policies include ensuring compliance with Scheduled Waste SW110 regulations, formalizing take-back schemes with certified recyclers, and embedding circular economy principles into procurement and asset management processes.

UGEMF demonstrates that sustainable e-waste management is achievable without major capital investment, relying primarily on clear governance clarity, targeted policies, and transparent reporting. By adopting the framework, universities can mitigate environmental risks, maximize resource recovery, and foster a culture of shared responsibility among campus stakeholders.

For future research, field trials of UGEMF implementation in selected universities are recommended to evaluate its operational feasibility and identify context-specific challenges. Additionally, quantitative studies could measure the framework's effectiveness in reducing e-waste, improving reuse and recycling rates, and enhancing awareness among students and staff. Future studies could also complement the present findings by analyzing cost implications, developing data-risk mitigation guidelines, and designing phased implementation

roadmaps to support the practical adoption of UGEMF across universities with varying resources and

capacities. Such investigations will further validate UGEMF and support its adaptation in other higher education institutions or public organizations regionally and globally.

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AUTHOR CONTRIBUTIONS

Conceptualization, Rushanim Hashim; Methodology, Validation, and Analysis, Fadhilah Mohd Zahari and Rushanim Hashim; Writing-Original Draft Preparation, Nurul Azita Salleh; Writing-Review and Editing, Jafni Azhan Ibrahim.

DECLARATION OF CONFLICT OF INTEREST

We declare that the manuscript entitled “Unified Green E-waste Management Framework Towards Sustainable Campus Development: Case Study of Malaysian Public Universities” is an original work, not previously published or under review elsewhere. All data, analyses, and interpretations are based on valid scientific methods, with proper citations provided for external contributions. The manuscript contains no plagiarism, and all authors listed have made significant contributions to the research and writing. We accept full responsibility for any breach of publication ethics.

REFERENCES

- Ahmed K, Dubey MK, Kumar A, Dubey S. Artificial intelligence and IoT driven system architecture for municipality waste management in smart cities: A review. *Measurement: Sensors* 2024;36:Article No. 101395.
- Akhtar R. Managing E-Waste is Key to Our Sustainability [Internet]. 2024 [cited 2025 Jan 2]. Available from: <https://theedgemalaysia.com/node/703393>.
- Andeobu L, Wibowo S, Grandhi S. Environmental and health consequences of e-waste: A critical review. *Sustainability* 2023;15(13):Article No. 10405.
- Barcelo J, Artuz MT, Tansengco M, Herrera D, Chuayana JM, Esguerra R. Waste analysis and characterization study in a Philippine science and technology research and development institution. *Environment and Natural Resources Journal* 2024;22(6):547-64.
- Bernama. Over half a million tonnes of e-waste processed as at June 2025, DOE wants tougher control [Internet]. 2025 [cited 2025 Sep 15]. Available from: <https://bernama.com/en/news.php?id=2451587>.
- Borges RM, Zagui GS, Bortoletto-Santos R, Ismail IAL, Souza MT, Simão L, et al. Data collection and elaboration of guidelines for waste electrical and electronic equipment management in Brazilian private higher education institutions. *Sustainability* 2024;16(24):Article No. 11091.
- Bowen GA. Document analysis as a qualitative research method. *Qualitative Research Journal* 2009;9(2):27-40.
- Braun V, Clarke V. *Thematic Analysis: A Practical Guide*. London: SAGE; 2021.
- Creswell JW, Poth CN. *Qualitative Inquiry and Research Design: Choosing among Five Approaches*. 4th ed. Thousand Oaks (CA): SAGE; 2018.
- Cristi KM. Redefining the e-waste management framework at the University of Leeds: Challenges and opportunities for sustainability. *Proceedings of the Sustainable Ecological Engineering Design for Society (SEEDS)*; 29-31 Aug 2023; Ipswich, UK: University of Suffolk; 2024.
- Dawodu A, Dai H, Zou T, Zhou H, Lian W, Oladejo J, et al. Campus sustainability research: Indicators and dimensions to consider for the design and assessment of a sustainable campus. *Heliyon* 2022;8(12):e11864.
- Dayaday MG, Galleto FA Jr. Electronic waste management of higher education institutions in South Central Mindanao, Philippines. *Environment and Natural Resources Journal* 2022;20(5):534-42.
- Department of Environment (DOE) Malaysia. *Environmental Quality (Scheduled Wastes) Regulations 2005 (P.U.(A) 294/2005)*. Putrajaya, Malaysia: DOE; 2005.
- Department of Environment (DOE) Malaysia. *Guidelines for the Transboundary Movement of used Electrical and Electronic Equipment in Malaysia*. Putrajaya, Malaysia: DOE; 2021.
- Department of Environment (DOE) Malaysia. *Environmental Quality Act 1974 (Act 127)*. Consolidated Text. Putrajaya, Malaysia: DOE; 2022.
- Ermayendri D, Simarmata M, Arianto W, Reflis, Riwardi, Sukiyono K. Dynamic integrated model for sustainable solid waste management in Bengkulu City. *Environment and Natural Resources Journal* 2025;23(6):494-515.
- Giurea R, Miino MC, Torretta V, Rada EC. Approaching sustainability and circularity along waste management systems in universities: An overview and proposal of good practices. *Frontiers in Environmental Science* 2024;12:Article No. 1363024.
- Grandhi SP, Dagwar PP, Dutta D. Policy pathways to sustainable e-waste management: A global review. *Journal of Hazardous Materials Advances* 2024;16:Article No. 100473.
- Hashim R, Salleh NA, Ibrahim JA, Zahari FM. E-waste management practices through the eyes of responsible departments at Malaysian public universities. *Journal of Advanced Research in Applied Sciences and Engineering Technology* 2025;52(1):309-19.
- International Telecommunication Union, United Nations Institute for Training and Research (ITU and UNITAR). *Global E-Waste Monitor 2024*. Geneva/Bonn: ITU/UNITAR; 2024.
- KPMG Malaysia. *Extended Producer Responsibility: Stepping Stone to Malaysia's Circular Economy*. Kuala Lumpur: KPMG; 2023.
- Korhonen J, Honkasalo A, Seppälä J. Circular economy: The concept and its limitations. *Ecological Economics* 2018;143:37-46.
- Lincoln YS, Guba EG. *Naturalistic Inquiry*. Beverly Hills (CA): SAGE; 1985.
- Malaysia Green Technology and Climate Change Corporation (MGTC). *Government Green Procurement (GGP) Guidelines 2.0*. Putrajaya, Malaysia: MGTC; 2018.
- Ministry of Investment, Trade and Industry (MITI). *Circular Economy Policy Framework for the Manufacturing Sector in*

- Malaysia. Kuala Lumpur, Malaysia: Ministry of Investment, Trade and Industry; 2024.
- Mlelwa R, Rother HA. Reviewing the current state of legacy POP-brominated flame retardants in plastic childcare products and toys: A scoping review protocol. *Systematic Reviews* 2024;13:Article No. 148.
- Molina ÁA, Helldén D, Alfvén T, Niemi M, Leander K, Nordenstedt H, et al. Integrating the United Nations Sustainable Development Goals into higher education globally: A scoping review. *Global Health Action* 2023;16(1):Article No. 2190649.
- Noranarttakun P, Pharino C. How does the green industry policy impact a developing country? A case study of the electronic products and electrical equipment manufacturing sector in Thailand. *Environment and Natural Resources Journal* 2021;19(5):402-12.
- Okeke ES, Enochoghene A, Ezeudoka BC, Kaka SD, Chen Y, Mao G, et al. Heavy metal risks around e-waste sites and comparable municipal dumpsites in major African cities. *Toxicology* 2024;501:Article No. 153711.
- Oliveira MC, Proença J. Sustainable campus operations in higher education institutions: A systematic literature review. *Sustainability* 2025;17(2):Article No. 607.
- Ramasubramanian B, Tan J, Chellappan V, Ramakrishna S. Recent advances in extended producer responsibility initiatives for plastic waste management in Germany and UK. *Materials Circular Economy* 2023;5(1):Article No. 6.
- Rimantho D, Syaiful S, Nurfaida, Sulandari U. Electronic waste bank model as a solution for implementing circular economy: Case study DKI Jakarta, Indonesia. *Frontiers in Built Environment* 2022;8:Article No. 1030196.
- Rodríguez-Guerreiro MJ, Torrijos V, Soto M. A review of waste management in higher education institutions: The road to zero waste and sustainability. *Environments* 2024;11(12):Article No. 293.
- Shad KM. Sustainable e-waste management in Malaysia: Legal and policy frameworks. *IIUM Law Journal* 2020;28(2):265-90.
- Stankevičienė J, Nikanorova M, Čera G. Analysis of green economy dimension in the context of circular economy. *Economics and Management* 2020;23(1):4-18.
- Sugiarto A, Lee CW, Huruta AD. A systematic review of the sustainable campus concept. *Behavioral Sciences* 2022;12(5):Article No. 130.
- UI GreenMetric. Methodology and Indicators. Depok: Universitas Indonesia; 2024.
- World Health Organization (WHO). Children and Digital Dumpsites: E-waste Exposure and Child Health. Geneva: WHO; 2021.
- World Health Organization (WHO). Q&A: Children and Digital Dumpsites—E-Waste and Health. Geneva: WHO; 2024.
- Yaacob NS, Nik Azman NAN, Mohd Salleh S, Alrazi B. Assessing the relationship of knowledge and attitudes on e-waste recycling practices among students of higher learning institutions. *Journal of Nusantara Studies* 2025;10(1):353-72.
- Yee GCJ, Humhashinee H, Kottegodage K, Perera SP, Lim L, Hen Z. Waste matters: Investigating the knowledge, awareness, and practice of electrical and electronic waste management among undergraduate medical students. *Environmental Disease* 2024;3(1):e2024002.
- Yin RK. Case Study Research and Applications: Design and Methods. 6th ed. Thousand Oaks (CA): SAGE; 2018.
- Yusof Y, Tun Ismail WNA, Mohd Noor NAA, Abu Bakar MA. E-Waste Management Toward Environmental Sustainability in Malaysia. IGI Global; 2023. p. 239-59.

Modeling PM2.5: Temperature Interactions Using Predator-Prey Dynamics

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ABSTRACT

This study introduces a novel application of the predator-prey concept to model and forecast daily PM2.5 concentrations, with PM2.5 treated as the prey and temperature as the predator. This formulation reflects the commonly observed inverse relationship between pollution levels and temperature in urban atmospheric environments. A dynamic equation was constructed to describe the rate of change in PM2.5, incorporating both intrinsic growth and the suppressive effect of temperature. Regular environmental cycles are also incorporated into the model structure. Parameters were estimated using daily observational data collected over a three-month period. The model successfully captures short-term variation and broader seasonal trends in PM2.5, despite relying on temperature as the sole external variable. This approach provides a simplified yet interpretable framework that explains how pollution levels respond to environmental drivers over time. It represents a conceptual shift from purely statistical models by offering an ecological perspective on air quality dynamics. Predictive validation yielded RMSE values of 15.7036 for PM2.5 and 0.9425 for temperature, demonstrating strong agreement with observed data. This is the first study to adapt predator-prey principles to describe and predict the interaction between temperature and PM2.5 on a daily time scale.

HIGHLIGHTS

A predator-prey model analyzes interactions between PM2.5 and temperature. PM2.5 is modeled as prey and temperature as predator with seasonal and daily effects. This approach supports improved air quality forecasting and pollution management.

1. INTRODUCTION

Over the past decade, particulate matter with a diameter of 2.5 micrometers or less (PM2.5) has emerged a critical global environmental and public health concern. Due to its extremely small size, PM2.5 can penetrate deep into the respiratory system and bloodstream, leading to serious health consequences such as cardiovascular diseases, respiratory disorders, and lung cancer. This issue is particularly severe in rapidly in urban areas, including Bangkok, Thailand. High traffic density, combustion, and industrial activities contribute to elevated PM2.5 concentrations. Recent studies, further confirm that urban air pollution poses significant health risks for Bangkok's population. Findings indicate a clear association between ambient PM2.5 exposure and increased all-cause mortality, with particularly strong links to stroke and chronic

obstructive pulmonary disease (COPD). Importantly, these health effects occur even at relatively low exposure levels, emphasizing that PM2.5 remains a persistent threat. This underscores the urgent need for effective and stringent pollution control measures to safeguard public health in major cities like Bangkok. (Phosri et al., 2018; Fold et al., 2020).

Studying the impacts of meteorological variables in Bangkok during the winter season offers distinct advantages. During the dry winter months of November to January, PM2.5 levels in Bangkok often peak, as precipitation is typically negligible. This period was selected to examine the influence of meteorological variables on PM2.5 without considering the effects of precipitation. For instance, analysis of PM2.5 data in Bangkok during November-December 2016 to 2018 revealed strong correlations

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with meteorological factors, including wind speed, relative humidity, and temperature. Understanding these complex relationships is essential for developing effective air quality management strategies (Ketjulan et al., 2023). This observation aligns with the findings of Sirithian and Thanatrakolsri (2022), who reported significant correlations between meteorological variables, particularly temperature, relative humidity, and wind speed and PM_{2.5} concentrations in northern Thailand during the dry haze season. Their study highlighted that during periods of minimal rainfall, these meteorological factors serve as the primary drivers influencing particulate matter level. Applying similar reasoning to Bangkok, which experiences similarly dry atmospheric conditions during the winter months, reinforces the importance of focusing on these variables when developing accurate daily forecasting models for PM_{2.5} concentrations (Ruttanawongchai et al., 2018).

Most studies primarily use statistical methods, such as correlation and regression analysis, to examine the relationship between PM_{2.5} and meteorological variables, rather than focusing on daily forecasting (Lu and Ma, 2020). This research proposes a novel approach by applying the predator-prey model, a mathematical framework originally developed to describe ecological interactions between species, such as the influence of the wolf populations on rabbit populations, which have the predator-prey relationship. The model uses differential equations to capture the dynamic interplay of growth and decline rates. The hypothesis of this study is that the predator-prey model can effectively capture the complex relationships between PM_{2.5} concentrations and temperature in Bangkok during the winter season (November to January). This approach is expected to facilitate the development of a highly accurate daily PM_{2.5} forecasting model.

Temperature has a complex, dual-phase effect on particulate matter dynamics. Higher temperatures increase molecular kinetic energy and promote vertical mixing processes, facilitating pollutant dispersion, whereas lower temperatures increase atmospheric density and limit convective mixing, promoting particulate accumulation in lower atmospheric layers (Yang et al., 2017). Temperature exerts a notable influence on PM_{2.5} concentration, with lower temperatures often correlating with higher PM_{2.5} levels. Cold conditions, particularly during in winter, contribute to the formation of temperature

inversion layers that trap pollutants near the surface, limiting vertical mixing, promoting particulate accumulation. Additionally, the use of coal for heating during colder months further exacerbates PM_{2.5} pollution. When combined with low wind speeds and high humidity, these conditions create an environment in which air pollutants are more likely to concentrate in the lower atmosphere (Yang et al., 2023).

Temperature is considered the “predator” within the PM_{2.5}-temperature dynamic system due to its demonstrably inverse relationship with PM_{2.5} concentrations. Elevated temperatures promote atmospheric instability and vertical dispersion of pollutants, thereby reducing particle accumulation an effect to how a predator regulates the growth of a prey population. Moreover, the observed interactions between PM_{2.5} and thermal profiles, such as the urban heat island effect, further support the suitability of this ecological modeling framework. This selection aligns with extensive research identifying temperature as a predominant meteorological factor influencing ambient PM_{2.5} levels. This approach provides a robust basis for analyzing the complex interplay between atmospheric conditions and particulate matter dynamics (Winalai et al., 2022). The proposed predator-prey model represents a novel approach to analyzing the interaction between PM_{2.5} concentrations and temperature. While traditional aerosol dynamics models like Chemical Transport Models, primarily focus on pollutant dispersion and chemical transformation, our predator-prey model introduces an ecological perspective by treating temperature as a “predator” and PM_{2.5} as its “prey”. This dynamic framework captures seasonal feedback loops and interactions between environmental factors, offering a fresh framework for understanding air pollution patterns over time (Lai et al., 2024).

The findings are expected to improve understanding of PM_{2.5} dynamics in Bangkok, a city facing persistent air pollution challenges. The predator-prey approach provides a novel tool for air quality forecasting. By introducing an ecological modeling perspective, this research offers a unique contribution to air quality management and advances the understanding of the complex interplay between PM_{2.5} and temperature. Utilizing a predator-prey model to develop a predictive framework for PM_{2.5} and temperature enables effective monitoring of air quality impacts and helps identify of critical factors for controlling PM_{2.5} concentrations.

2. METHODOLOGY

2.1 PM2.5-temperature interaction model

Predator-prey model

The predator-prey model is a mathematical framework that describe the dynamics interaction between two populations: predators and prey. It illustrates how the population of prey increases when resources are abundant and declines in the presence predators, while the predator population grows when prey is plentiful and declines as prey becomes scarce. This interaction typically leads to oscillating population sizes for both groups, with predators and prey populations rising and falling in a cyclical pattern. The model provides insights into natural population control and the balance between species in ecosystems (Murray, 2002).

We use PM2.5 and temperature data obtained from the Thailand Pollution Control Department and Weather Underground, focusing on the winter season during November and December 2024 to January 2025. The study specifically considered the area around Don Mueang International Airport, located at 13.92°N, 100.6°E in Bangkok, Thailand. The stability and accuracy of the model were further evaluated through the eigenvalues analysis, and the Routh-Hurwitz criterion was applied to assess system stability, ensuring the robustness of the proposed model.

The present investigation adapts and modifies the classical predator-prey framework, originally formulated by Lotka and Volterra, to explore dynamic interactions between PM2.5 concentrations and meteorological parameters (temperature). Within this conceptual framework, PM2.5 is treated as the “prey” species, while temperature acts as predatory forces exerting regulatory influence upon particulate matter concentrations. In this model, we adopted a sigmoid function to represent the temperature’s effect on PM2.5, which qualitatively mirrors the Holling Type III functional response (Holling, 1959a; Holling, 1959b). This approach captures the critical-point and saturating nature of environmental interactions, where temperature only significantly reduces PM2.5 after concentrations exceed a certain level. Such a response is more realistic than linear forms, and aligns with ecological and atmospheric dynamics (Jianhua and Susumu, 2015). We will define the PM2.5 and temperature model as;

Prey equation (PM2.5),

$$\frac{dP}{dt} = \alpha P \left(1 - \frac{P}{K}\right) - \beta PT \left(\frac{1}{1 + e^{-k(P-P_0)}}\right)$$

$$-\delta PT^2 + \xi_1 \sin(\omega_1 t + \phi_1) + \xi_2 \cos(\omega_2 t + \phi_2) \quad (1)$$

Predator equation (Temperature),

$$\frac{dT}{dt} = -\gamma PT + \mu \left(\frac{1}{1 + e^{-k(P-P_0)}}\right) \quad (2)$$

We set $P_0=85$ for the transitions in thermal effect in the model. Most model parameters (listed in Table 1) were estimated using nonlinear regression on the 92-day PM2.5-temperature dataset, while all remaining parameters were determined through optimization using real observational data. Data preprocessing included handling any missing values and normalizing the observations prior to model fitting. These steps ensure that the model reproduces both short-term fluctuations and seasonal patterns in the observed data.

The methodology is designed to produce robust, and replicable results, suitable for air quality forecasting and environmental policy development.

2.2 Stability of the model

To ensure the robustness and reliability of the proposed predator-prey model, we conducted a stability analysis to verify the equilibrium points under varying conditions. This analysis is essential to confirm that the model behaves consistently and provides meaningful predictions over time. Specifically, we use Eigenvalues and the Routh-Hurwitz Criterion to assess the model stability, ensuring that the equilibrium points remain stable and the system responds predictably to parameter changes.

Our focus is on the equilibrium point where both PM2.5 and temperature exist at non-zero values, reflecting their observed presence in real-world data. Based on calculations, we get the equilibrium point for the system of interest.

$$(P^*, T^*) = (120.14, 37.32) \quad (3)$$

Jacobian matrix at equilibrium point,

$$J(P^*, T^*) = \begin{bmatrix} -0.0153 & 0.1705 \\ -0.0033 & -0.0106 \end{bmatrix} \quad (4)$$

We get the eigenvalues,

$$\lambda_1 = -0.0129 + 0.0236i \quad (5)$$

$$\lambda_2 = -0.0129 - 0.0236i \quad (6)$$

Table 1. Meaning of parameters in the model

Symbol	Meaning	Values of the parameters
P	PM2.5 concentration	
T	Temperature	
t	Time	
K	Carrying capacity of PM2.5	172
α	Growth rate of PM2.5	0.015
β	Predation rate	0.00191764
k	The slope of the sigmoid function	0.5
δ	PM dispersion rate	-0.0000447
ξ_1	Seasonal forcing	5.9800
ξ_2	Daily forcing	5.5955
ω_1	Frequency of seasonal	0.0100
ω_2	Frequency of daily	6.2458
ϕ_1	Phase shift	2.1401
ϕ_2	Phase shift	3.7893
γ	Temperature decrease rate by PM2.5	0.0000881
μ	Temperature increase by PM2.5 effect	0.3949

All eigenvalues have negative real parts, the system is stable (Basak and Lee, 2008).

Routh-Hurwitz criterion test, from the eigenvalues (5) and (6) we get the characteristic equation,

$$s^2 + 0.259s + 0.000723 = 0 \quad (7)$$

Which,

$$a_2 = 1, a_1 = 0.259, a_0 = 0.00072$$

There are no sign changes, which mean the system is stable (Medhi et al., 2024).

3. RESULTS AND DISCUSSION

This study developed a nonlinear predator-prey model to investigate the interaction between PM2.5 concentrations and temperature in Bangkok during the winter season. The system comprises two coupled differential equations, with PM2.5 modeled as the “prey” and temperature as the “predators”, representing a novel framework for urban air quality modeling. This analogy provides a dynamic systems perspective, capturing not only correlation but also causality and regulatory mechanisms, in contrast to conventional statistical or machine learning approaches. Key mechanisms, such as logistic growth, threshold responses, and periodic external forcing, were incorporated to reflect seasonal and diurnal dynamics. While previous studies often rely on

regression analysis to analyze air pollution, the predator-prey framework naturally integrates nonlinear feedback and stability analysis, making it more suitable for modeling complex environmental systems with the ability to capture feedback loops and saturation effects (Murray, 2002).

Model calibration and equilibrium analysis were conducted, using daily observations from November 2024 to January 2025 (92 days total). Model parameters were either derived empirically or estimated through regression fitting as shown in Table 1. The stability of the model was validated using eigenvalue analysis and the Routh-Hurwitz criterion, confirming the presence of a locally stable equilibrium under the observed conditions (Themairi and Alqudah, 2020).

To evaluate model performance, the predicted values of PM2.5 and temperature were compared with actual observations. Figure 1 illustrates the comparison between the observed PM2.5 concentrations and the values predicted generated by the proposed predator-prey model, while. Figure 2 presents the comparison between the observed temperature and model-predicted temperature during the study period and Figure 3 shows both variables together. The root mean square error (RMSE) for PM2.5 was 15.7036 and 0.9425 for temperature. These values demonstrate strong agreement, especially given the inherent variability and nonlinearity of urban atmospheric systems.

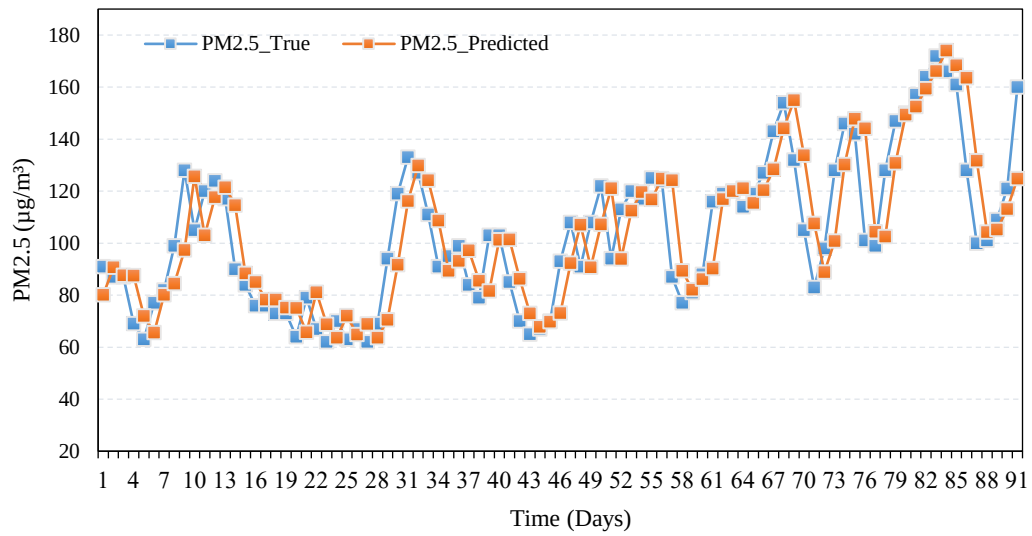


Figure 1. PM2.5 true vs predicted

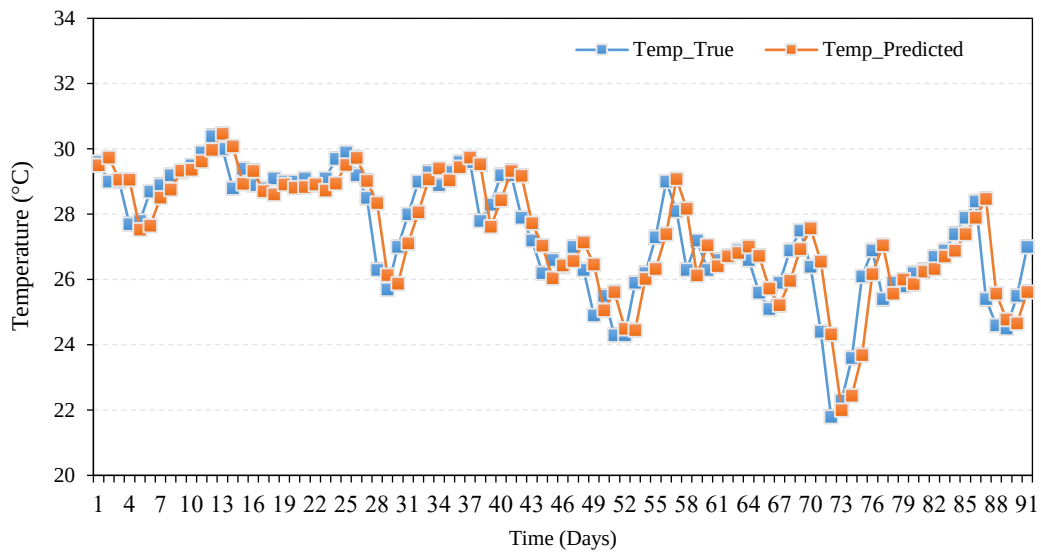


Figure 2. Temperature true vs predicted

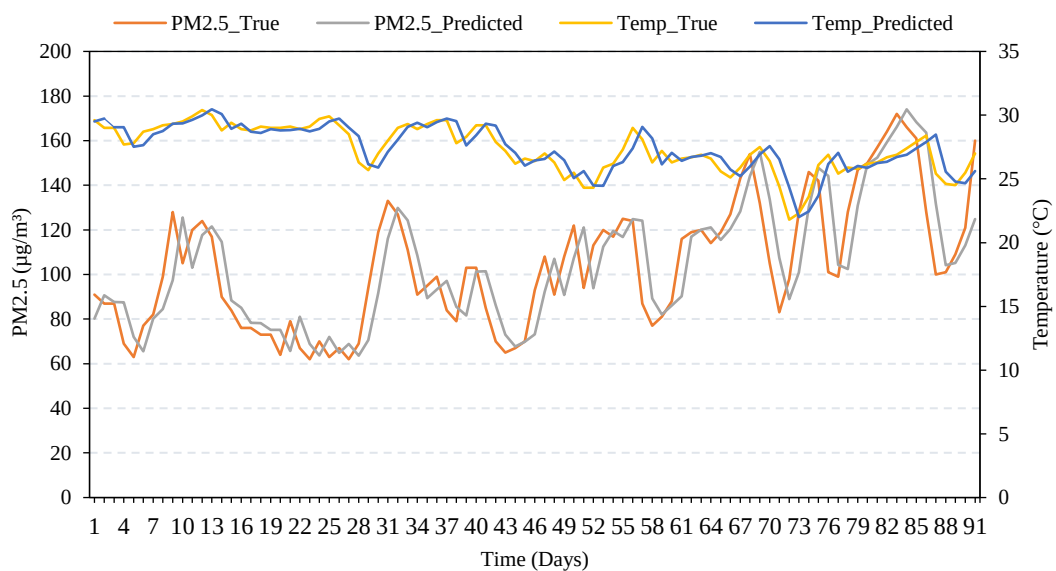


Figure 3. PM2.5 and Temperature true vs predicted

Interpretation and Implications: The model not only confirms the known inverse relationship between temperature and PM_{2.5} but also provides a mechanistic explanation for threshold effects: temperature effectively reduces PM_{2.5} only when pollution levels exceed a critical point, consistent with urban temperature inversions. This insight goes beyond empirical findings by identifying causal thresholds, which can help inform more effective timing of policy interventions. Additionally, the inclusion of periodic forcing terms such as daily traffic cycles, enhances the model's accuracy, allowing it to capture recurring PM_{2.5} peaks driven by daily traffic patterns and seasonal variations in solar radiation.

The predator-prey analogy treating (temperature as the “predator”, PM_{2.5} as “prey”) was adopted to represent the dynamic interaction between temperature and PM_{2.5}. In urban environments, the boundary-layer dynamics play a crucial role in regulating the PM_{2.5} dispersion, with temperature influencing atmospheric stability and turbulence. Additionally, diurnal temperature variation affects the daily cycle of PM_{2.5} concentrations, as higher day time temperatures enhancing dispersion and lower concentrations, while nighttime inversions trap pollutants near the surface (Miao et al., 2019). This mechanistic understanding of physical processes supports the predator-prey analogy and strengthens the ecological basis of the model.

Compared to conventional empirical or data-driven models, the predator-prey approach offers greater theoretical depth, by enabling formal analysis of system stability and potential regime shifts. For example, the identification of an equilibrium state allows for simulation of long-term outcomes under various policy scenarios, which is often not possible with purely statistical models.

Despite its simplified two-variable structure, the model effectively represents urban air pollution. It also offers a flexible foundation for future extensions, such as incorporating additional meteorological variables to enhance predictive performance. In future work, extending the model to include multiple “prey” or “predator” species (e.g., different pollutants or atmospheric drivers) could further broaden its applicability and realism.

Practical Implications: The developed model offers a practical tool for daily air quality forecasting, enabling relevant authorities to issue more accurate public health advisories and pollution warnings. This study focuses on modeling PM_{2.5} concentrations

during the winter season, when pollution levels are typically highest. As a result, the findings and policy recommendations are most applicable to the winter months, and the model's applicability to other seasons remains limited. By predicting PM_{2.5} peaks based on temperature forecasts, proactive measures such as traffic control or industrial emission reductions can be implemented in advance to mitigate severe pollution episodes. Furthermore, the identification of a stable equilibrium state provides insights for long-term environmental policy planning, suggesting that managing key drivers like urban heat could help maintain air quality within acceptable limits. This model can be integrated into early warning systems, it can support targeted interventions, such as restricting high-emission vehicles during predicted high-pollution periods. Additionally, the conceptual framework of temperature as a regulatory “predator” offers an intuitive way to communicate complex atmospheric dynamics to the public, fostering greater awareness and adherence to health guidelines during critical periods. By integrating this model into early warning systems to support targeted interventions, such as limiting high-emission vehicles during forecasted high-pollution events. Moreover, framing temperature as a regulatory “predator” provides an intuitive and accessible way to communicate complex atmospheric dynamics to both policymakers and the general public, potentially increasing awareness and compliance with health guidelines during critical periods (Rizwan et al., 2008).

While the model demonstrated good accuracy with RMSE values during the three-month validation period, we acknowledge that the short duration limits its robustness. Future work will focus on to expand the validation period by incorporating data from several years of winter seasons, which is when PM_{2.5} levels in Thailand are typically the highest. Additionally, out-of-sample validation will be conducted using data from other regions to test the model's generalizability and long-term applicability across different locations and environmental conditions.

4. CONCLUSION

This study presents a nonlinear model that captures the dynamic interaction between PM_{2.5} concentration and ambient temperature, introducing a novel concept through the predator-prey model framework. By incorporating logistic growth, a threshold response, and periodic external forcing, the model captures key behaviors observed in urban

atmospheric systems-particularly the delayed suppressive effect of temperature on PM_{2.5} and the recurrence of pollution peaks linked to seasonal and daily cycles.

The model was calibrated with real-world data spanning 92 days across winter months, and equilibrium analysis confirmed local stability with realistic PM and temperature levels. Predictive validation yielded good agreement between simulated and observed values, indicating that the model can capture short-term fluctuations as well as broader seasonal patterns with reasonable accuracy.

Beyond its predictive capability, the model contributes conceptually by reinterpreting temperature as a regulatory agent-analogous to a predator in ecological systems-acting nonlinearly upon pollution accumulation. This reinterpretation offers a valuable lens for understanding how environmental variables interact not merely through correlation, but through dynamic control mechanisms involving thresholds and feedbacks. Such an approach bridges the gap between empirical atmospheric analysis and mechanistic ecological modeling, enabling the use of well-established mathematical tools such as equilibrium analysis, Jacobian stability, and phase-space behavior.

The identification of a stable equilibrium with interpretable values for both PM_{2.5} and temperature suggests that the system, under typical winter conditions, tends toward a quasi-stable state unless perturbed by strong external forcing. This reinforces the practical relevance of the model in providing not just forecasts, but also insights into the stability and major changes in urban air quality systems.

Future applications may include integrating this model with meteorological forecast inputs, or coupling it with emission inventories for localized policy testing. Furthermore, the structure lends itself to extensions, such as adding humidity and wind variables or implementing spatial diffusion terms to account for inter-area interaction. In sum, the proposed framework offers a compact yet expressive tool for both analysis and predicting complex urban pollution dynamics.

This model offers a new ecological perspective that can stimulate interdisciplinary research in urban environmental management. It underscores the potential of leveraging well-established biological frameworks to understand and predict complex environmental phenomena, ultimately contributing to more resilient and sustainable cities amid escalating air pollution challenges.

AUTHOR CONTRIBUTIONS

Conceptualization, W.S., I.N., and S.R.; Methodology, W.S.; Validation, W.S., I.N., and S.R.; Model Analysis, W.S. and I.N.; Writing-Original Draft Preparation, W.S.; Writing-Review and Editing, I.N. and S.R.; Supervision, I.N. and S.R.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Basak GK, Lee P. Asymptotic properties of an estimator of the drift coefficients of multidimensional Ornstein-Uhlenbeck processes that are not necessarily stable. *Electronic Journal of Statistics* 2008;2(1):1309-44.
- Fold NR, Allison MR, Wood BC, Thao PTB, Bonnet S, Garivait S, et al. An assessment of annual mortality attributable to ambient PM_{2.5} in Bangkok, Thailand. *International Journal of Environmental Research and Public Health* 2020;17(19):Article No. 7298.
- Holling CS. The components of predation as revealed by a study of small-mammal predation of the European Pine Sawfly. *The Canadian Entomologist* 1959a;91(5):293-320.
- Holling CS. Some characteristics of simple types of predation and parasitism. *The Canadian Entomologist* 1959b;91(7):385-98.
- Jianhua W, Susumu O. Effects of meteorological conditions on PM_{2.5} concentrations in Nagasaki, Japan. *International Journal of Environmental Research and Public Health* 2015;12(8):9089-101.
- Ketjulan A, Humphries U, Suadee W. A study on PM_{2.5} concentration in Bangkok, Thailand: A case study of Bang Na Station. *International Journal of Advanced and Applied Sciences* 2023;10(10):55-61.
- Lai N, Song W, Wang M, Zhao L, Zhou J, Cai X, et al. Qualitative and quantitative analyses of meteorological impacts on fine particle pollution in winters of cold region in China. *Processes* 2024;12(12):Article No. 2713.
- Lu H, Ma X. Hybrid decision tree-based machine learning models for short-term water quality prediction. *Chemosphere* 2020;249:Article No. 126169.
- Medhi D, Sarma G, Shyam A. Stability analysis of linear systems using the Routh-Hurwitz Criterion: Theory and applications. *Journal of Computational Analysis and Applications* 2024;33(8):903-7.
- Miao Y, Liu S, Sheng L, Huang S, Li J. Influence of boundary layer structure and low-level jet on PM_{2.5} pollution in Beijing: A case study. *International Journal of Environmental Research and Public Health* 2019;16(4):Article No. 616.
- Murray JD. *Mathematical Biology I: An Introduction*. 3rd ed. New York, NY: Springer; 2002.
- Phosri A, Ueda K, Phung VLH, Tawatsupa B, Honda A, Takano H. Effects of ambient air pollution on daily hospital admissions for respiratory and cardiovascular diseases in Bangkok, Thailand. *Science of the Total Environment* 2018;651:1144-53.
- Rizwan AM, Dennis LYC, Liu C. A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences* 2008;20(1):120-8.
- Ruttanawongchai S, Raktham C, Khumsaeng T. The influence of meteorology on ambient PM_{2.5} and PM₁₀ concentration in

- Chiang Mai. Journal of Physics: Conference Series 2018;1144(1):Article No. 012088.
- Sirithian D, Thanatrakolsri T. Relationships between meteorological and particulate matter concentrations (PM2.5 and PM10) during the haze period in urban and rural areas, Northern Thailand. Air, Soil and Water Research 2022;5(2):1-15.
- Themairi A, Alqudah MA. Predator-prey model of Holling-type II with harvesting and predator in disease. Italian Journal of Pure and Applied Mathematics 2020;43:744-53.
- Winalai C, Nanthasen S, Chadsuthi S. The effect of weather on PM2.5 in Bangkok area and Bangkok metropolitan region using machine learning. Life Sciences and Environment Journal 2022;23(2):409-21.
- Yang Q, Yuan Q, Li T, Shen H, Zhang L. The relationships between PM2.5 and meteorological factors in China: Seasonal and regional variations. International Journal of Environmental Research and Public Health 2017;14(12): Article No. 1510.
- Yang Z, Yang X, Xu C, Wang Q. The effect of meteorological features on pollution characteristics of PM2.5 in the South Area of Beijing, China. Atmosphere 2023;14(12):Article No. 1753.

Implementation of the Groundwater Live Observation for Water-Quality (GLOW) in Bojong District, Indonesia

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ABSTRACT

Many developing countries still predominantly rely on conventional monitoring of groundwater quality parameters. Emerging technologies have shown significant potential for advancing automated water quality monitoring in recent years. This study developed the Groundwater Live Observation for Water-quality (GLOW) system, which leverages Internet of Things (IoT) technologies combined with water quality sensors. In future applications, this remote sensing-based groundwater monitoring system holds strong potential for detecting pollutant intrusion in water bodies. The GLOW system was tested during two periods, namely from June 2023 to November 2023 and from January 2024 to March 2024, in Bojong District, Sukabumi Regency, Indonesia. The system employed Aqua TROLL 500 sensors capable of measuring water temperature, electrical conductivity (EC), pH, salinity, and total dissolved solids (TDS). The data generated by the GLOW system were transmitted to a website server and subsequently evaluated against laboratory-based data using statistical analyses. The Wilcoxon Signed-Rank Test was applied to assess differences between the two approaches. Most parameters showed no statistically significant differences ($p > 0.05$), except for TDS and salinity ($p = 0.02$). The Bland-Altman analysis confirmed good overall agreement between the two methods, with small mean differences for pH (0.19), EC (8.45 $\mu\text{S}/\text{cm}$), water temperature (-0.34°C), salinity (0.02 PSU), and TDS (0.01 ppm). Future research should expand monitoring by including nitrogen and phosphorus compounds.

HIGHLIGHTS

- Developed IoT-based sensors for continuous groundwater quality monitoring
- Findings support sustainable groundwater management and monitoring assessment
- Autonomous monitoring system validated using real field observations

1. INTRODUCTION

Groundwater is a widely utilized source of drinking water, with approximately 2.5 billion people globally relying on it (Grönwall and Danert, 2020). Consequently, groundwater management is considered one of the key strategies for addressing water scarcity (Carrard et al., 2019). In recent years, an alarming decline in groundwater quality has been reported in several Asian countries, particularly China, India, and Pakistan (Yin et al., 2020; Li et al., 2022,

Ullah et al., 2022; Thakur et al., 2024). Groundwater contamination is commonly attributed to industrial pollution, domestic waste, agricultural runoff, and saltwater intrusion, and this widespread issue raises growing concerns as it poses significant health risks, contributes to environmental degradation, and exacerbates water scarcity. Providing early assessments of groundwater contamination and establishing strategic frameworks to address these issues are crucial first steps toward achieving resilient

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groundwater quality. Traditionally, groundwater quality monitoring has relied on field sampling and laboratory analysis, methods that have been well established and validated over decades, and whose results are widely accepted for regulatory and legislative purposes (Madrid and Zayas, 2007). However, this conventional monitoring approach is time-consuming, labor-intensive, and cost-inefficient (Abdulkadir et al., 2023; Jayaraman et al., 2024). Moreover, extensive and careful sample handling is required to prevent measurement errors and biases introduced by external factors such as exposure to sunlight or high air temperatures (Sani et al., 2023), which may cause deviations from the actual condition of the samples at the time of collection.

Fortunately, the limitations of conventional groundwater quality monitoring can be addressed through remote monitoring. By utilizing sensors to measure water-quality parameters directly in the field, there is no need to transport samples to a laboratory. This approach helps prevent exposure-related changes that could alter the chemical composition of groundwater. Sensors have been well developed to measure physicochemical parameters, such as pH, temperature, electrical conductivity (EC), and dissolved oxygen (DO). Further developments have broadened to even wider water quality parameters, such as total organic carbon (TOC), dissolved organic carbon (DOC), biological oxygen demand (BOD), chemical oxygen demand (COD), bacteria, agricultural pollutants, ions, and heavy metals (Park et al., 2020; Kumar et al., 2024). Besides single-parameter sensors, several configurable multi-parameter sensors are also available for long-term monitoring (Danielson, 2020). Nevertheless, the sensors must still be calibrated regularly to ensure that their accuracy is maintained. Another recent approach involves the use of Internet of Things (IoT) (Akrouf et al., 2024), virtual sensing (Grisez et al., 2025), a cyber-physicochemical system (CPS) (Yoon et al., 2024), and optical techniques (Zainurin et al., 2022). As a result of combining the sensors with the capacity of the current cloud system (hence the IoT services), groundwater monitoring is now capable of storing, transmitting, and analyzing real-time water quality data at almost real-time temporal scale. Such a platform is developed on IP-enabled devices and applications through wired (Ethernet) or wireless (Wi-Fi) interfaces (Wong and Kerkez, 2016).

One example of a monitoring system application was demonstrated in a study by Yoon et al.

(2024), which utilized an IoT-integrated groundwater monitoring system to measure physicochemical parameters related to organic decomposition from livestock carcasses at a burial site. Four parameters were monitored: EC, chloride (Cl^-), nitrate nitrogen ($\text{NO}_3\text{-N}$), and ammonium nitrogen ($\text{NH}_4\text{-N}$). The monitoring system achieved high levels of accuracy and precision, ranging from 93.3% to 100.0% and 0.1% to 5.0%, respectively. EC was identified as the most reliable indicator among these parameters, as sensor readings differed by only 1.1 times compared with laboratory measurements. In contrast, the other parameters showed larger variations, with differences ranging from 1.6 to 2.5 times higher. On the other hand, real-time groundwater monitoring has not been widely implemented in Indonesia. Existing studies (Lubis et al., 2008; Hutabarat and Ilyas, 2017) are limited to single-parameter observations, such as groundwater table elevation or depth-temperature profiles. The studies conducted by Fakhurroja et al. (2023) and Andayani et al. (2021) also assessed the feasibility of using sensors to measure groundwater quality parameters. However, both investigations were limited to laboratory-scale experiments, and to date, no field-based, real-time groundwater quality monitoring system has been implemented in Indonesia. The limited monitoring network restricts efforts to relate groundwater quality to spatial factors such as abstraction, land cover, and industrial pollution. A practical solution is installing multi-parameter monitoring systems, which allow real-time data collection and more accurate interpretations of groundwater characteristics, particularly in data-scarce regions.

Therefore, this study aims not only to develop but also to evaluate the application of the Groundwater Live Observation for the Water Quality (GLOW) system in Indonesia. The GLOW system was deployed in Bojong District, Sukabumi Regency, where a web-based platform continuously monitored groundwater quality parameters. Building on the success of previous studies (Yoon et al., 2024), which indicated that EC showed the closest agreement with field measurements among monitored parameters, this study focused on five other parameters: temperature, pH, EC, salinity, and total dissolved solids (TDS). These parameters were simultaneously measured in the laboratory through conventional sampling for comparison. Once the core parameters have been established, additional physicochemical parameters (Cl^- , $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$) will be incorporated into the

monitoring framework. Sensor-laboratory agreement is evaluated using uni-variate statistical metrics to validate the reliability of the GLOW system. Although no new sensor hardware is introduced, this study provides novel field-based evidence on the performance of real-time groundwater monitoring in data-scarce regions such as Indonesia. In future applications, the GLOW system may also be used to detect potential pollutant intrusion into water bodies.

2. METHODOLOGY

2.1 Study location

The monitoring well, equipped with the aforementioned sensors, is located in the Sukabumi Regency, near the south coast of West Java Province, Indonesia. Figure 1 shows the Sukabumi Regency's relative position and the exact position. Geologically,

the northern part of the Sukabumi area is dominated by alluvium deposits and young volcanic deposits of the Quaternary Age. Considering their alluvial nature, the geologically young and unconsolidated soils should support productive aquifer potential in these areas. On the other hand, a high-water table might also leave the area prone to flooding without proper stormwater management. As the Sukabumi Regency is situated in a tectonically active region between the Indo-Australian and Eurasian plates, fractured tertiary rocks and volcanic structures may lead to amplified risk of seismic potential. The groundwater hydraulic head especially that from confined aquifers, is harder to qualitatively predict, as the fragility to seismic activities could coerce the aquifers to karsting and perching exposure.

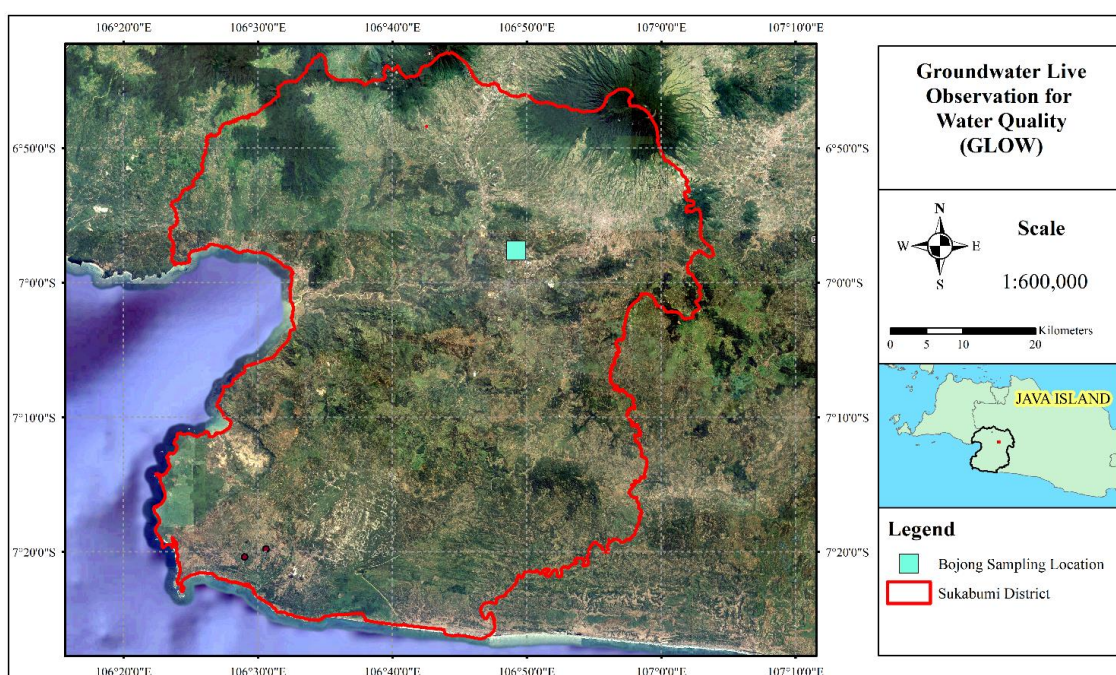


Figure 1. The monitoring well in Bojong District, Sukabumi Regency, Indonesia

The geographical coordinates of the Bojong monitoring well are 106.82°E and 6.96°S. The planned design of the well is shown in Figure 2(a), where the borehole was drilled to a depth of 120 m. As illustrated, two types of PVC casing were installed. From the surface to a depth of 6 m, a non-perforated PVC pipe was used and reinforced with cement grouting. From 6 m down to 120 m, a perforated PVC pipe was installed to allow groundwater to enter the well. The perforated section was surrounded by gravel, sized 0.50-1.00 cm, to ensure the pipe remained stable and properly positioned within the

borehole. During the drilling process, geophysical logging was conducted to determine the resistivity profile and classify subsurface lithology down to 120 m. Based on resistivity values, the subsurface materials can be categorized as tuff (1-10 Ω .m), tuffaceous sand (10-50 Ω .m), and gravel (50-100 Ω .m) (Palacky, 1998; Telford et al., 1990). The resulting lithological classification is presented in Figure 2(b), which shows that the subsurface is predominantly composed of tuff layers. Geo-electric measurements further indicate that the monitoring well intersects a shallow aquifer between depths of 3 and 30 m.

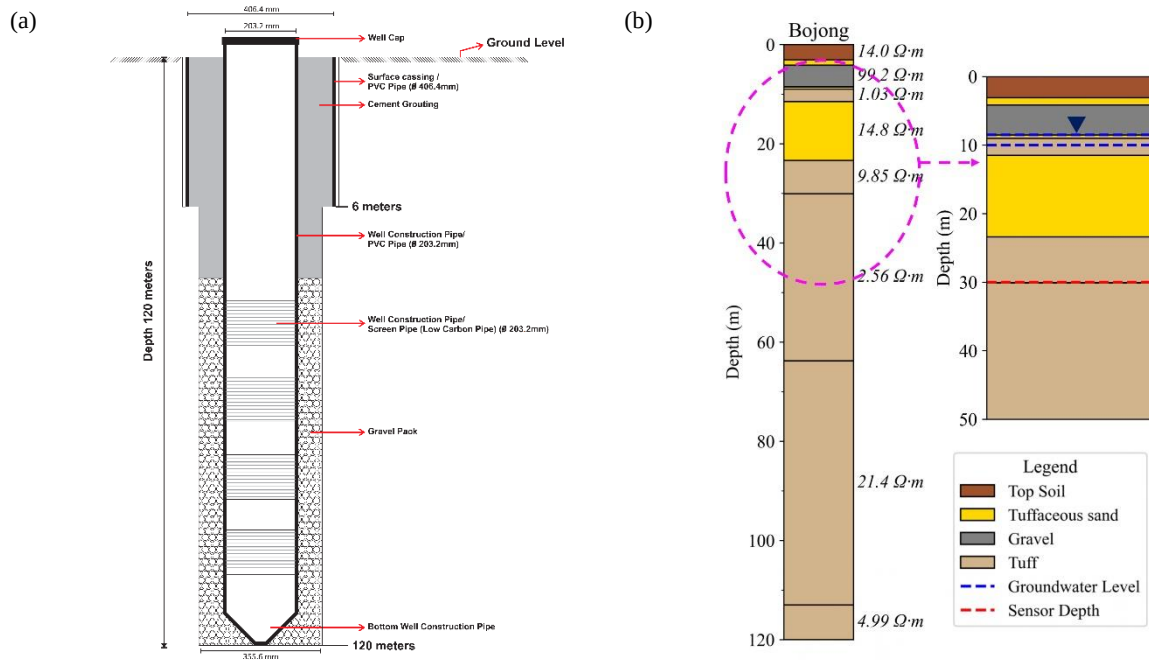


Figure 2. (a) Well construction design plan and (b) the soil stratigraphy of the Bojong Site

2.2 The GLOW system

The Aqua TROLL 500 sensor was selected for its proven effectiveness in monitoring water quality parameters (Acrohm, 2020; Snow et al., 2020). It comes in two main sondes, vented and non-pressurized, whose specifications for measuring water quality parameters are presented in Table 1. Both sondes were installed at a depth of 30 meters, situated in the tuff layer in the well. The soil layer is characterized by soft, porous volcanic rock (Asniar et al., 2019), facilitating groundwater flow around the sondes. Nevertheless, the tuff layer is less permeable than the gravel layer (Siegesmund et al., 2023), resulting in more stable concentrations of water-

quality parameters within the well compared to those in the gravel layer. This consideration formed the primary basis for selecting a depth of 30 m as the installation level for both sondes. A gateway panel was also installed with a protective box, which safeguards the internal components from external elements such as extreme weather conditions and insects. A weather sensor is also integrated into the GLOW system to monitor ambient air temperature. The system is programmed to record all parameters at 10-minute intervals. It has been maintained and calibrated monthly from June 2023 to March 2024.

Table 1. The Aqua Troll 500 sensor specifications (Acrohm, 2020)

Parameter	Accuracy	Range	Methodology
EC	±0.5% of reading plus 1 $\mu\text{S}/\text{cm}^*$	0 to 350,000 $\mu\text{S}/\text{cm}$	Std. Methods 2510, EPA 120.1
TDS	-	0 to 350 ppm	-
Salinity	-	0 to 350 PSU	Std. Methods 2520A
pH	±0.1 pH units	0 to 14 pH units	Std. Methods 4500-H+, EPA 150.2
Temperature	±0.1°C	-5 to 50°C	EPA 170.1

Within the box of the gateway panel, several components are installed to enable data visualization, sensor calibration, and automated data uploading to the website server. During the initial testing period, the system was powered by the state electricity grid (220V AC). This power was stored in an uninterruptible

power supply (UPS) and then converted to 12V DC to meet the system's operational requirements. A supporting 18 V DC solar panel was integrated, with its output regulated to 12 V DC via a 0.50. A solar charge controller (SCC). Unstable power supply may cause sudden spikes in the sensor readings. Therefore,

all sensor outputs must be verified manually before being accepted as valid final data. Wi-Fi connectivity is established to facilitate real-time data transmission. As a contingency measure, flash drives are employed

for local data storage in the event of transmission failures. A complete schematic diagram of the GLOW system is presented in Figure 3, while the installed system is shown in Figure 4.

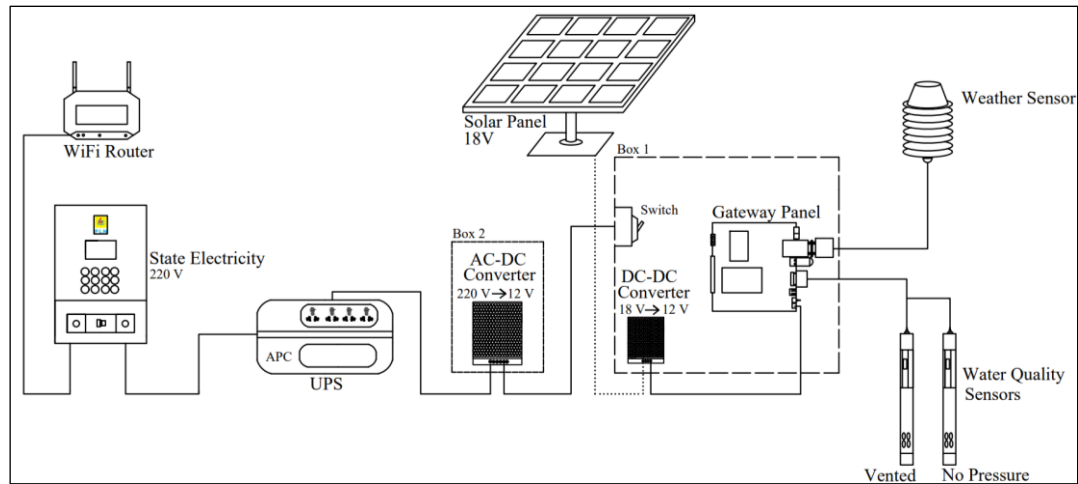


Figure 3. The schematic diagram of the GLOW system



Figure 4. The installed GLOW system at the Bojong Site

2.3 Conventional monitoring of water quality parameters

In conventional monitoring, water samples are assessed using in-situ tools based on established physical principles (YSI Inc, 2021). The groundwater level within the well fluctuated between depths of 7 and 10 m; therefore, water sampling was conducted within this interval. As shown in Figure 2(b), the groundwater is hosted within the tuff and tuffaceous sand layers. Although the water sampling depth and the sensor installation depth differ, the surrounding lithological units at these elevations are comparable. This approach was adopted to minimize variations in groundwater quality concentrations, as discussed in the previous section. pH is measured using an ion-selective electrode (ISE), with an accuracy of ± 0.2 . Water temperature is monitored using a thermistor, typically covering a range from -5°C to 70°C , with an accuracy of $\pm 0.2^{\circ}\text{C}$. EC is determined via a conductivity electrode sensor (conductometry), operating within a range of 0 to $200\ \mu\text{S}/\text{cm}$ and with an accuracy of $\pm 0.5\%$. Salinity and TDS are not measured directly but are calculated from EC values using the Practical Salinity Scale 1978 (PSS-78) and an empirical conversion factor, respectively.

2.4 Statistical methods

This study employed three methods to assess the performance of the GLOW system: normality tests, non-parametric statistical methods, and Bland-Altman plots. The normality test was used to evaluate the sensor's data distribution. One commonly used normality test is the Kolmogorov-Smirnov test, which is suitable for large sample sizes ($n > 5,000$) (Ghasemi and Zahediasl, 2012). The characteristics of the Kolmogorov-Smirnov statistical test are well suited to this study, as the dataset analyzed can comprise tens of thousands of observations for a single parameter. If the p-value generated by the Kolmogorov-Smirnov test is less than 0.05, the data are considered not normally distributed.

When data are not normally distributed, non-parametric statistical methods are more appropriate for evaluating accuracy (Holmes, 2020). One such method is the Wilcoxon Signed-Rank Test, which assesses whether the differences between paired observations are statistically significant. The

Wilcoxon Signed-Rank Test is specifically designed for paired observations collected at corresponding time points. Moreover, since it is based on median differences rather than means, this method is more robust to outliers and non-normal data distributions. Like the normality test, the Wilcoxon Signed-Rank Test evaluates its difference using p-values. If the p-value in the Wilcoxon Signed-Rank Test is greater than 0.05, the parameter does not differ significantly. Since this study aims to evaluate the performance of the GLOW system, the laboratory-based measurements are considered the reference or "true" values.

Finally, Bland-Altman plots were employed to visually examine the agreement between the sensor-based and laboratory-based data at corresponding time points. These plots help identify the number of data points within an acceptable range, commonly defined as within 95% of the reference range (Mansournia et al., 2021). This analysis provides insight into the extent to which the sensor-based data either underestimates or overestimates the laboratory-based data. This method is highly relevant for instrumentation and sensor studies, as sensors may exhibit small but consistent differences that can be statistically significant yet remain acceptable from an operational perspective.

3. RESULTS

3.1 The GLOW's reading

The 10-minute interval sensor data were aggregated into daily averages before being plotted with the laboratory-based data. Sensor readings and laboratory analyses are divided into two periods. The first period, covering both sites, spans from 27 June 2023 to 14 November 2023, as presented in Figure 5. The second period extends from 29 January 2024 to 15 March 2024, as illustrated in Figure 6. As previously mentioned, this separation was necessitated by a maintenance interval caused by power fluctuations in late November 2023. Another distinguishing factor between the two periods is that the GLOW system operated solely on the state electricity grid during the first period. In contrast, it was powered by combining a solar panel system and the state electricity grid in the second period.

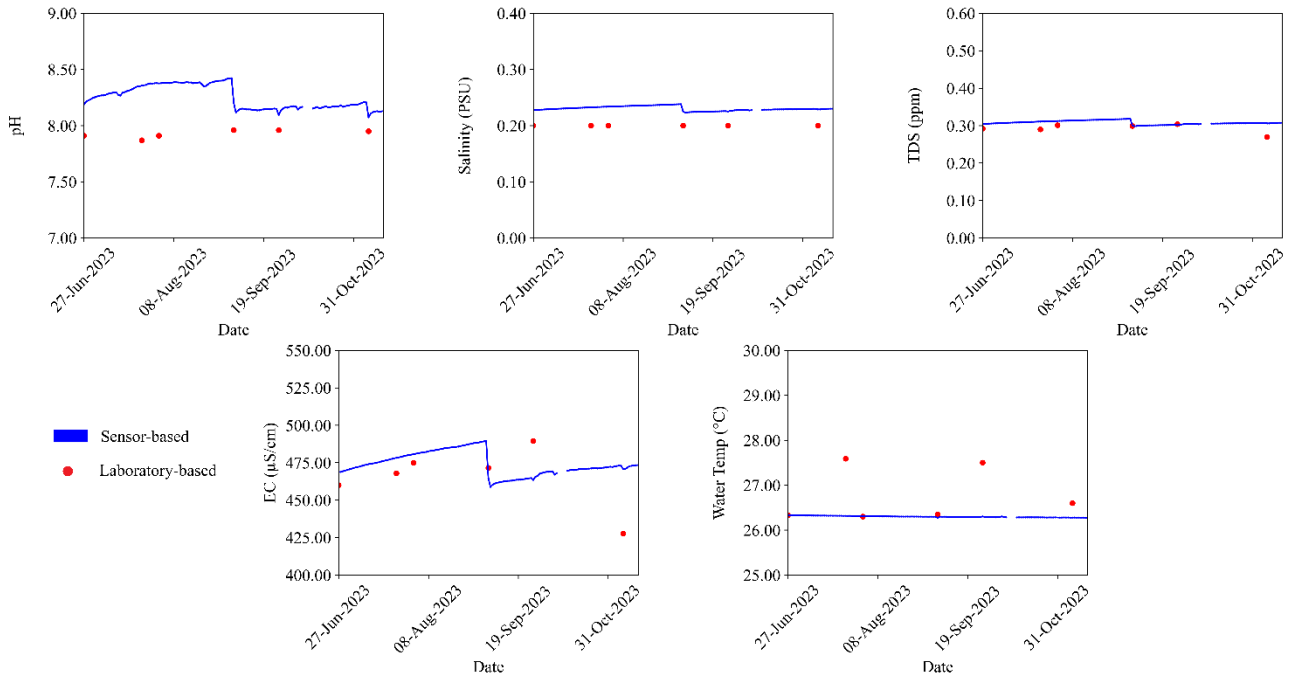


Figure 5. Time series of water quality parameters during the first monitoring period

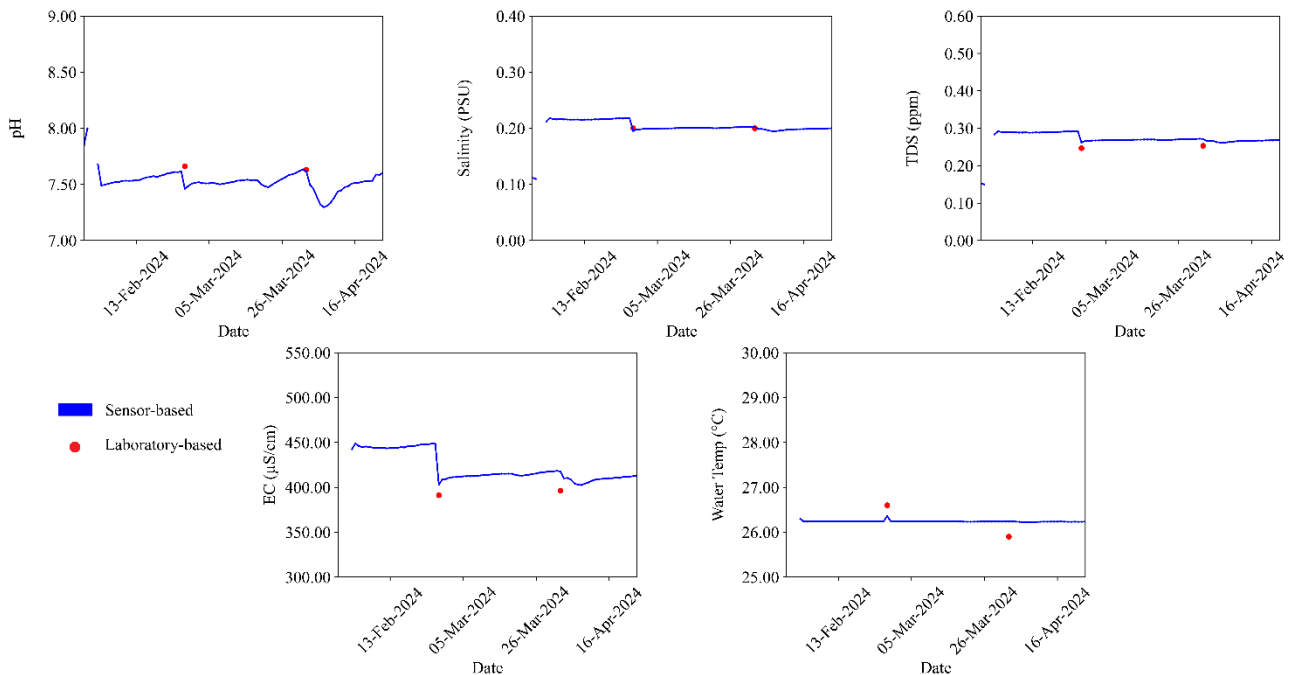


Figure 6. Time series of water quality parameters during the second monitoring period

During the first period, a three-day data loss occurred in early October 2023. The data loss could not be recovered due to a complete shutdown of the GLOW system. As shown in Figure 5, the sensor readings for the five water quality parameters appear to be sufficiently accurate, although pH, salinity, and EC tend to be slightly overestimated. This discrepancy may also be attributed to the fact that the water

samples were taken from a shallower depth, potentially resulting in higher laboratory-based values than sensor readings. Notably, the TDS parameter exhibited the most accurate agreement between the two data sources. In the second period, a one-day data loss still occurred at the beginning, as shown in Figure 6. Although data loss persisted, the duration of sensor data unavailability was significantly reduced.

The percentage of system uptime during both monitoring periods was quantified by calculating the difference between the total monitoring duration and the system downtime, divided by the total monitoring period. During the first monitoring period, the system experienced three days of downtime over 140 days of observation, while during the second monitoring period, one day of downtime occurred over 46 days of monitoring. Based on these values, the system uptime for the first and second monitoring periods was 97.86% and 97.83%, respectively. Nevertheless, the GLOW system can still be further improved to ensure a more stable and continuous power supply.

Based on the visual inspection of the time-series results from both monitoring periods, the sensor-generated data can be considered sufficiently reliable. One or two parameters exhibited noticeable fluctuations, which posed challenges for data validation; however, highly fluctuating readings were carefully filtered prior to analysis to ensure data quality. Several field improvements were implemented, including the installation of a solar panel to supplement electricity demand and the use of an uninterruptible power supply (UPS) to stabilize grid-supplied power. Despite these efforts, power instability was not fully resolved, as the addition of only one solar panel during the second monitoring period was insufficient to meet the system's energy requirements. Another limitation of this study relates to its location in relatively underdeveloped areas with limited internet connectivity, which occasionally disrupted data transmission to the web server. To

mitigate this issue, flash drives were employed for local data storage, as described in the previous section.

3.2 Outcomes of statistical analysis

A Kolmogorov-Smirnov test for normality was applied to the sensor-based data with a temporal resolution of 10 minutes, and the results are presented in Table 2. Since all water quality parameters have a p-value of 0, the parameters are stated as not normally distributed. These findings indicate the Wilcoxon Signed-Rank Test is a suitable method for subsequent analysis. The results of the Wilcoxon Signed-Rank Test are shown in Table 3. Most parameters show no significant difference between the GLOW system and the laboratory-based data. The parameters with significant differences are TDS and salinity. However, one thing that might be considered is that our method's precision in measuring the salinity is relatively low. The salinity value can only be detected with one significant number, either 0.20 or 0.30. This condition is undoubtedly affecting the Wilcoxon Signed-Rank Test results.

Table 2. The Kolmogorov-Smirnov test results

Parameter	KS Statistic	p-value
pH	0.23	0
Salinity	0.19	0
TDS	0.46	0
EC	0.20	0
Water Temp.	0.47	0

Table 3. The Wilcoxon Signed-Rank test results

Parameter	Number of data used	p-value	Remarks
EC	8	0.25	There is no significant difference
pH	8	0.08	
Water Temp.	8	0.20	
TDS	8	0.02	There is a significant difference
Salinity	8	0.02	

Next, the differences between the two types of data were visualized using the Bland-Altman Plot, as presented in Figure 7. The outcomes of these plots are consistent with those obtained from the Wilcoxon Signed-Rank Test. In the study location, as shown in Figure 7, the pH, EC, water temperature, salinity, and TDS parameters exhibited mean differences of 0.19, 8.45 $\mu\text{S}/\text{cm}$, -0.34°C , 0.02 PSU, and 0.01 ppm, respectively. Despite being identified as having

significant differences, the Bland-Altman plots of salinity and TDS parameters are still acceptable. Furthermore, all the sensor-based data remained within a safe reference range. These small differences suggest that, despite some inconsistencies, the GLOW system remains reliable for real-time groundwater quality monitoring purposes.

Despite the operational challenges encountered in the field, the sensor-based data demonstrated

sufficient accuracy in providing reliable real-time measurements of groundwater quality parameters. The results of the Wilcoxon Signed-Rank Test for all parameters were statistically promising, except TDS and salinity. Furthermore, the Bland-Altman plots provided a complementary assessment, showing that all paired sensor and laboratory measurements for each water quality parameter fell within the 95% limits of agreement, indicating acceptable agreement between the two methods. In addition, this study was limited to eight water sampling events conducted over

the eight-month system testing period. With such a small sample size, hypothesis-testing methods may place excessive emphasis on statistical significance and may not fully reflect practical sensor performance. Consequently, agreement-based approaches, such as the Bland-Altman limits of agreement, provide a more appropriate framework for evaluating sensor reliability. To strengthen future validations, more frequent or extensive laboratory measurements are recommended to better support the assessment of sensor-based data.

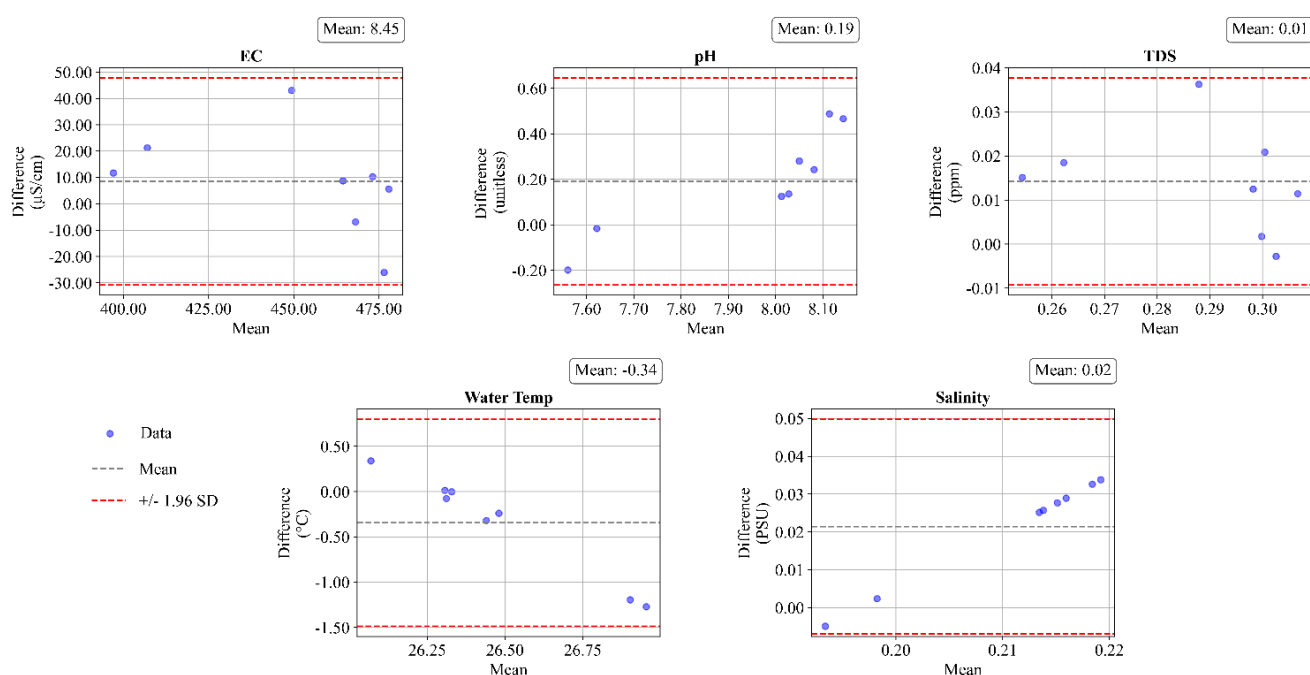


Figure 7. Bland-Altman Plots for each water quality parameter

4. DISCUSSION

The addition of one solar panel during the second monitoring period did not result in a significant improvement in the stability of the electricity supply. During this period, the system employed a 0.5 A SCC, for which the calculated power generation was only approximately 30 Wh per day. In contrast, the GLOW system requires 54.72 Wh per day to operate reliably. In evaluating the net energy balance between power consumption and power generation, state electricity was excluded from the analysis because frequent power outages rendered it unreliable. As the SCC capacity remained at 0.5 A, the addition of an extra solar panel did not increase the effective power output. Instead, increasing the SCC current rating represents a more viable solution. Therefore, an energy budget analysis comparing power consumption and power generation was conducted, as presented in Table 4. In

this analysis, the solar panel was assumed to charge the battery for an effective duration of 5 hours per day. Power generation was estimated for SCC capacities of 1.0 A, 1.5 A, and 2.0 A. The results indicate that the system's energy demand can be met when an SCC with a capacity of at least 1.0 A is employed. However, as a precautionary measure, an SCC capacity of 1.5-2.0 A is recommended to account for external factors such as prolonged cloudy or rainy conditions. This configuration is expected to provide a stable 12 V DC output to sustain continuous system operation.

The results demonstrate that real-time groundwater quality monitoring using IoT-based systems is technically feasible and potentially scalable to other developing regions. However, a careful assessment of site-specific conditions is essential to ensure that the data produced is sufficiently reliable for decision-making. Collaborations with local

stakeholders could support such systems' long-term sustainability and scalability. This study provides a foundational case for developing a nationwide groundwater monitoring network, which could inform both short-term groundwater pollution alerts and long-term aquifer management strategies. Future efforts should focus on developing sensors capable of measuring additional chemical parameters, particularly nitrogen and phosphorus compounds.

These parameters serve as direct indicators of water quality degradation, as their concentrations are strictly regulated to ensure the safety of human consumption. Including such indicators would significantly enhance the comprehensiveness of the monitoring system and support early detection of nutrient pollution, particularly in areas influenced by agricultural runoff or domestic wastewater discharge.

Table 4. Energy budget comparing power consumption and power generation

Parameter	Power consumption	Power generation			
		SCC with capacity			
		0.5 A	1.0 A	1.5 A	2.0 A
Voltage (V)	12				
Electricity Current (I) [A]	0.19	0.50	1.00	1.50	2.00
Power (P) [W]	2.28	6.00	12.00	18.00	24.00
Time [hour]	24.00	5.00			
Energy [Wh]	54.72	30.00	60.00	90.00	120.00
Net energy [Wh]		-24.72	5.28	35.28	65.28
Suffice?		Not Sufficient	Sufficient	Sufficient	Sufficient

One of the parameters that can be directly compared with the previous study by [Yoon et al. \(2024\)](#) is EC. As mentioned earlier, sensor-based EC values in the prior study were 1.1 times higher than those obtained from laboratory measurements, with a reported correlation coefficient of 0.3834. However, this result alone does not provide sufficient evidence regarding whether the recorded values fall within a statistically acceptable confidence interval. In the present study, as shown in [Figure 7](#), all paired comparisons between sensor- and laboratory-based EC measurements fall within the 95% confidence interval, with an average error of only 8.45 $\mu\text{S}/\text{cm}$. These finding underscores progress in the implementation of groundwater monitoring systems. Furthermore, other parameters showed a similar trend, with consistently small mean error values.

5. CONCLUSION

The groundwater live observation for water-quality (GLOW) system was successfully implemented in the Bojong study area to continuously monitor five groundwater quality parameters: pH, EC, temperature, salinity, and TDS. Comparative analysis between sensor-based and laboratory-based measurements demonstrated acceptable agreement, with most parameters showing no statistically significant differences based on the Wilcoxon Signed-

Rank Test. The Bland-Altman plots further confirmed the small magnitude of discrepancies, with mean differences of 0.19 for pH, 8.45 $\mu\text{S}/\text{cm}$ for EC, -0.34°C for temperature, 0.02 PSU for salinity, and 0.01 ppm for TDS, underscoring the reliability of the system in capturing key physicochemical dynamics of groundwater. Nonetheless, data loss persisted even after solar panel installation, indicating insufficient power availability and the need for a more robust solution, such as increasing the SCC capacity to 1.5-2.0 A. Despite this limitation, the GLOW system proved to be an effective tool for real-time groundwater monitoring and holds promising potential for early detection and management of water quality degradation in Indonesia.

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AUTHOR CONTRIBUTIONS

Conceptualization, D.Y. and Y.C.S.; Methodology, F.F.; Validation, A.W. and A.T.; Formal Analysis, S.K.H. and S.S.; Investigation, N.G.S.; Resources, S.K.C.; Writing-

Original Draft Preparation, S.K.C.; Writing-Review and Editing, S.R.R.; Visualization, S.R.R.; Supervision, O.W.T.; Funding Acquisition, NC Environment Technology.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Abdulkadir Z, Ibrahim A, Muhammad A, Sani SA, Baballe MA. The water monitoring system's disadvantages. *Global Journal of Research in Engineering Computer Science* 2023;3(4):5-10.
- Acrohm. AT500 User Manual. Version V1.0.1. Daejeon: Acrohm Co., Ltd.; 2020.
- Akrout H, Baccouche H, Mellah T, Mansouri L, Ghrabi A. HRMS-based innovative monitoring of Grombalia Groundwater (Tunisia). In: Çiner A, Barbieri M, Khan MF, editors. *Recent Research on Environmental Earth Sciences*. Marrakesh: Advances in Science, Technology, and Innovation; 2024. p. 55-9.
- Andayani U, Hizriadi A, Junaidi A. Groundwater feasibility test system by using wireless sensor network. *IOP Conference Series: Materials Science and Engineering* 2021;1122:Article No. 012033.
- Asniar N, Purwana YM, Surjandari NS. Tuff as rock and soil: Review of the literature on tuff geotechnical, chemical and mineralogical properties around the world and in Indonesia. *Exploring Resources, Process and Design for Sustainable Urban Development: Proceedings of the 5th International Conference on Engineering, Technology, and Industrial Application (ICETIA)*: AIP Publishing; 2019.
- Carrard N, Foster T, Willetts J. Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water (Switzerland)* 2019;11(8):Article No. 1605.
- Danielson T. *Sensor Recommendations for Long Term Monitoring of the F-Area Seepage Basins*. Office of Scientific and Technical Information (OSTI); 2020.
- Fakhrurroja H, Nuryatno ET, Munandar A, Fahmi M, Mahardiono NA. Water quality assessment monitoring system using fuzzy logic and the internet of things. *Journal of Mechatronics, Electrical Power, and Vehicular Technology* 2023;14:198-207.
- Ghasemi A, Zahediasl S. Normality tests for statistical analysis: A guide for non-statisticians. *International Journal of Endocrinology and Metabolism* 2012;10(2):486-9.
- Grisez L, Sharma S, Pileggi P. ML-based virtual sensing for groundwater monitoring in the Netherlands. *Proceedings of the 17th International Conference on Agents and Artificial Intelligence (ICAART 2025)*; 2025. p. 175-84.
- Grönwall J, Danert K. Regarding groundwater and drinking water access through a human rights lens: Self-supply as a norm. *Water (Switzerland)* 2020;12(2):Article No. 419.
- Holmes DT. Statistical methods in laboratory medicine. In: Clarke W, Marzinko MA, editors. *Contemporary Practice in Clinical Chemistry*. 4th ed. London: Academic Press; 2020. p. 15-35.
- Hutabarat LE, Ilyas T. Mapping of land subsidence induced by groundwater extraction in urban areas as basic data for sustainability countermeasures. *International Journal of Technology* 2017;8(6):1001-11.
- Jayaraman P, Nagarajan KK, Partheeban P, Krishnamurthy V. Critical review on water quality analysis using IoT and machine learning models. *International Journal of Information Management Data Insights* 2024;4(1):Article No. 100210.
- Kumar M, Khamis K, Stevens R, Hannah DM, Bradley C. In-situ optical water quality monitoring sensors-applications, challenges, and future opportunities. *Frontiers in Water* 2024;6:Article No. 1380133.
- Li J, Sun C, Chen W, Zhang Q, Zhou S, Lin R, et al. Groundwater quality and associated human health risk in a typical basin of the Eastern Chinese Loess Plateau. *Water (Switzerland)* 2022;14(9):Article No. 1371.
- Lubis RF, Sakura Y, Delinom R. Groundwater recharge and discharge processes in the Jakarta groundwater basin, Indonesia. *Hydrogeology Journal* 2008;16(5):927-38.
- Madrid Y, Zayas ZP. Water sampling: Traditional methods and new approaches in water sampling strategy. *Trends in Analytical Chemistry* 2007;26(4):293-9.
- Mansournia MA, Waters R, Nazemipour M, Bland M, Altman DG. Bland-Altman methods for comparing methods of measurement and response to criticisms. *Global Epidemiology* 2021;3:Article No. 100045.
- Palacky GJ. 3: Resistivity characteristics of geologic targets. In: Nabighian MN, Corbett JD, editors. *Electromagnetic Methods in Applied Geophysics*. Vol. 1. 1998. p. 52-129.
- Park J, Kim KT, Lee WH. Recent advances in information and communications technology (ICT) and sensor technology for monitoring water quality. *Water (Switzerland)* 2020;12(2):Article No. 510.
- Sani SA, Ibrahim A, Musa AA, Dahiru M, Baballe MA. Drawbacks of traditional environmental monitoring systems. *Computer and Information Science* 2023;16(3):Article No. 30.
- Siegesmund S, Gross CJ, Dohrmann R, Marler B, Ufer K, Koch T. Moisture expansion of tuff stones and sandstones. *Environmental Earth Sciences* 2023;82(6):Article No. 146.
- Snow C, Zeng J, Nonas-Hunter L, Diggins D, Bennett K, Bennett A. Design of a cable-mounted robot for near shore monitoring. *Global Oceans 2020: Singapore-US Gulf Coast*; 2020. p. 1-9.
- Telford WM, Geldart LP, Sheriff RE, Keys DA. *Applied Geophysics*. London: Cambridge University Press; 1990.
- Thakur R, Nath H, Neog N, Bora PK, Goswami R. Groundwater hydrogeochemistry and potential health risk assessment through exposure to elevated arsenic in Darrang District of north bank plain of the Brahmaputra. *Scientific Reports* 2024;14(1):Article No. 29843.
- Ullah Z, Rashid A, Ghani J, Nawab J, Zeng XC, Shah M, et al. Groundwater contamination through potentially harmful metals and its implications in groundwater management. *Frontiers in Environmental Science* 2022;10:Article No. 1021596.
- Wong BP, Kerkez B. Real-time environmental sensor data: An application to water quality using web services. *Environmental Modelling and Software* 2016;84:505-17.
- Yin S, Xiao Y, Han P, Hao Q, Gu X, Men B, et al. Investigation of groundwater contamination and health implications in a typical semiarid basin of North China. *Water (Switzerland)* 2020;12(4):Article No. 1137.
- Yoon J, Park S, Han K. Research on real-time groundwater quality monitoring system using sensors around livestock Burial Sites. *Agriculture (Switzerland)* 2024;14(8):Article No. 1278.

Xylem. ProQuatro: Portable Multiparameter Water Quality Meter: Specifications Sheet. SKU: 606962. Yellow Springs (OH): YSI Inc.; 2021.
Zainurin SN, Wan Ismail WZ, Mahamud SNI, Ismail I, Jamaludin

J, Ariffin KNZ, et al. Advancements in monitoring water quality based on various sensing methods: A systematic review. International Journal of Environmental Research and Public Health 2022;19(21):Article No. 14080.

Exploring the Relationship between Climate Parameters and Water Salinity Fluctuations: A Case Study in Binh Chanh District, Ho Chi Minh City

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ABSTRACT

Climate change is expected to worsen drought conditions, which may elevate the risk of salinity intrusion in many regions of Vietnam. Therefore, this research analyzed the annual variations in water salinity in Binh Chanh District by employing the Modified Innovative Trend Analysis method, which interprets not only specific trends but also avoids distributional assumptions found in classical approaches, including normality, independence, and pre-whitening. Additionally, the study proposed a Sobol Index to investigate the relationship between salinity levels and weather variables from 2007 to 2024. The findings indicated a notable increase in annual salinity, reaching up to 8.12% at the Ong Thin station. In contrast, a significant decrease of less than 2% was noted, primarily at the Cong Kenh C station. While An Ha recorded a significant sensitivity value for mean temperature at 56.5%, salinity levels at the Cong Kenh C and Ong Thin stations were highly responsive to precipitation, accounting for over 77.2% and 69.6% of sensitivity, respectively. These findings enhance the understanding of salinity trends and provide a robust scientific basis for informing policy interventions related to land and water resource management, agricultural planning, and estuarine environmental governance in Binh Chanh District under accelerating climate change.

HIGHLIGHTS

- Positive salinity trends appeared at almost all stations in Binh Chanh District.
- The impact of precipitation on salinity was shown to be the most significant.
- Sobol sensitivity analysis was useful in assessing climate change's effect on water salinity.

1. INTRODUCTION

Vietnam is one of five nations most severely impacted by climate change, with Ho Chi Minh City (HCMC) serving as a focal point of the country's economy. Further, due to its social, economic, and environmental characteristics, the World Bank identifies HCMC as one of the cities most vulnerable to climate change (World Bank Group and Asian Development Bank, 2021). Binh Chanh District, a suburban area of HCMC, boasts a strategic river network that supports both agricultural growth and waterway transportation. Nonetheless, being a low-lying area near large rivers has led Binh Chanh to be among the districts most susceptible to climate

change. Low-income households are particularly affected, as they have limited resources to cope with and adapt to climate-related challenges (Martin and Thanh, 2003). In recent years, natural disasters and rising sea levels have had a significant impact on the Binh Chanh District. Heavy rainfall has become more frequent and concentrated during the rainy season, reducing arable land and increasing the risk of flooding (Truong et al., 2022). The infrastructure system of the region's industrial zones-including factories, internal traffic, drainage systems, and production equipment-has been severely inundated, which in turn has had a great impact on business productivity. Rising sea levels also cause aquaculture

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ponds and rice-growing regions to become increasingly saline, which leads to further significant negative economic effects.

Salinization is one of the most serious environmental risks in Vietnam and Southeast Asia, and one of the primary causes of desertification and soil degradation worldwide. Numerous scholars have examined long-term salinity changes using a variety of approaches. For example, several pertinent researchers have used both parametric and non-parametric statistical tests to track and determine salinity changes. For example, to understand seasonal changes in the most heavily saline-intruded areas during the wet-monsoon seasons, the nonparametric Mann-Kendall and Sen's slope tests were applied to detect historical trends in surface water salinity (Shammi et al., 2017), as well as seasonal characteristics of groundwater salinity in the coastal zone of Bangladesh (Meem et al., 2025). Also, the degree and temporal tendencies of salinization in inland rivers in China have been found to be severely aggravated (Meng et al., 2024). Thematic maps and GIS mapping were used to determine the regional variability and trends of groundwater salinity on Munda-Kachchh coastal aquifers over ten years (Shah et al., 2022). By using ANOVA variance analysis and frequency analysis based on data sets from 1996 to 2018 at monitoring stations, Thanh et al. (2023) employed statistical techniques to evaluate salinity variations in the Mekong Delta. The findings indicate that salinity is on the rise (Thanh et al., 2023). Though research has produced significant findings, there are still many issues that need to be resolved. Reliable and long-term input data collection is a challenge in research, and the precision and quality of this data are critical to models' efficacy. For instance, whereas remote sensing methods provide a wide range of spatial coverage, their temporal resolution is constrained by weather and satellite orbital cycles, which lowers the accuracy and dependability of salinity intrusion simulations (Taghadosi and Hasanlou, 2017). Furthermore, parametric approaches have application-related restrictions, such as the need for residuals in normal distributions (Kocsis et al., 2017).

This study uses the non-parameter approach of Innovative Trend Analysis (ITA) to evaluate salinity variations at monitoring stations in order to overcome these problems. ITA has been used for a wide range of environmental parameters, such as temperature (Esit, 2023), precipitation (Caloiero et al., 2019), and

relative humidity (Esit, 2023), and it has numerous benefits over standard trend assessment methods in managing assumptions. Among the various tests, the Pettitt test is one of the most widely used in hydro-climatological studies to detect abrupt changes at an unknown point in a time series to deal with extremes. For example, Villarini detected temporal trends in flood peaks and abrupt changes in the mean and variance of flood peak distributions by using the Pettitt test (Villarini and Smith, 2010). Another simulation was studied to examine the sensitivity of the Pettitt test when detecting abrupt changes in climate parameters, and it was found that the Pettitt test performed effectively (Mallakpour and Villarini, 2016). Hence, the strength of the ITA and Pettitt tests and their ability to become more effective for trend detection were integrated into what is known as the modified ITA method. These studies have provided convincing evidence of the effectiveness of the ITA method in exploring climate trends. However, most researches have analyzed salinity at regional or river-basin scales, with limited district-scale studies using advanced statistical methods.

Sensitivity analysis is an important part of research on climate assessment, and currently a major interest in hydrometeorology, where it is used to detect correlations between relevant climatic factors (Haj-Amor et al., 2023). A number of scholars have also detected and noted an association between temperature, precipitation, solar radiation, and evapotranspiration (Aizen et al., 2001; Danlu et al., 2017; Gupta et al., 2020; Luo et al., 2023; Tyagi et al., 2019). In sum, the global sensitivity analysis is a powerful tool that provides a complete and consistent sensitivity measure of climate variables, while also assessing a wide range of climate change possibilities for different models with varying data requirements (Wagener and Pianosi, 2019). However, there remains a lack of research concerning the applicability of SA methods for salinity in climate change conditions.

Given the importance of salinity parameter assessment, our study aims to assess the tendencies of salinity and its correlations to temperature and precipitation in Binh Chanh District by applying the Modified Innovative Trend Analysis, and Sobol sensitivity analysis methods, respectively. These results have been anticipated to offer an overall view of salinity across various climatic scenarios, and to aid in water enhancement, management, and salinization prevention at both regional and global levels.

2. METHODOLOGY

2.1 Study area

Binh Chanh is a rural district located in the southwest of HCMC. It covers an area of 253 square kilometers. The Binh Chanh district borders the Binh Tan, Hoc Mon, and Nha Be districts (Figure 1). The landscape of Binh Chanh is relatively wide and elongated, with a substantial amount still dedicated to agricultural use. Serving as a gateway for trade with the Mekong Delta, a major economic region in the south, Binh Chanh has increasingly become a conduit for economic exchanges between the Mekong Delta and the key zones of the southeastern economic region. Binh Chanh is characterized by extensive

agricultural land, and agricultural production constitutes a notably larger proportion of the economic framework when compared to the inner city districts (Prime Minister's Office of Vietnam, 2023).

Climate change impacts are another important consideration. Due to its lowland natural features and the terrain being divided by a system of rivers and canals, Binh Chanh district is heavily affected by climate change. Currently, the impact of saltwater intrusion on rivers and canals in Ho Chi Minh City has increased to an alarming level, and Binh Chanh is one of the most seriously affected provinces (Danh et al., 2024).

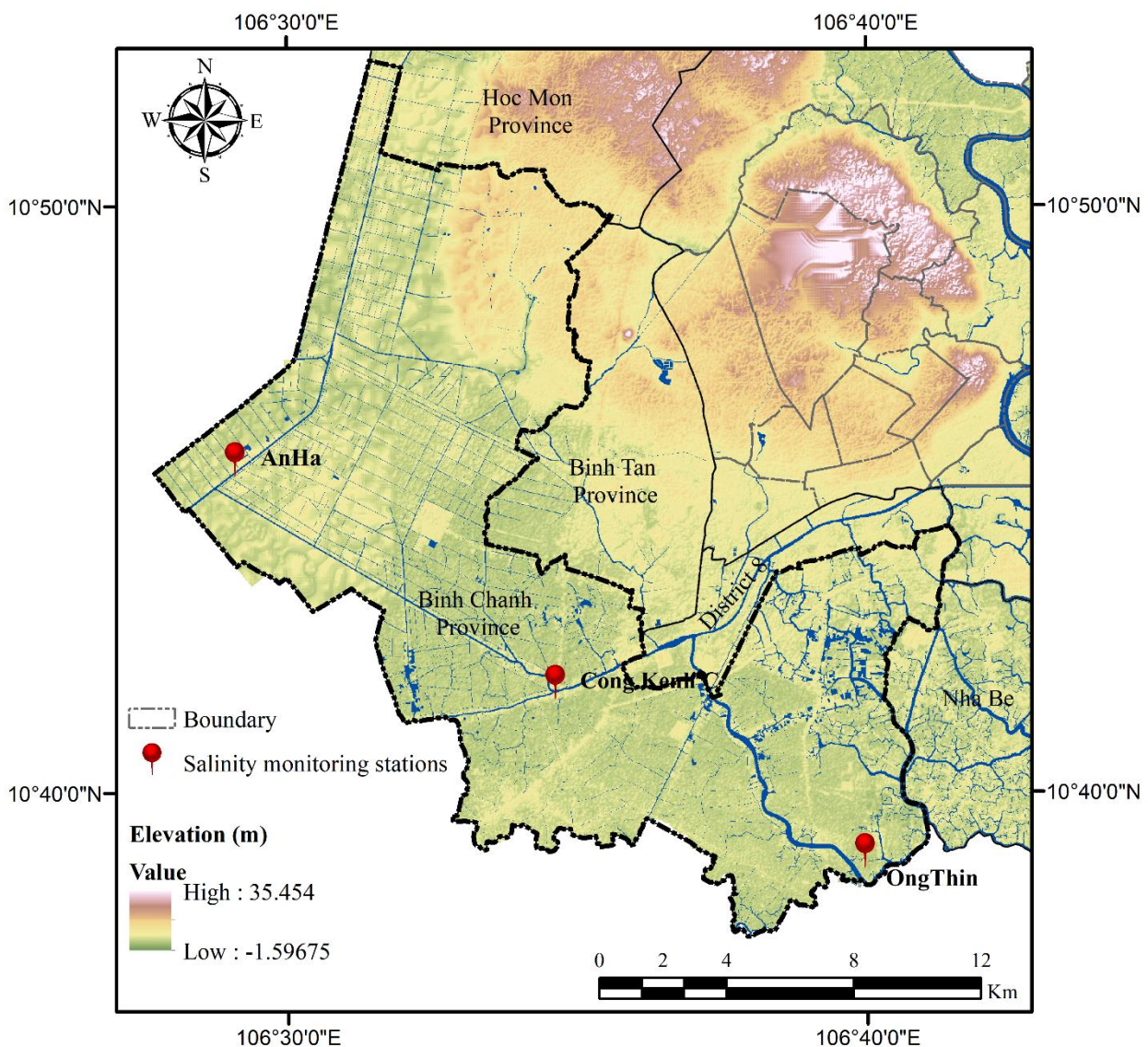


Figure 1. The geography and salinity monitoring stations of Binh Chanh Province in Ho Chi Minh City.

This study used salinity data (g/L) from three monitoring stations, namely An Ha, Cong Kenh, and

Ong Thin (Figure 1), along with weather variables, including rainfall (mm), average temperature (°C),

maximum temperature (°C), and minimum temperature (°C), obtained from the Tan Son Hoa station of the Meteorological Administration for the period 2007-2024.

2.2 Modification of Sen-ITA method

Trend detection investigations in hydro-meteorological series have increasingly gained attention over the last few decades. The modification of ITA has produced several versions, including one known as the parameter trend test. In the original ITA, a time series was plotted in a two-dimensional Cartesian coordinate system after being split into two equal sub-series. This modification of ITA was defined as a way to demonstrate different types of trends, and depict the dimensions and quantity of time series data by combining with the Pettitt test to identify sudden change points (Mallakpour and Villarini, 2016).

In this study, the annual salinity dataset in Binh Chanh Province was divided into two halves in the coordinate system, with the horizontal axis representing the number of years of collection data (from 2007 to 2024) and the vertical axis representing the values of salinity (g/L) in Binh Chanh District. Values falling above or below the horizontal line ($y=0$) show an increasing or decreasing tendency. Furthermore, by combining the Pettitt tests, the quantitative salinity trends for low and high-value categories were computed, including the change magnitude, change point, and percentage of growing and declining trends.

The Pettitt test is a non-parametric method derived from the Mann-Whitney two-sample test, and designed to identify a single change occurring at an unspecified point in time t (Anthony, 1979). The non-change appears in the distribution of a sequence of random variables; the change point exists when the distribution function $F_1(X)$ of the random variables from X_1 to X_t is different from the distribution function $F_2(X)$ of the random variables from X_{t+1} to X_T (Equation 1).

$$D_{ij} = \text{sgn}(X_i - X_j) = \begin{cases} -1 & (X_i - X_j) < 0 \\ 0 & (X_i - X_j) = 0 \\ 1 & (X_i - X_j) > 0 \end{cases} \quad (1)$$

The next step involves computation of test statistic U_k by using the following (Equation 2)

$$U_{t,T} = \sum_{i=1}^t \sum_{j=t+1}^T D_{ij} \quad (2)$$

Finally, the significant change point (K_T) is selected (Equation 3) where the value of $|U_{t,T}|$ and each is the largest:

$$K_T = \max |U_{t,T}| \quad (3)$$

2.3 Sobol sensitivity analysis method

For hydro-meteorological models, accurately estimating weather parameters can be challenging, especially when numerous parameters lack a distinct effect on the output variables-or when many parameters exhibit similar impacts on the output variables (Song et al., 2015). In such situations, the Sobol method is effective for identifying critical parameters. Specifically, this method analyzes the interactions of climatic factors (rainfall (R), maximum temperature (Tmax), minimum temperature (Tmin) and mean temperature (Tmean)) with average salinity. The results from Sobol's analysis provide the first-order (S_i) and total sensitivity indices (S_{Ti}), expressed in the respective equations (4) and (5) (Sobol, 1990). The first-order indices measure the direct individual influence of each temperature or precipitation parameter on salinity, while the total indices consider variance contributions from each input variable, including their interactions with other variables, concerning the overall variance of the salinity model.

$$S_i = \frac{V_{X_i}(E_{X_{\sim i}}(Y|X_i))}{V(Y)} \quad (4)$$

$$S_{Ti} = \frac{E_{X_{\sim i}}(V_{X_i}(Y|X_{\sim i}))}{V(Y)} = 1 - \frac{V_{X_i}(E_{X_{\sim i}}(Y|X_i))}{V(Y)} \quad (5)$$

3. RESULTS AND DISCUSSION

3.1 Salinity trend analysis results

One of our aims was identifying potential trends in salinity values recorded over 18 years at various stations in Binh Chanh Province. With this end in mind, a modified version of the ITA method was applied to the annual data for this parameter. The results, displayed in Figure 2, illustrated the findings from three stations: An Ha, Cong Kanh C, and Ong Thin. Most data from the selected stations exhibited positive trends, with variations extending up to 2.5 g/L per year. Notably, the An Ha station showed two distinct trends, according to the Pettitt test on the difference series; the modified ITA indicated a growth trend of 1.81% for the Low Values category, while the High Values category

demonstrated a 0.98% growth trend. Although all trend tests yielded the same conclusion for Ong Thin, the modified ITA indicated an increasing trend of 3.19% for Low Values and 8.12% for High Values (Figure 2(c)). At the Cong Kenh C station, the High Salinity values exhibited a notable decreasing trend of -1.6%, whereas the trend for Low values showed a slight and

insignificant increase of 0.79% (Figure 2(b)). Additionally, the change points identified by the Pettitt test in the alternative version of ITA revealed differing numbers for Low and High values. Figure 2 further illustrates the quantity and range of salinity data, reflecting variations in different salinity stations within a single scale.

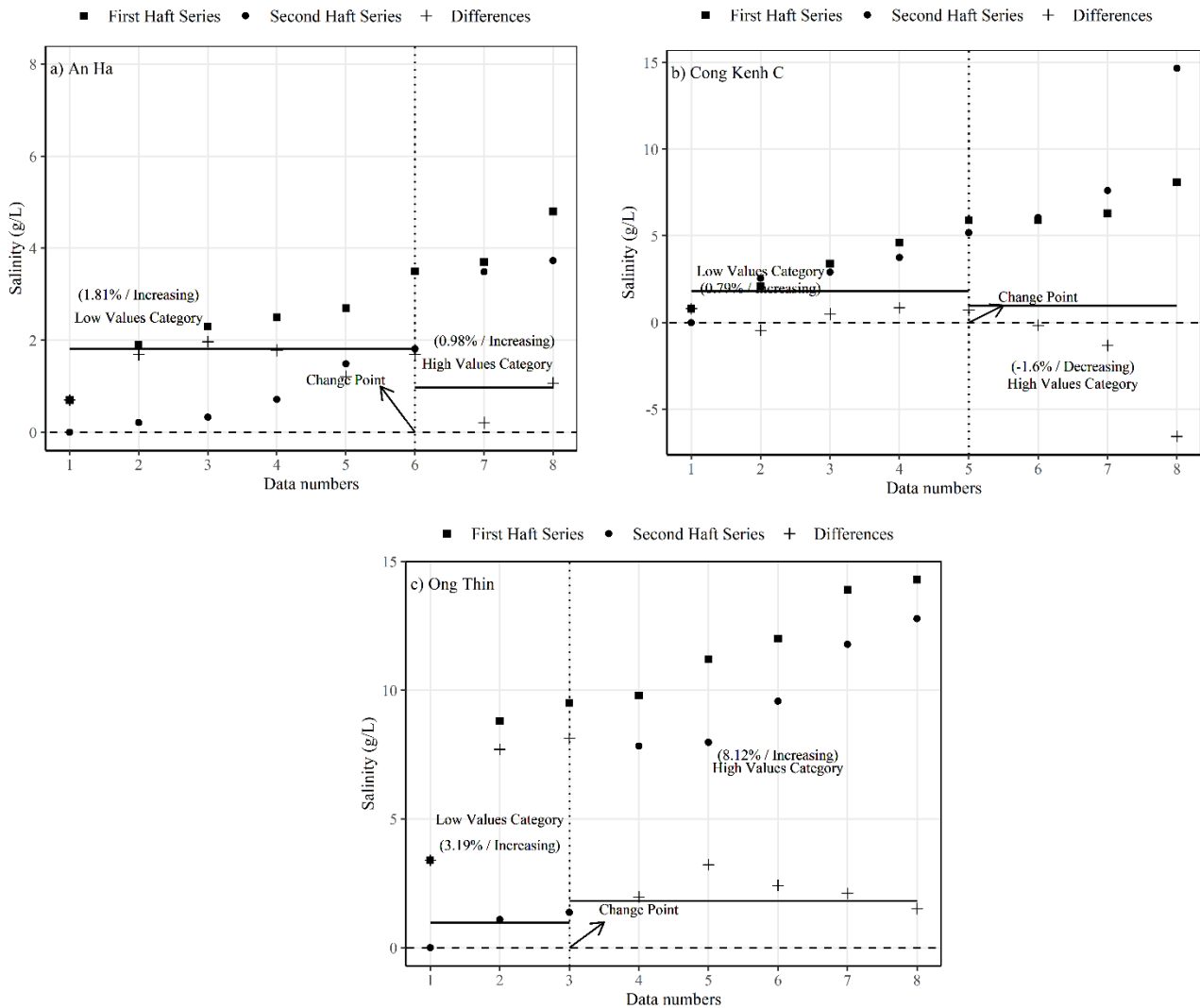


Figure 2. The results of salinity trend analysis in Binh Chanh province from 2007 to 2024.

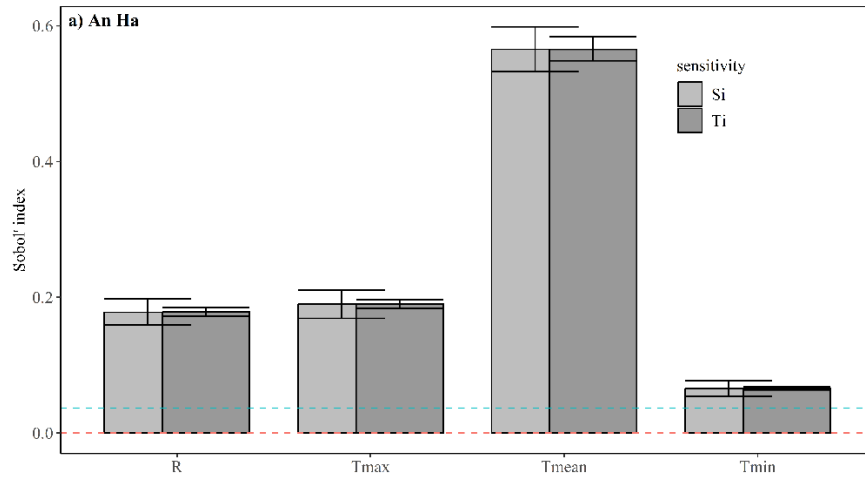
3.2 The association between climate variables and salinity changes

One of the study's key objectives was evaluating how climate variables affect salinity variations. In this regard, sensitivity analysis results for An Ha, Cong Kenh C, and Ong Thin were performed and designed to be analyzed separately. Figure 3 illustrates that both precipitation and average temperature positively impacted maximum salinity. The horizontal, blue, and red dash lines represent the upper boundaries of the S_{Ti} and S_i indices for the

parameters. This study indicated which parameters influence the model output; when the S_i and S_{Ti} of parameters exceed the horizontal lines, they can be considered significant. The findings accurately identified the sensitivity parameters affecting salinity as R for both Ong Thin and Cong Kenh, with precipitation emerging as the most impactful (at 69.6% and 77.2%, respectively), followed by mean and minimum temperatures (at about 20%). Conversely, maximum temperature had only a minor effect, remaining below the red and blue boundary

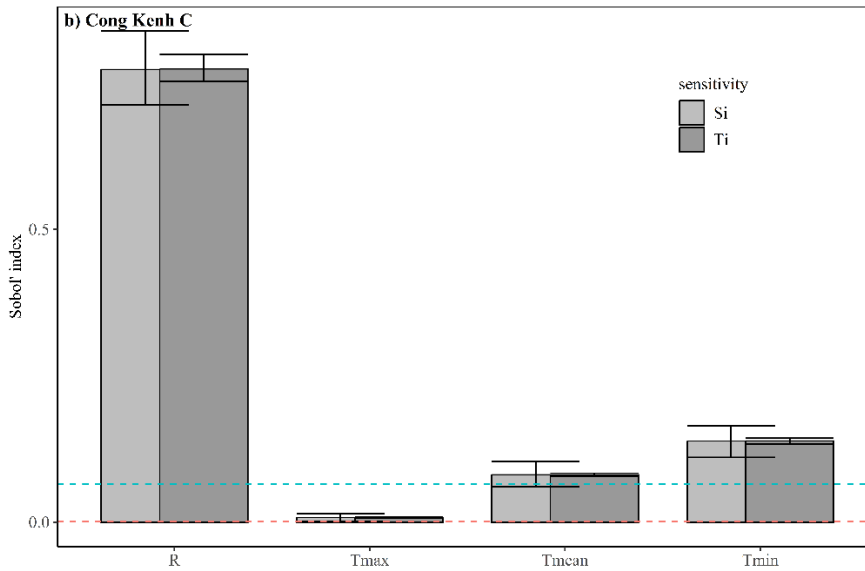
lines. At the An Ha station, however, among the climate variables, mean temperature was the most

influential factor, accounting for 56.5% of the impact on salinity.



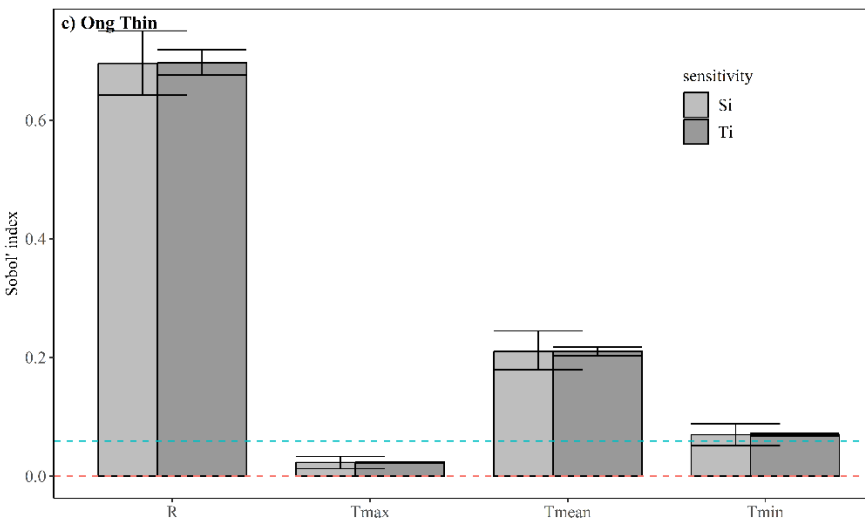
sensitivity indices_An Ha

sensitivity	parameters	value
Si	R	0.178
Si	Tmean	0.565
Si	Tmax	0.190
Si	Tmin	0.066
Ti	R	0.179
Ti	Tmean	0.565
Ti	Tmax	0.190
Ti	Tmin	0.066



sensitivity indices_Cong Kanh C

sensitivity	parameters	value
Si	R	0.772
Si	Tmean	0.081
Si	Tmax	0.008
Si	Tmin	0.138
Ti	R	0.774
Ti	Tmean	0.081
Ti	Tmax	0.008
Ti	Tmin	0.138



sensitivity indices_Ong Thin

sensitivity	parameters	value
Si	R	0.696
Si	Tmean	0.210
Si	Tmax	0.023
Si	Tmin	0.070
Ti	R	0.697
Ti	Tmean	0.210
Ti	Tmax	0.023
Ti	Tmin	0.070

Figure 3. Sensitivity of climate parameters on salinity in Binh Chanh Province (Si: grey color; STi: dark-grey color)

4. CONCLUSION

This research investigated the changes in salinity from 2007 to 2024 and responsiveness to climate factors in Binh Chanh Province. The findings indicated an increase in annual salinity at almost all monitoring locations, with the most significant upward trend observed at Ong Thin station, which showed approximately 8.12% growth. In contrast, Cong Kenh C, situated in the center of Binh Chanh district, was an exception and exhibited declining salinity within the higher value group, decreasing by about 16%. The outcome aligned closely with earlier research in Ho Chi Minh City (Danh et al., 2024; Hong and Dong, 2022), which showed that trends in salinity and their association with impacted areas differ, depending on both the geographical location and size of specific sluices, as well as the width of rivers where salinity exists upstream and is increasing by 0.002% (Hong and Dong, 2022). The salinity levels in stations were also influenced by flows coming from upstream. When the upstream flow decreases, it often results in a greater intrusion of saltwater into inland regions. Conversely, an increase in discharge helps mitigate this saltwater intrusion.

Sensitivity analysis also showed that salinity was more heavily affected by precipitation and mean temperature. The flow and amount of fresh water from rainfall both increase upstream, and both are decisive factors in reducing salinity. This finding supports the broader argument that when freshwater flows are reduced, whether due to less rain or water exploitation, this in turn enables salinity to penetrate further inland.

An increase in sensitivity can elevate crop water demands, exacerbate water loss (due to salinization in surface reservoirs), reduce agriculture productivity, and intensify competition among different water-use sectors (Leeuwen et al., 2016; Thien et al., 2015). Consequently, we recommend that the district explore strategies to minimize consumption where feasible, and optimize the distribution of available resources wherever possible. At the same time, it is essential to prioritize freshwater storage during the rainy season. These reserves serve many purposes, including for use during periods of salinity intrusion, as reservoirs, in underground tanks, and for water storage lakes.

One final note, this study relied on an 18-year historical dataset, and the limited duration of climate data utilized may lead to drawbacks. Therefore, it is vital to extend the time series when future data becomes accessible. Additionally, further research

could focus on assessing the influence of topography, land use dynamics, hydraulic infrastructure, and climate change on the salinity trends in Binh Chanh Province.

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AUTHOR CONTRIBUTIONS

Conceptualization: Ha PT, Khanh PQ, Ngan TTK, Hai LT, Loi NK; Methodology: Ha PT, Khanh PQ, Loi NK; Formal analysis and investigation: Ha PT, Khanh PQ, Ngan TTK, Hai LT, Loi NK; Writing-original draft preparation: Ha PT, Khanh PQ, Loi NK; Writing-review and editing: Ha PT, Khanh PQ, Ngan TTK, Hai LT, Loi NK; Supervision: Hai LT, Loi NK.

DECLARATION OF CONFLICT OF INTEREST

There are no conflicts of interest to declare in this manuscript.

REFERENCES

- Aizen E, Aizen V, Melack J, Nakamura T, Ohta T. Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. *International Journal of Climatology* 2001;21:535-56.
- Anthony P. A non-parametric to the approach problem. *Applied Statistics* 1979;28:126-35.
- Caloiero T, Coscarelli R, Ferrari E. Assessment of seasonal and annual rainfall trend in Calabria (southern Italy) with the ITA method. *Journal of Hydroinformatics* 2019;22(4):738-48.
- Danh VT, Linh DQ, Thuy NTD. Assessing impact of sluice gate operation on salinity intrusion in Ho Chi Minh City. *IOP Conference Series: Earth and Environmental Science* 2024;1349:Article No. 012028.
- Danlu G, Seth W, Holger M. Sensitivity of potential evapotranspiration to changes in climate variables for different Australian climatic zones. *Hydrology and Earth System Sciences* 2017;21:2107-26.
- Esit M. Investigation of innovative trend approaches (ITA with significance test and IPTA) comparing to the classical trend method of monthly and annual hydrometeorological variables: A case study of Ankara region, Turkey. *Journal of Water and Climate Change* 2023;14:305-29.
- Gupta D, Debnath S, Santosh DT. Sensitivity analysis of reference evapotranspiration under different protected cultivation structures. *International Journal of Modern Agriculture* 2020;9:237-44.

- Haj-Amor Z, Araya T, Kim DG, Bouri S. Climate change effects on soil salinity in rainfed maize areas: A case study from South Africa. *Water Supply* 2023;23:2447-65.
- Hong NV, Dong NP. Study to assess the impact of saltwater intrusion in Ho Chi Minh City under climate change conditions. *Vietnam Journal of Hydrometeorology* 2022;10:11-23.
- Mallakpour I, Villarini G. A simulation study to examine the sensitivity of the Pettitt test to detect abrupt changes in mean. *Hydrological Sciences Journal* 2016;61:245-54.
- Kocsis T, Kovács-Székely I, Anda A. Comparison of parametric and non-parametric time-series analysis methods on a long-term meteorological data set. *Central European Geology* 2017;60:316-32.
- Leeuwen V, Dan NP, Dieperink C. The challenges of water governance in Ho Chi Minh City. *Integrated Environmental Assessment and Management* 2016;12:345-52.
- Luo S, Yong S, Lin J, Najah A. Local and global sensitivity analysis and its contributing factors in reference crop evapotranspiration. *Water* 2023;23(4):1672-83.
- Martin, Thanh D. People's Committee of Ho Chi Minh City. Ho Chi Minh Sub-Project Management Unit of VUUP. Vol. 6. Marti,i Associates P/L (Australia) and Duongthanh Water and Environment Ltd. (Vietnam); 2003.
- Meem FF, Rabbeny AKS, Musa T, Mamud M, Halder C, Karmakar S, et al. Groundwater salinity dynamics and seasonal water quality trends in coastal Bangladesh: A case study from Khulna. *Applied Water Science* 2025;15:Article No. 275.
- Meng G, Zhu G, Jiao Y, Qiu D, Wang Y, Lu S, et al. Soil salinity patterns reveal changes in the water cycle of inland river basins in arid zones. *Hydrology and Earth System Sciences* 2024;29:5049-63.
- Prime Minister's Office of Vietnam. Ho Chi Minh City's Master Planning Revision 2040 vision to 2060. Vietnam: 2023.
- Shah Y, Bhimani S, Thacker H, Borah AJ, Jadeja Y, Thakkar M, et al. Spatial variations and trend analysis of groundwater salinity along coastal aquifers of Mundra-Kachchh over a decade—using thematic maps and GIS mapping. *Applied Water Science* 2022;12:Article No. 243.
- Shammi M, Rahman M, Islam A, Doza B, Zahid A, Akter Y, et al. Spatio-temporal assessment and trend analysis of surface water salinity in the coastal region of Bangladesh. *Environmental Science and Pollution Research* 2017;24:14273-90.
- Tyagi S, Singh N, Sonkar G, Mall RK. Sensitivity of evapotranspiration to climate change using DSSAT model in sub humid climate region of Eastern Uttar Pradesh. *Modeling Earth Systems and Environment* 2019;5:1-11.
- Sobol IM. On sensitivity estimation for nonlinear mathematical models. *Meteorological Model* 1990;2:112-8.
- Song X, Zhang J, Zhan C, Xuan Y, Ye M, Xu C. Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. *Journal of Hydrology* 2015;523:739-57.
- Taghadosi MM, Hasanlou M. Trend analysis of soil salinity in different land cover types using Landsat time series data (case study Bakhtegan Salt Lake). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 2017;42:251-7.
- Thanh TN, Van HH, Minh HV, Tri VPD. Salinity intrusion trends under the impacts of upstream discharge and sea level rise along the Co Chien River and Hau River in the Vietnamese Mekong Delta. *Climate* 2023;11:60-75.
- Thien NM, Lee JM, Lee HA, Woo NC. The sustainability risk of Ho Chi Minh City, Vietnam, due to saltwater intrusion. *Geosciences Journal* 2015;19:547-60.
- Truong DD, Dat TT, Hang ND, Huan LH. Vulnerability Assessment of Climate Change in Vietnam: A Case Study of Binh Chanh District, Ho Chi Minh City. *Frontiers in Environmental Science* 2022;10:Article No. 880254.
- Villarini G, Smith JA. Flood peak distributions for the eastern United States. *Water Resources Research* 2010;46(6):1-17.
- Wagener T, Pianosi F. What has global sensitivity analysis ever done for us? A systematic review to support scientific advancement and to inform policy-making in earth system modelling. *Earth-Science Reviews* 2019;194:1-18.
- World Bank Group, Asian Development Bank. Climate Risk Country Profile: Vietnam. World Bank and Asian Development Bank; 2021.

A Numerical Investigation of Perforated Inlet Baffle Configurations on Flow Behavior in a Rectangular Oil / Water Separator using CFD

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ABSTRACT

Gravity separation tanks are generally utilized to separate water and oil in treatment applications. The operating behavior of such tanks is likely to be sensitive to tank operation, as these factors will largely determine whether or not oil droplets stratify easily and float independently of water. Within the present investigations, the influences of several holes in the baffles on water and oil separation within a rectangular tank were explored through the utilization of a numerical model and the consequent simulation of fluid flow. Moreover, in order to ensure the credibility of the simulations, validation was carried out through utilization of a model based on work already conducted experimentally. FLOW-3D (version 11.04) software was applied to model a steady-state, incompressible flow within a two-dimensional (x-z) domain using the Reynolds Averaged-Navier-Stokes (RANS) equations. The RNG k- ϵ turbulence model was adopted to approximate the hydraulic behavior, while the volume of fluid (VOF) approach was employed to capture the air-water interface. In addition, the FAVOR (Fractional Area/Volume Obstacle Representation) technique was used to represent the geometric details of the perforated baffles. 2 perforated baffle geometry cases were explored: differing in the number of holes but with the same hole diameter in both cases. Performance was strongly validated through operational uniformity based on the standard deviation of horizontal velocity within the tank, and the flow field pattern was utilized to determine the characterization of the streamlines and recirculation areas. A kinetic energy analysis was carried out to illustrate turbulence in the flow approximation. The results indicated that an inlet baffle with fewer holes had significantly enhanced operating uniformity and lower turbulence compared with more holes, and correspondingly, these flow field patterns depicted more streamlined movement and lower recirculation areas.

HIGHLIGHTS

A CFD model was used to analyze flow behavior in a rectangular gravity separator. 2 perforated inlet baffles with equal hole diameter were numerically investigated. The 2-hole baffle improved flow uniformity, flow field pattern and reduced kinetic energy. Improved hydraulic characteristics enhances droplet coalescence and oil-water separation. Results support optimizing a perforated baffle design for enhanced separator performance.

1. INTRODUCTION

Issues related to fats, oils, and greases (FOGs) in sewer infrastructure have generally not received adequate attention. However, from another perspective, these problems are part of the reasons for impediments and sewer discharges (Mattsson et al., 2014). FOG accumulation is the main contributor to sewer overflows, constituting 40%-50% of the total overflows. Nationally, the percentage of sewer

overflows is between 10% and 25%, with about 138,000 sanitary sewer overflow (SSO) events annually due to the obstruction brought about by the solid, undissolvable FOG material clogging the sewers in the country (Jameel et al., 2011; Keener et al., 2008). The sources of these wastes include residues from refining and processing of petroleum and petrochemicals, as well as tramp oil generated in mechanical repair facilities and utility operations, among others

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(Southerland, 2002). Such challenges emphasize the urgency of developing reliable and efficient treatment and separation methods. Among the available techniques, gravity separation remains the most common and cost-effective method for removing dispersed oil droplets from wastewater in both municipal and industrial applications (Metcalf et al., 2014; Aziz, 2010). Hydrodynamic conditions such as velocity distribution, turbulence intensity, and internal tank configuration strongly influence the performance of gravity separators. This highlights the necessity for design enhancements to boost flow stability and separation efficiency (Hussein et al., 2013).

Equally, the separation of oil droplets from water is a basic operation used widely in industrial applications, especially within oil and gas industries. Moreover, this separation is crucial for separating free oil within products of water and for providing clean crude oil before processing or conversion into final products. Oil-water separators are essential equipment utilized within oil industries, and they help create efficiencies that lead to low oil transport expenses and meet all aspects of environmental regulations (Yu et al., 2017). Hafsi et al. (2020) performed a numerical simulation of two-phase flows through API-type separator systems. Their study aimed at investigating the oil droplets' coalescence phenomenon and optimizing their performances, while paying close attention to the essential role that CFD techniques play in optimizing industrial separator system performances.

Internal baffles have been widely recognized as effective and economical design features to improve the hydraulic performance of separation units (Akpan, 2013; Nascimento et al., 2024). For instance, Efendioglu et al. (2014) reported that perforated plates and optimized diverters enhanced the separation efficiency of an oil-gas separator to above 99% using ANSYS CFX simulations, while Al-Yacouby and Ahmed (2022) showed that perforated baffles were most effective in mitigating sloshing pressure in rectangular tanks. Ibrahim et al. (2024) performed a CFD simulation using Flow-3D software on a three-phase gravity separator for oil, gas, and water separation and showed that baffle design and number of perforations significantly and directly affected fluid distribution and separation, emphasizing that these could be optimized through CFD simulations for improved separator separation efficiency. These studies highlight the critical role of baffle configuration in controlling internal flow behavior.

Advancements in computational fluid dynamics (CFD) have further enabled detailed investigations of flow fields and separator performance using tools such as Flow-3D, Ansys Fluent, COMSOL Multiphysics, and others (Yusuf and Micovic, 2020). Recent studies confirm that perforated baffles contribute to reducing recirculation zones and promoting more uniform velocity distributions, which in turn enhance droplet coalescence and rise (Mee and Nor, 2011; Kim et al., 2025). In addition, hydrodynamic parameters such as kinetic energy (TKE) and velocity gradients have emerged as reliable indicators of separation efficiency. This advantage was also demonstrated by Joshy et al. (2022) in three-phase separators, where CFD was successfully applied to optimize internal baffles and perforated plates based on performance indicators such as KE, further confirming the relevance of CFD in design optimization.

Although inlet baffles are commonly used to improve hydraulic conditions in gravity separation tanks, most previous studies have either focused on solid baffles or have examined perforated designs without considering how the numbers of openings at a fixed diameter influences internal flow. As a result, the effect of perforation number on flow stability and separation performance is still not well defined. In this study, 2 perforated baffle configurations, 1 with 2 openings and another with 3 openings, each 6 cm in diameter, were evaluated numerically using FLOW-3D under single-phase (water-only) conditions. Flow uniformity, recirculation regions, and kinetic energy with a velocity profile were analyzed to assess how the number of openings affects the hydraulic behavior of the separator.

2. METHODOLOGY

2.1 Mathematical model

2.1.1 Equations of time-average flow

In the hydraulic numerical modeling, generally establish the flow conditions with the assumption of an incompressible, steady-state flow and consider the action of viscosity. The flow model of turbulence was employed in the estimation of the stresses of Reynolds and in the research of the tank of separation, assuming that the flow in the x and z coordinates was two-dimensional, while the mass continuity and the momentum equations are generally employed in the research of the governing equations (Hussein et al., 2013; Yakhot and Smith, 1992; Yakhot and Orszag, 1986; Hirt and Sicilian, 1985). The general mass continuity equation is:

$$V_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u A_x) + \frac{\partial}{\partial z} (\rho w A_z) = 0 \quad (1)$$

Here, ρ represents fluid density, u and w are velocity components along the x and z directions, respectively, and V_f represents the volume fraction of fluid within a computational cell. The momentum equations, taking into account a region that becomes two-dimensional, are given:

$$\frac{\partial u}{\partial t} + \frac{1}{V_f} \left\{ u A_x \frac{\partial u}{\partial x} + w A_z \frac{\partial u}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + G_x + f_x \quad (2)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_f} \left\{ u A_x \frac{\partial w}{\partial x} + w A_z \frac{\partial w}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + G_z + f_z \quad (3)$$

Where; viscous acceleration terms are given by f_x and f_z , and gravitational accelerations are given by G_x and G_z . The dynamic viscosity μ is defined by the formulas below:

$$\rho V_f f_x = ws_x - \left\{ \frac{\partial}{\partial x} (A_x \tau_{xx}) + \frac{\partial}{\partial z} (A_z \tau_{xz}) \right\} \quad (4)$$

$$\rho V_f f_z = ws_z - \left\{ \frac{\partial}{\partial x} (A_x \tau_{xz}) + \frac{\partial}{\partial z} (A_z \tau_{zz}) \right\} \quad (5)$$

Where; $\tau_{xx} = -2\mu \frac{\partial u}{\partial x}$, $\tau_{zz} = -2\mu \frac{\partial w}{\partial z}$, $\tau_{xz} = -\mu \left\{ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right\}$

Where; ws_x and ws_z are wall shear stress values applied in their directions. The air-water free-surface interface was modeled by implementing the volume of fluids (VOF) method so that the time evolutions of the interface could be calculated accurately (Azimi and Shabanlou, 2018). The volume fraction evolution that governs the equation is

$$\frac{\partial F}{\partial t} + \frac{1}{V_f} \left\{ \frac{\partial}{\partial x} (F A_x u) + \frac{\partial}{\partial z} (F A_z w) \right\} = 0 \quad (6)$$

The intricate internal geometry, such as hole-perforated baffles, was modeled using the Fractional Area/Volume Obstacle Representation (FAVOR) method. The method cleverly depicts solid boundaries using cell fractions as a function of porosity.

2.1.2 Turbulence model

The Renormalization Group (RNG) method is applicable to the governing equations of turbulence, utilizing difference equation methods to obtain both turbulent kinetic energy (k) and the turbulent dissipation rate (ϵ) (Selim et al., 2023; Adams and Rodi, 1990). The RNG method contains a statistical system with a systematic approach in identifying significant turbulent formulas, particularly those for

turbulent kinetic energy and dissipation rate (ϵ). Further, mathematically modeled with eddy streamlining in tanks, this research presents insight that can be applied to a general situation relevant to a range of turbulence scales. Hence, RNG models have less dependency on a set of constant values obtained experimentally; hence, a unifying set of parameters emerges (Yakhot and Smith, 1992; Yakhot and Orszag, 1986). The RNG model demonstrates improved predicting capability regarding higher values, with functional shapes similar to those previously derived from standard models, hence allowing a comparative study regarding reasonable curvature and strain rate compared to a similar k - ϵ model. It's worth noting that the RNG model reproduces constant values previously derived by experimentation from a standard k - ϵ model. The modeling regarding turbulent kinetic energy (k), together with the relevant dissipation rate for a two-dimensional flow, is outlined as follows:

$$\frac{\partial k}{\partial t} + \frac{1}{V_f} \left\{ u A_x \frac{\partial k}{\partial x} + w A_z \frac{\partial k}{\partial z} \right\} = p + \text{Diff} - \epsilon \quad (7)$$

$$\frac{\partial \epsilon}{\partial t} + \frac{1}{V_f} \left\{ u A_x \frac{\partial \epsilon}{\partial x} + w A_z \frac{\partial \epsilon}{\partial z} \right\} = C_{1\epsilon} \frac{p\epsilon}{k} + \text{DDif} - C_{2\epsilon} \frac{\epsilon^2}{k} \quad (8)$$

The most significant parameters considered under this study are the dissipation rate (ϵ), turbulent kinetic energy (k), gravitational acceleration (G), and pressure (P). The RNG model, as expressed by Yakhot and Orszag (1986), contains constants given by $C_{1\epsilon}=1.42$, $C_{2\epsilon}=1.68$, $C_{3\epsilon}=0.2$.

2.2 Numerical model

In this work, computational simulations from the Navier-Stokes equations using the finite volume method (FVM) as given by Versteeg and Malalasekera (2007) provided the simulation of the steady-state, two-dimensional, incompressible flow. The simulation of the conservation of mass and momentum was done using viscous, pressure, and inertial terms. The FLOW-3D program employed the calculations by implementing the Volume of Fluid (VOF) technique included in it to simulate oil and water phase interfaces quite effectively (Hirt and Nichols, 1981). The technique is more effective at replicating multiphase flows and is widely used in separation studies because it successfully emulates the motion of the free surface. The RNG k - ϵ model has been utilized for the computational simulation of turbulent flow dynamics. The model is highly effective for the analysis of

detailed internal flow patterns and is widely adopted for simulating turbulent flow inside reservoirs. (Yakhot and Orszag, 1986; Hussein et al., 2013). Here, gravitational force is assumed to be the main responsible force of the separation process, whereas heat transfer and chemical reaction have usually been omitted with an assumption of incompressibility. It provides good representation of hydraulic performance as well as separation performance. It is in contrast with the specification of only general flow behavior, as it provides room for further evaluation of flow characteristics with hole arrangement geometries of varying natures with perforations. It can be utilized specifically for the purpose of evaluating the whole

arrangement's effect on velocity distribution and kinetic energy distribution, as well as the flow uniformity of the separation tank.

2.2.1 Comparison test

The obtained results are consistent with the findings of both experimental and numerical investigations. Shahrokhi et al. (2012) constructed a physical model in the hydraulic laboratory to examine the flow characteristics within a rectangular tank, as shown in Figure 1. The experiments were performed in a tank measuring 200 cm in length, 50 cm in width, and 50 cm in height, with an inlet opening of 10 cm and a discharge rate of 0.002 m³/s.

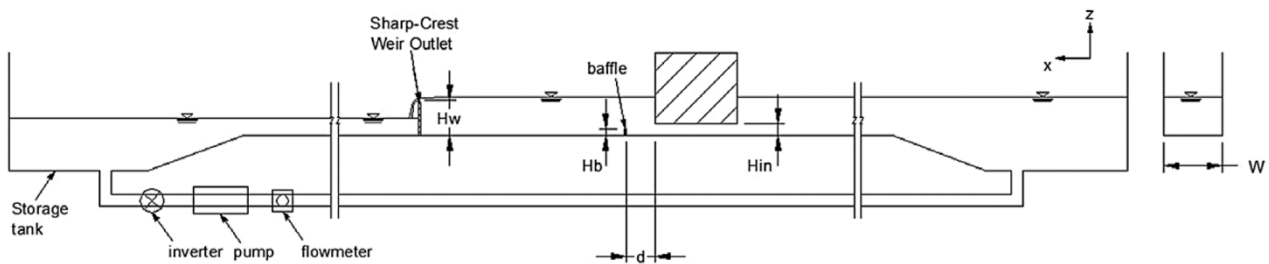


Figure 1. Schematic representation of the physical model of the rectangular tank (Shahrokhi et al., 2012).

The rectangular tank containing a single baffle was simulated in Flow-3D (v11.04) to replicate the experimental setup and define the computational domain, as illustrated in Figure 2(a). The model employed suitable boundary conditions, including a specified inlet velocity, a pressure-outflow boundary at the outlet, an open top surface, and no-slip

conditions along the tank walls and bottom (Figure 2(b)). A structured mesh with a uniform cell size of 0.01 m was applied to achieve an optimal balance between computational efficiency and numerical accuracy, with aspect ratios evaluated to confirm mesh quality (Figure 2(c)-(d)).

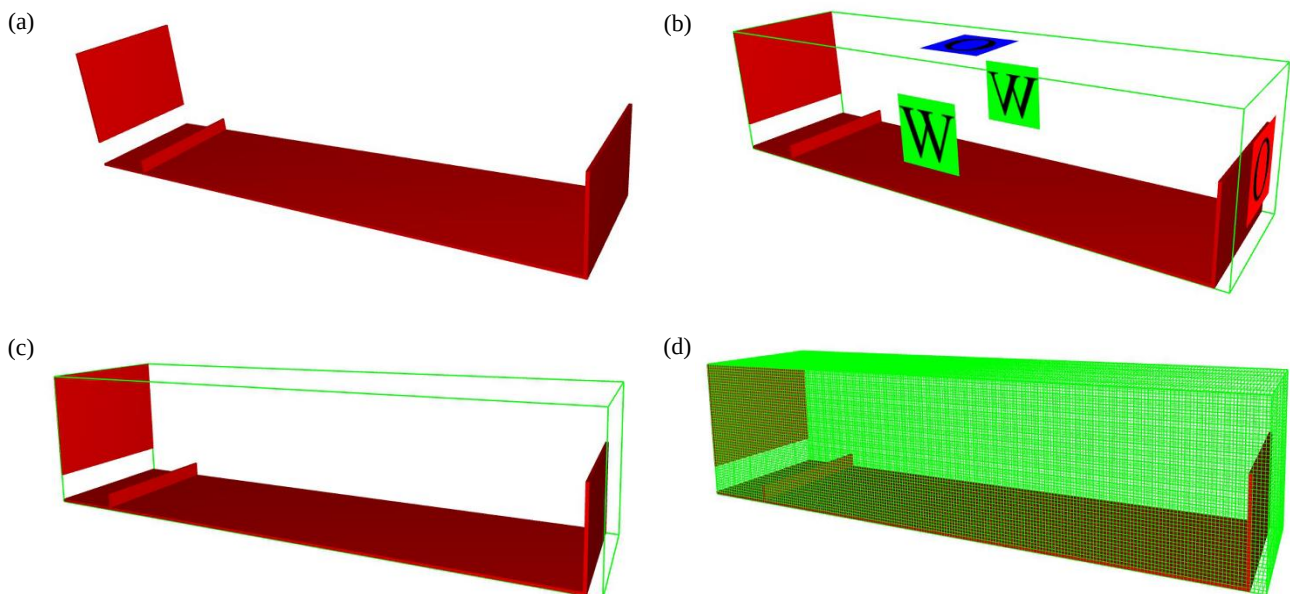


Figure 2. Numerical model: (a) model geometry, (b) boundary condition, (c) mesh block, (d) the computational cells

Velocity profiles were evaluated at three different set points, located 10, 46, and 82 cm away from the intake in the stream wise direction. As can be seen from Figure 3, by synchronizing the two sets of profiles with respect to inlet height (Z/H in) and horizontal velocity (U/U_0), the results achieved by the model exhibited significant coincidence with

experimental data. The numerical model effectively simulated velocity gradient in association with the general flow setup. A high correlation between numerical and experimental outcomes was noted, thus verifying the model, as can be seen from the statistical examination ($R=0.98$ and $R^2=0.96$).

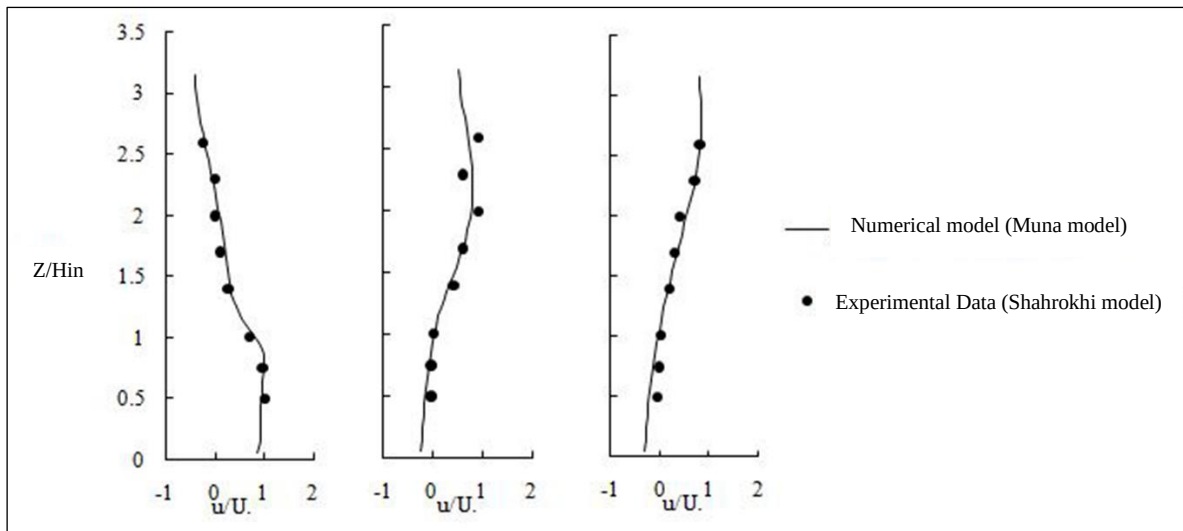


Figure 3. Comparison between numerical model and experimental data

2.2.2 Geometry generation

The separation tank was modeled in two dimensions to minimize computational requirements. As illustrated in Figure 4, the tank has a horizontal rectangular shape with a uniform depth of 0.5 m and an overall length of 2 m. The inlet was specified on the

left vertical boundary, where a constant horizontal velocity of 0.04 m/s was applied, equivalent to a total discharge of 0.002 m³/s. The outlet was defined on the right boundary at an elevation of 0.45 m above the tank bottom to allow the release of surface runoff.

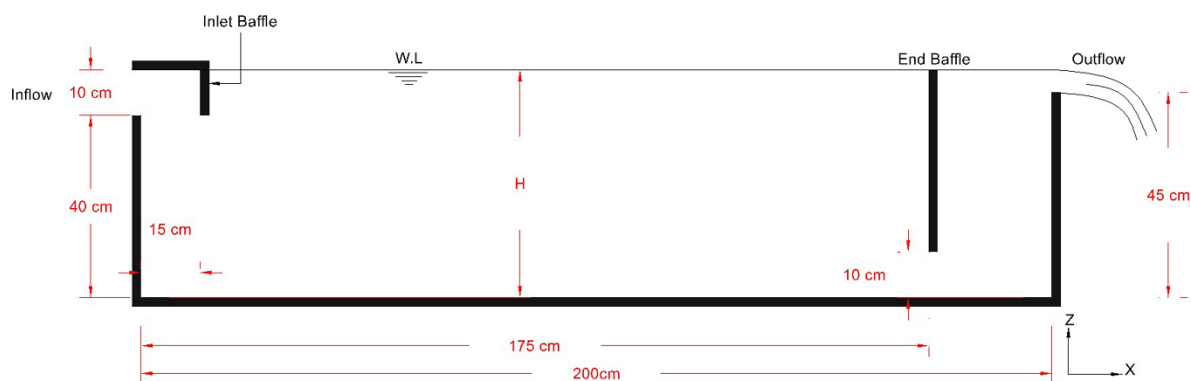


Figure 4. Longitudinal section for horizontal gravity separation tank (case study)

The tank geometry was modeled using the FLOW-3D platform, while the perforated baffles were created in AutoCAD and subsequently imported in STL format. The inlet baffle consisted of a vertical steel plate spanning the separator width ($W=50$ cm)

and located at a depth of 0.40 m above bottom. The choice of a thickness of 10 mm ensured that it remained stable. Two baffle arrangements were considered, having 2 and then 3 circular holes (diameter of 6 cm) that helped reduce the jet inlet and

hence improve the velocity distribution. The baffle placement of 0.15 m away from the inlet kept the inlet

flow steady into the separation region, as shown in [Figure 5](#) below.

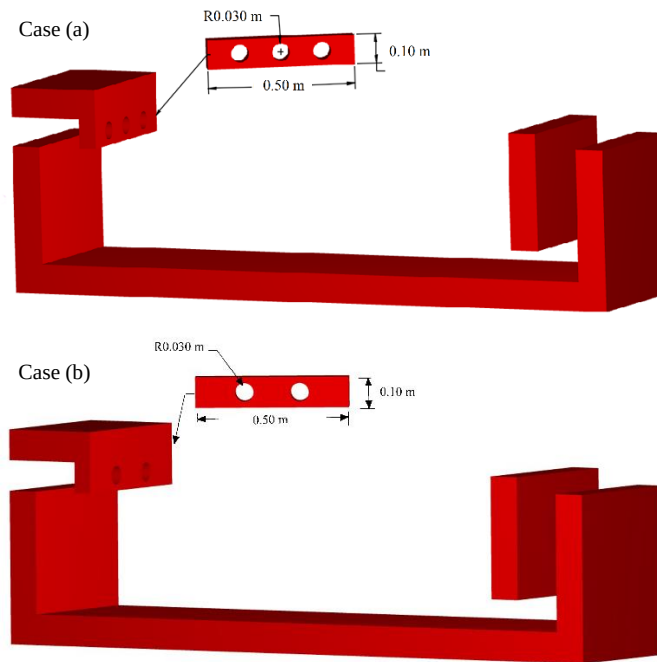


Figure 5. Displays 3D models of a rectangular gravity separator tank, illustrating the inlet perforated baffles: (a) the baffle with 3 openings, and (b) the baffle with 2 openings

Flow-3D models are capable of simulating the behavior of multiphase and turbulent flows using physical models. The model that I used includes the solution of the basic equations using Cartesian coordinates, while the gravity vector is set to the negative z-direction. The standard water property model includes a density of 1,000 kg/m³ and a viscosity of 0.001 Pa·s at 20°C, which corresponds to the SI units system of measurement ([Sadiq et al., 2025](#)). The model I employed integrated the RNG k-ε model, which effectively simulates the dynamics of

turbulent flows ([Acharya and Potter, 2021; Laleh et al., 2012](#)). The computational domain was discretized using a structured rectangular mesh, as shown in [Figure 6\(a\)](#). A base cell size of 0.03 m was applied, yielding 9,625 cells over the domain. To enhance resolution, the mesh was refined to 0.02 m around the inlet baffle ([Figure 6\(b\)](#), 1,150 cells) and further to 0.015 m near the perforation openings ([Figure 6\(c\)](#), 490 cells around 1 opening) to accurately capture the velocity gradients and shear layers in these regions.

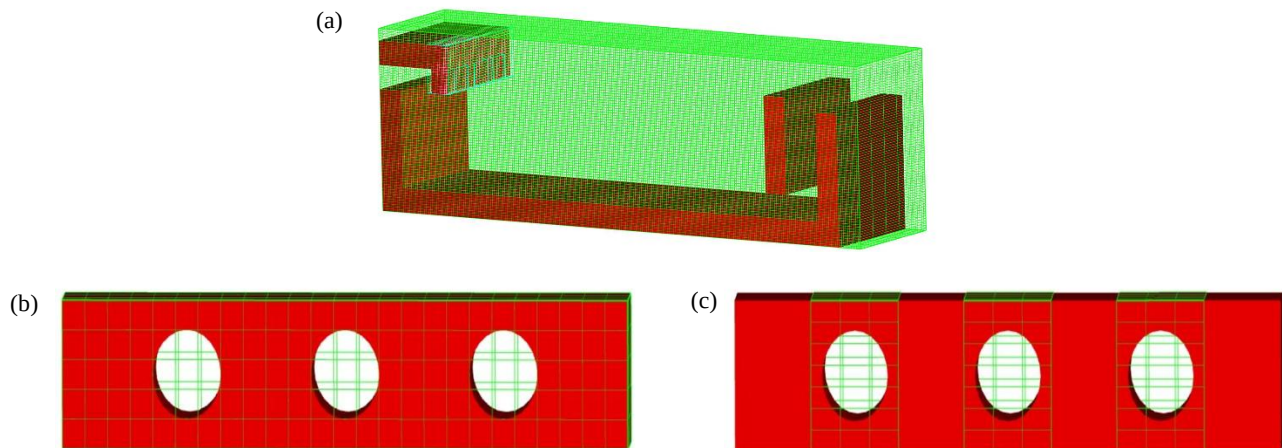


Figure 6. Mesh distribution and refinement in the numerical model: (a) Overall mesh domain, (b) around the inlet baffle, (c) the perforation openings of the baffle

The boundary conditions are illustrated in Figure 7(a). No-slip boundary conditions were also applied on every immobile wall. The inlet was also defined as a specific velocity boundary in the x-direction, the outlet was used as the outflow boundary condition, and the free surface on the top was modeled

using the volume of fluid (VOF) method. Additionally, the FAVOR (Fractional Area/Volume Obstacle Representation) technique was used to accurately represent the internal geometry and the shape of the baffle within the computational domain, as seen in Figure 7(b).

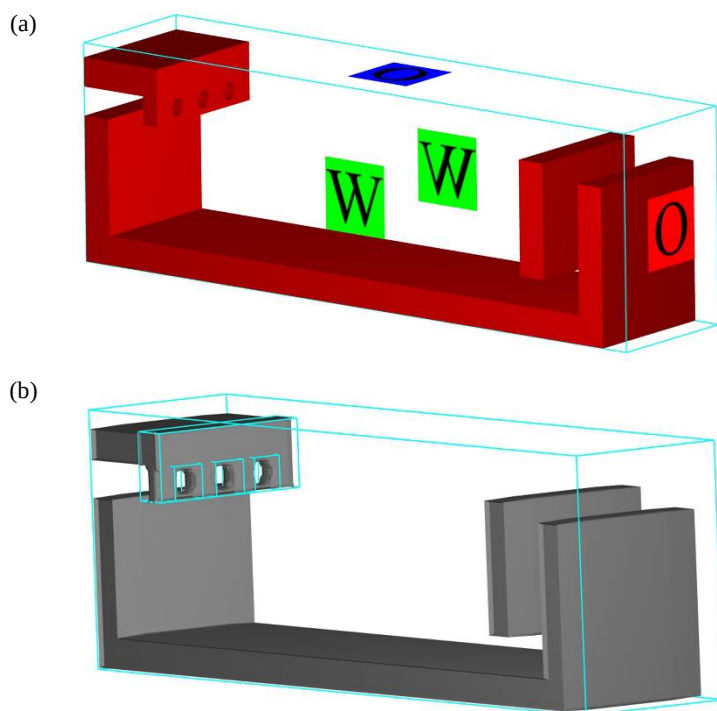


Figure 7. Numerical model of the gravity separation tank: (a) boundary condition, (b) FAVOR render

3. RESULTS AND DISCUSSION

3.1 Flow field pattern

In the current study, as shown in Figure 8, streamline analysis identified significant differences in the recirculation zones for the two perforated baffle geometries, both measuring an equal hole diameter of 6 cm. The recirculation area was calculated based on the total tank area using a numerical technique. In case (a), which represented the 3-hole baffle, the recirculation area covered about 59% of the tank area, reflecting a larger internal circulation area. By contrast, case (b), utilizing the 2-hole baffle, had a smaller recirculation area that covered about 45% of the tank area. A larger recirculation area is undesirable, as it represents stagnant regions and flow short-circuiting that decrease the effective separation zone. Conversely, smaller recirculation areas in case (b) indicate more stable flow patterns and enhanced conditions for oil-water separation. Such flow conditions are typically desirable for promoting the coalescence and upward movement of oil droplets,

hence increasing the overall efficiency of FOG separation.

3.2 Flow uniformity

For maximum separation effectiveness, there is a need to have a low horizontal velocity in the tank since this facilitates oil droplet coalescence, resulting in a more balanced flow pattern. Vertical motion of oil droplets is controlled mainly by the density and viscosity of fluids, along with size (Hussein et al., 2013). Droplets that are larger in size mostly rise faster than those that are small in size. It is, therefore, necessary to reduce horizontal velocity variations around the region near the inlet to improve internal flow structure. Consequently, the tank should be designed so that the velocity of the incoming flow is reduced to a minimum. The efficiency of the baffle with openings at the position of 0.15 m was analyzed through the comparison of the deviations of horizontal velocity (x-velocity) at various points across the longitudinal section. The standard deviations of the

horizontal velocity within the separation tank across the locations of $x=0.2, 0.6, 1.00$, and 1.60 are presented in [Table 1](#) for both baffle arrangements at the measurement position of 0.15 m.

The baffle arrangement case (b) showed the highest efficiency since it registered the smallest deviations in velocity.

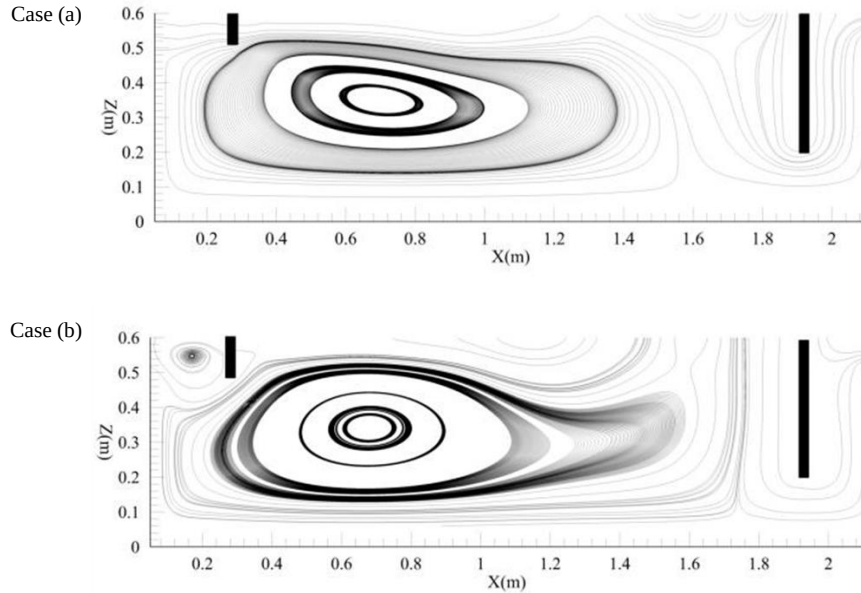


Figure 8. Streamline patterns in a rectangular gravity separator tank with inlet perforated baffles: (a) baffle with 3 openings, (b) baffle with 2 openings

Table 1. Velocity deviation in the separation tank

Cases	Description of inlet perforated baffle	SD of x-velocity (m/s)*E-02			
		Sections x(m)			
		0.20	0.60	1.00	1.60
a	3 openings with a diameter of 6 cm	5.22	8.06	8.43	4.06
b	2 openings with a diameter of 6 cm	1.55	0.49	0.25	0.41

3.3 Kinetic energy and velocity profile

Kinetic energy (KE) is a key parameter for evaluating the degree of turbulence within a separation tank. In this research, KE values have been calculated based on the horizontal velocity components measured at different points around the tank. In this research, two types of baffles have been considered, namely the two-hole and three-hole baffle types. When fluid flows through three holes created at one point on a baffle, three equal jets are generated, and then they meet, as observed from [Figure 9\(a\)](#). In this case, a large turbulent region is observed, situated above half of the tank volume. Two equal jets of fluid pass through holes situated on the boundary of the two-hole baffle,

as observed from [Figure 9\(b\)](#). The shear layers around the jets create localized areas of increased turbulence. Downstream of the baffle, these jets expand and merge, forming a turbulent zone that extends through the upper part of the tank toward the outlet, while the lower region remains relatively calm, except for limited disturbances near the bottom.

Lower turbulence levels in this case promote better conditions for oil droplet rise and coalescence. The two-hole baffle recorded a KE value of $4.24\text{E-}04$ m^2/s^2 , indicating a stable flow pattern, whereas the three-hole baffle showed a higher KE of $8.50\text{E-}03$ m^2/s^2 , reflecting stronger turbulence that can reduce separation efficiency.

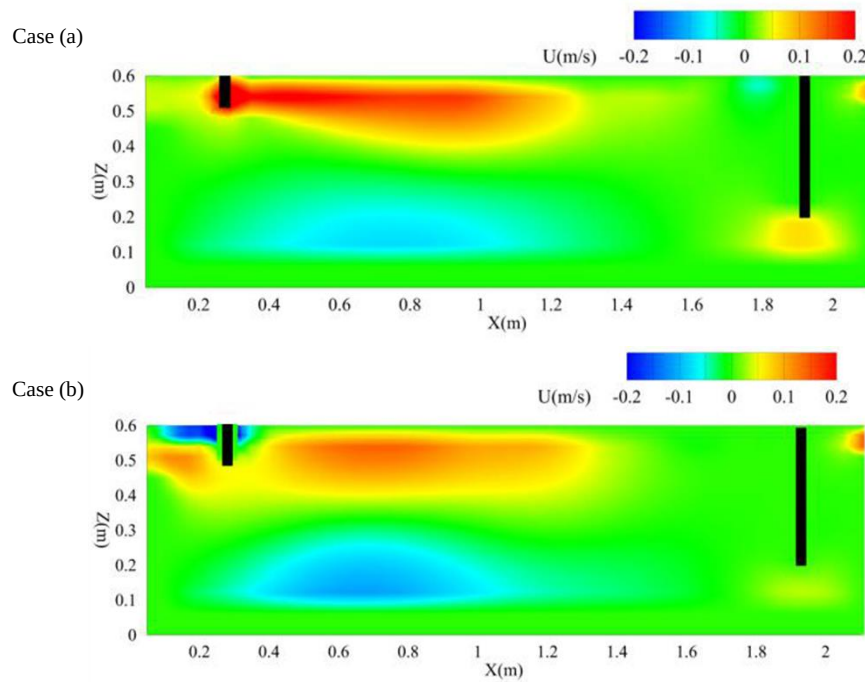


Figure 9. The x-velocity contours in a rectangular gravity separator tank that uses inlet perforated baffles: (a) baffle with 3 openings, (b) baffle with 2 openings.

As seen in Figure 10, the velocity distribution indicates the fact that the 2-hole baffle increases the tank's flow stability by inducing a uniform flow profile at reduced velocities. The 3-hole baffle, however, produced higher relative velocities. Overall,

the number of perforations had a marked impact on the hydraulic behavior of the separator, with a smaller number of openings being associated with enhanced separation efficiency and reduced turbulence intensity.

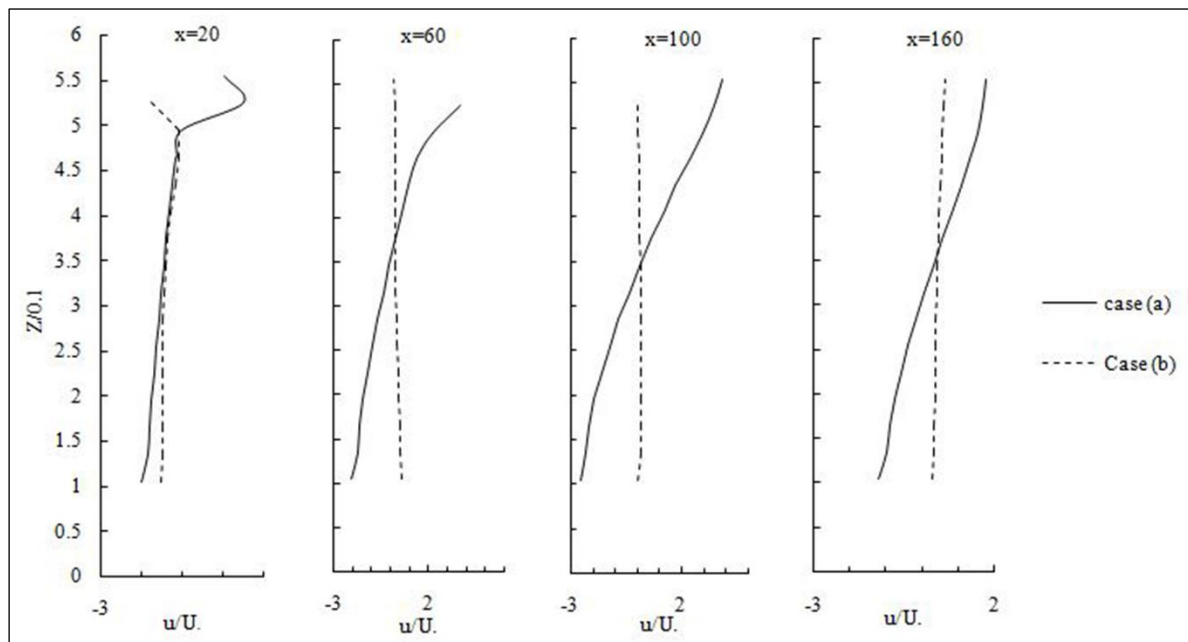


Figure 10. Compares the x-velocity distribution for two different cases of perforated baffles: (a) baffle with 3 openings, (b) baffle with 2 openings

Finally, the present results indicate that a reduced number of perforations is associated with improved separator performance, as indicated by reduced standard deviation in velocity, decreased kinetic energy, and reduced recirculation areas. The result supports the assertions made by [Wilkinson et al. \(2000\)](#) on the efficacy of perforated baffles in creating flow uniformity, and the optimal number of openings with the highest possible value of free area was also advocated to produce velocity uniformity with suppressed velocity variations. Moreover, [Mee and Nor \(2011\)](#) recognized that the greater the number of openings, the greater is the value of the free area, hence the reduction in the inlet velocity with turbulence. The variations may be due to geometric or operational considerations. In particular, [Mee and Nor \(2011\)](#) clearly support the importance of utilizing the perforated baffles in managing the dynamics of the flow process, leading to the intensification of separation efficiency.

4. CONCLUSION

This work used numerical simulation to analyze the hydraulic performance of the rectangular gravity separator with the perforated inlet baffles. The CFD simulation was validated with the existing experiments, which ensured the simulation result's accuracy for the simulation process. Although the opening diameter of both models was the same (6 cm), the number of openings had an effect on the flow inside. The outcomes of the study indicated that the 2-hole baffle provided better hydraulic performance compared to the 3-hole baffle design. In particular, the 2-hole design assisted in the reduction of the kinetic energy (KE) from $8.50\text{E-}03$ to $4.24\text{E-}04$, the standard deviation of velocity from $2.85\text{E-}01$ to $2.71\text{E-}02$, and the recirculation area from 59% to 45%. The observed improvements demonstrated a significant reduction in turbulence levels, which enhanced the uniformity of the velocity profile and increased the efficiency of oil droplet coalescence, rise, and oil-water separation. The study indicates that the fewer the number of inlet baffle perforations, the more efficient the gravity separation process will be.

AUTHOR CONTRIBUTIONS

The first author (Muna S. Resin) developed the research idea and study design. She conducted the numerical modeling, executed the simulation tasks, analyzed the obtained results, and prepared the initial manuscript draft.

The corresponding author (Haitham A. Hussein) provided scientific oversight throughout the study, reviewed and interpreted the results, and contributed to manuscript refinement and final approval of the version submitted for publication.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Acharya T, Potter T. A CFD study on hydrocarbon mean residence time in a horizontal oil-water separator. *SN Applied Sciences* 2021;3(4):1-10.
- Adams EW, Rodi W. Modeling flow and mixing in sedimentation tanks. *Journal of Hydraulic Engineering* 1990;116(7):895-913.
- Akpan DG. Performance of Internals in Three-Phase Tank Separators [dissertation]. Norway, Norwegian University of Science and Technology; 2013.
- Al-Yacoubi AM, Ahmed MM. A numerical study on the effects of perforated and imperforate baffles on the sloshing pressure of a rectangular tank. *Journal of Marine Science and Engineering* 2022;10(10):Article No. 1335.
- Azimi H, Shabanlou S. U-shaped channels along the side weir for subcritical and supercritical flow regimes. *ISH Journal of Hydraulic Engineering* 2018;26(4):365-75.
- Aziz TN. Analysis of Grease Abatement Devices and the Measurement of Fat, Oil, and Grease in Food Service Establishment Waste Streams [dissertation]. Raleigh, North Carolina, USA, North Carolina State University; 2010.
- Efendioglu A, Mendez J, Turkoglu H. The numerical analysis of the flow and separation efficiency of a two-phase horizontal oil-gas separator with an inlet diverter and perforated plates. *Advances in Fluid Mechanics* 2014; 82:133-42.
- Jameel AT, Muyubi SA, Karim MIA, Alam MZ. Removal of oil and grease as emerging pollutants of concern (EPC) in wastewater stream. *IIUM Engineering Journal* 2011;12(4):161-9.
- Joshay A, MA A, Nambiar A. CFD Analysis and optimization of three phase oil separator. *Proceedings of the International Conference on Systems, Energy and Environment*; 2022 Aug 5-6; Kannur, Kerala, India; 2022.
- Hafsi Z, Elaoud S, Mishra M, Wada I. Numerical study of droplets coalescence in an oil-water separator. *Proceedings of the 7th International Conference on Advances in Mechanical Engineering and Mechanics*; 2019 December 16-18; Hammamet, Tunisia; 2020. p. 449-54.
- Hirt C, Sicilian J. A porosity technique for the definition of obstacles in rectangular cell meshes. *Proceedings of the 4th International Conference on Ship Hydrodynamics*; 1985 Sep 24-27; Washington, DC; 1985.
- Hirt CW, Nichols BD. Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics* 1981;39(1):201-25.
- Hussein HA, Abdullah R, Harun S, Abdulkhaleq M. Numerical model of baffle location effect on flow pattern in oil and water gravity separator tanks. *World Applied Sciences Journal* 2013;26(10):1351-6.

- Ibrahim AA, Najim YM, Dawood AS. Three phase oil separator simulation using CFD analysis: A review study. *Al-Rafidain Engineering Journal* 2024;29(2):10-8.
- Kim S, Kim H, Jeong HS, Kim Y. Optimal design of perforated baffles for enhancing oil-water separation performance using genetic algorithms. *Results in Engineering* 2025;26:Article No. 104668.
- Keener KM, Ducoste JJ, Holt LM. Properties influencing fat, oil, and grease deposit formation. *Water Environment Research* 2008;80(12):2241-6.
- Laleh AP, Svrcek WY, Monnery WD. Design and CFD studies of multiphase separators: A review. *The Canadian Journal of Chemical Engineering* 2012;90(6):1547-61.
- Mattsson J, Hedström A, Viklander M, Blecken G-T. Fat, oil, and grease accumulation in sewer systems: Comprehensive survey of experiences of Scandinavian municipalities. *Journal of Environmental Engineering* 2014;140(3):Article No. 04014003.
- Mee CG, Nor MIM. Flow pattern in a horizontal primary separator with a perforated baffle. *Journal of the Institution of Engineers Malaysia* 2011;72(3):19-25.
- Metcalf, Eddy A. *Wastewater Engineering: Treatment and Resource Recovery*. 5th ed. McGraw-Hill Education; 2014.
- Nascimento JBDS, Ferreira AD, Vasconcelos AL, De Farias Neto SR. Study of the influence of Semi-porous baffles on the three-phase separation efficiency in a horizontal separator vessel via CFD. *Journal of Petroleum Science and Technology* 2024;14(3):50-9.
- Sadiq FA, Hussien HA, Zainol MR. Numerical investigation of hydraulic performance in Makhool Spillway Dam. *Environment and Natural Resources Journal* 2025;23(2): 142-9.
- Selim T, Hamed AK, Elkiki M, Eltarabily MG. Numerical investigation of flow characteristics and energy dissipation over piano key and trapezoidal labyrinth weirs under free-flow conditions. *Modeling Earth Systems and Environment* 2023;10(1):1253-72.
- Shahrokhi M, Rostami F, Said MAM, Yazdi SRS. The effect of number of baffles on the improvement efficiency of primary sedimentation tanks. *Applied Mathematical Modelling* 2012;36(8):3725-35.
- Southerland R. Sewer fitness: Cutting the fat. *American City and County* 2002;117(15):27-31.
- Versteeg HK, Malalasekera W. *An Introduction to Computational Fluid Dynamics the Finite Volume Method*. 2nd ed. India: Pearson Education; 2007.
- Wilkinson D, Waldie B, Nor MM, Lee HY. Baffle plate configurations to enhance separation in horizontal primary separators. *Chemical Engineering Journal* 2000;77(3):221-6.
- Yakhot V, Smith LM. The renormalization group, the ϵ -expansion and derivation of turbulence models. *Journal of Scientific Computing* 1992;7(1):35-61.
- Yakhot V, Orszag SA. Renormalization group analysis of turbulence. I. Basic theory. *Journal of Scientific Computing* 1986;1(1):3-51.
- Yusuf F, Micovic Z. Prototype-scale investigation of spillway cavitation damage and numerical modeling of mitigation options. *Journal of Hydraulic Engineering* 2020;146(2):Article No. 04019057.
- Yu L, Han M, He F. A review of treating oily wastewater. *Arabian Journal of Chemistry* 2017;10:1913-22.

Analyzing the Seasonal Relationship between Vegetation Variation and Land Surface Temperature Dynamics in Eastern Maharashtra

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ABSTRACT

Understanding land surface temperature (LST) change trend is very important in Eastern part of Maharashtra state, India as this region is undergoing rapid land-use change. Vegetation plays a critical role in regulating land surface temperature in such region. The main objective of this study is to analyze the vegetation change trend and investigate the seasonal relationship between vegetation variation and land surface temperature fluctuation from the years 2014 to 2022. Using Landsat 8 satellite imagery, the Normalized Difference Vegetation Index (NDVI) is derived to monitor vegetation variation and thermal infrared (TIR) bands is used to calculate LST. The methodology is divided into data collection, preprocessing, NDVI and LST calculation. Based on NDVI and adaptive vegetation classification, land use (LU) classification is carried out and finally correlation analysis between the various classes of LU, NDVI value with LST is calculated. The results suggest a clear seasonal pattern where the post-monsoon period has higher average NDVI values and lower average LST values as compared to the pre-monsoon periods. There was a declining trend of overall vegetation health throughout the study period, although 2022 showed a slight recovery in pre-season NDVI and improved vegetative health in post-monsoon dense vegetation classes. Correlation analyses consistently indicated a moderate-strong negative association (~ -0.2 to -0.5) of LST with vegetation cover (vegetation cooling effect) and a positive association (~ 0.1 to 0.5) with built-up areas (urban heat island effect). It highlights the importance of vegetation cover for local temperature management and has significant implications for the assessment of recent changes in the local environment.

HIGHLIGHTS

- Seasonal NDVI-LST dynamics were assessed using multi-temporal Landsat-8 data from 2014 to 2022.
- Adaptive NDVI percentile classification captured seasonal vegetation variability effectively.
- Post-monsoon periods showed higher NDVI values with consistently lower surface temperatures.
- NDVI showed a strong negative correlation with LST, confirming cooling effects.

1. INTRODUCTION

Ecologists and environmental scientists have consistently raised concern about global warming and its far-reaching effects (Li et al., 2025). Global warming leads to a temperature rise, which in turn causes the melting of glaciers, a rise in seawater levels, etc. (Venkataramanan and Smitha, 2011). While examining the adverse consequences of global warming, it is equally essential to analyze its anthropogenic and natural drivers. Out of all the driving factors, loss of vegetation is the primary cause of global warming

(Longobardi et al., 2016). Plants and forests are crucial in regulating the Earth's weather patterns, as they absorb carbon dioxide from the air through photosynthesis and act as a carbon sink (Nassif et al., 2023). Expanding urban areas, infrastructure development, industrialization, and deforestation have had severe consequences on vegetation cover locally as well as globally (Pawade and Patil, 2025; Zhan et al., 2013). From an environmental perspective, this mechanism leads to massive imbalances within local ecosystems while limiting the planet's natural ability to

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capture carbon emissions (Psistaki et al., 2024). Moreover, this phenomenon simultaneously affects land surface temperature (LST) (Li et al., 2023). Through evapotranspiration, vegetation helps to moderate the land surface temperature. Evapotranspiration is a combination of two processes: evaporation of land water into vapor and transpiration, where water vapor is released from plants during photosynthesis. The vegetation loss diminishes the natural cooling mechanism, resulting in increased heat absorption by bare soil and built-up surfaces, which typically have lower albedo and higher heat retention (Islam et al., 2024). Consequently, areas with sparse vegetation tend to experience significantly higher land surface temperatures, especially during the day (Wei et al., 2025).

Many studies have been done focusing on local as well as global changes in the temperature and its driving factors (Bandh et al., 2021; De Frenne et al., 2021; Yuxi et al., 2024). In that regard, (Rahimi et al., 2025) derived the global correlation between Normalized Difference Vegetation Index (NDVI) and LST, using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. While offering valuable global insights, the research identifies the need for higher-resolution data, an understanding of seasonal variations, and the assessment of extreme climate event impacts to provide better analysis. (Kumar and Shekhar, 2015) investigated the similar relationship for Kalaburagi City, India. Finding highlighted a negative correlation with green spaces and a positive correlation with the Normalized Difference Build-up Index (NDBI). The study acknowledged the unavailability of in-situ LST measurements as limitation. Another study (Ullah et al., 2023) comprehensively analyzes the relationships between LST, Land Use Land Cover (LULC), NDVI, and topographic elements in the Lower Himalayan region. This study is focused on a multi-dimensional spatial analysis. The key finding underscores the relationship between elevation and LST. The LST decreases with elevation while built-up areas exhibiting the highest LST. LULC misclassification errors inherent by Maximum Likelihood Classification (MLC) method hampered the accuracy for few classes, despite its overall good accuracy. Researchers (Alademomi et al., 2022) further investigated the interrelationship between LST, NDVI, NDBI, and land cover changes in Amuwo-Odofin, Lagos, Nigeria, using Landsat imagery from 2002 to 2019. The study showed a negative correlation

between LST and NDVI and between NDVI and NDBI. The analysis revealed that the NDVI and LST changes are driven by the built-up area expansion. (Ferreira and Duarte, 2019) studied the correlation of urban morphology (Local Climate Zones (LCZ)) and LST in Sao Paulo. The study revealed an inverse relationship between day and night LST with vegetation. It also emphasised that building area and impervious surface have a positive relationship with LST at night, but pervious surface is negatively related. This study has effectively operationalized LCZ in a subtropical context and provides key lessons for the climate-sensitive urban design. Yet the accuracy of the LCZ map was 68% but several LCZ classes were estimated with much error which could lead to biased correlation findings. Zhibin et al. (2015) demonstrate the effect of spatial arrangement of urban greenery on LST. The study suggests that even the green patches are not increased in number but greater aggregation and cohesion of vegetation patches reduce the LST. Anbazhagan and Paramasivam (2016) explored the statistical relationship between LST and NDVI in India's Salem magnesite mining zone, using Landsat TM data from 1992, 2001, and 2010. Their key contribution revealing an inverse correlation where increased emissivity coincided with negative NDVI anomalies. B values for NDVI and LST were consistently negative across the all the years studied (-0.209 in 1992, -0.143 in 2001, and -0.190 in 2010), confirming high LSTs in mining areas due to sparse vegetation and high soil emissivity. Anbazhagan and Paramasivam (2016) validated the satellite-derived LST results against India Meteorological Department (IMD) ground observations. This study does not address the effects of variables such as rain, urbanization on NDVI. The paper by Zhan et al. (2013) critically reviews disaggregation of LST, identifying Thermal Sharpening (TSP) and Temperature Unmixing (TUM) as primary subtopics. A key contribution is its comprehensive taxonomic classification of existing research and insights into future research directions. However, limitations include the field's disorderly development, a lack of citation for foundational works, and challenges arising from unrealistic assumptions regarding surface properties and aggregation patterns, which collectively hinder algorithm improvement and the accuracy of disaggregated LST products.

While numerous studies assess the association between vegetation indices (VI) and land surface

temperature (LST), most work is constrained by fine-resolution data, limited temporal coverage or a single season analysis especially in monsoon-dominated regions. Further, long-term and seasonally-specific investigation on the mining and urbanization affected landscapes of eastern Maharashtra is still limited. This study fills this gap by applying a multi-temporal (2014-2022) vegetation dynamics and LST analysis over part of eastern Maharashtra which is not yet considered for study, with an explicit separation of the pre- and post-monsoon stages.

The eastern part of Maharashtra, particularly around Chandrapur, comprises a diverse and resource-rich landscape, including a wildlife sanctuary, extensive forest cover, mining zones, urban and rural settlements, etc. This area has undergone extensive ecological transformations over the past few decades, largely due to mining, industrialization, urbanization, etc. Therefore, a thorough investigation is required to analyze the correlation between the vegetation cover changes and the LST dynamics. These statistical insights will be advantageous for formulating effective strategies for future vegetation ecosystem restoration and management planning. This study aims to assess the trend of vegetation change and its temperature implication in the Eastern Maharashtra region (2014-2022). The novelty of the study is to apply LULC transition analysis combined with adaptive NDVI-based vegetation classification for studying vegetation-temperature dynamics. Based on combination of seasonal NDVI, LST and land-use classes, the vegetation cooling effect is characterized specifically for the region and urban heat dynamics. The study advances the knowledge of surface temperature and vegetation interaction within the research area. The primary objectives are to

1. Evaluate the seasonal variation in vegetation dynamics using NDVI
2. Compute the change in LST between 2014-2022
3. Estimate the correlation between vegetation and LST fluctuation for the study area over the period, considering seasonal variation

These objectives lay the foundation for the following hypothesis:

H_0 : There is a negative relationship between vegetation changes and LST variations during the study period.

H_1 : There is a no/positive correlation between vegetation dynamics and LST over the study period.

The major contribution of this study is to analyze temporal variation in vegetation and assess their potential correlation with fluctuations in LST for the study area during pre- and post-monsoon seasons.

2. METHODOLOGY

Figure 1 shows the high-level implementation overview of the proposed workflow. For the time series analysis of the vegetation and LST change detection, Landsat 8 OLI satellite images are retrieved from the Google Earth Engine (Kumar and Mutanga, 2018). The initial phase of the study involves defining the spatial and temporal parameters. The spatial parameters include selection of the study area, and the temporal parameter includes selection of study duration.

The study area shown in Figure 2, includes the eastern part of the Maharashtra state bounded by 19°40'48" N to 20°18'1" N latitude and longitude from 78° 52' 12" E to 79° 37' 48" E, which is imported by considering a geospatial boundary from Google Earth Engine. Concurrently, the temporal window is established between 2014-2022 with an interval of 4 years.

Vegetation and surface temperature behaviour differ for post- and pre-monsoon seasons (Sinha et al., 2019). Hence, to capture medium-term changes, GEE's Landsat 8 Surface Reflectance Tier 1 Image Collection images for the month of May are considered for pre-monsoon analysis, while November images are considered for post-monsoon analysis. Table 1 gives the detailed information about the collected Landsat 8 images. The area of interest is delimited by the study area boundary polygon. These satellite images undergo various pre-processing techniques like Filtering, Radiometric Correction, Spectral Band selection, NDVI calculation, Mosaicking.

Landsat-8 Collection-2 Tier-1 Surface Reflectance imagery, used for this study incorporates Land Surface Reflectance Code based atmospheric correction scheme. This corrects the effects of atmospheric gases, aerosols, and water vapor using auxiliary atmospheric data. This preprocessing step ensures radiometric consistency across multi-temporal observations and is particularly suitable for long-term vegetation and surface temperature analysis. Radiometric calibration is applied to convert the raw digital numbers (DN) into top-of-atmosphere (TOA) reflectance. Pixel-level quality control was performed using the QA_PIXEL band. QA_PIXEL band is a bit-encoded quality assurance layer that flags cloud, cloud

shadow, and cirrus contamination. Cloud-affected pixels were identified through bitwise evaluation of cirrus (bit 2), cloud shadow (bit 3), and high-confidence cloud flags (bit 5) and were excluded from further analysis. Based on these criteria, a binary cloud mask $M(x)$ indicated by Equation 1 was generated for each pixel x , retaining only clear-sky observations and

thereby minimizing atmospheric artefacts. This mask minimizes cloud-induced radiometric distortion. This conservative masking strategy is particularly important for monsoon-affected regions such as eastern Maharashtra, where residual cloud contamination can significantly bias surface reflectance and land surface temperature estimates.

$$M(x) = \begin{cases} 1 & \text{if bits cirrus (bit 2), shadow (bit 3), and cloud (bit 5) all are 0} \\ 0 & \text{Otherwise} \end{cases} \quad (1)$$

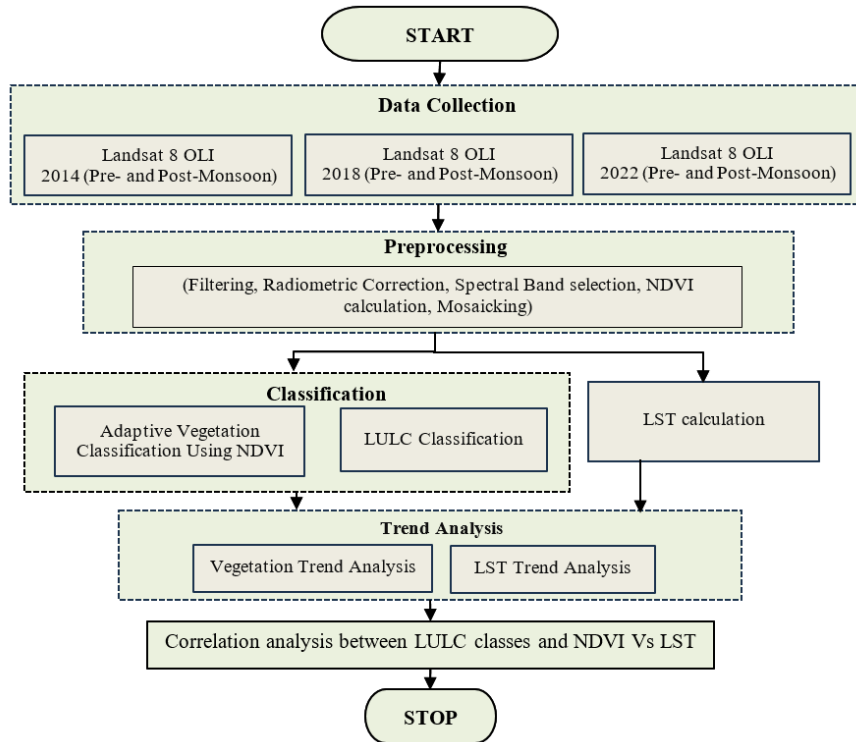


Figure 1. Overview of implementation

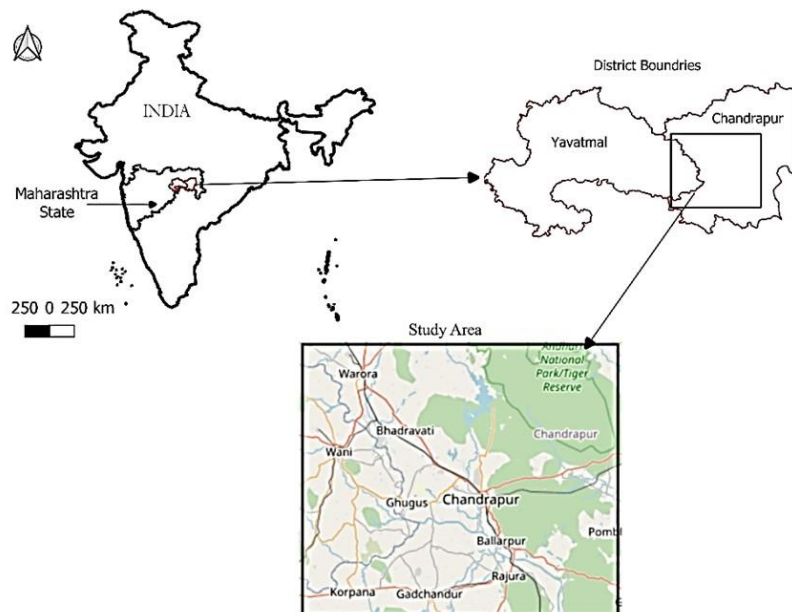


Figure 2. Study area covering eastern part of the Maharashtra state

Table 1. Data description of Landsat 8 remote sensing data acquired for study area

Season	Year	Date of acquisition	Path-row	Resolution of visible and near infrared band (m)	Resolution of TIR (m)
Pre-Monsoon	2014	2014-05-11	143-045	30	100
Post-Monsoon	2014	2014-11-19	143-045	30	100
Pre-Monsoon	2018	2018-05-13	143-045	30	100
Post-Monsoon	2018	2018-11-14	143-045	30	100
Pre-Monsoon	2022	2022-05-17	143-045	30	100
Post-Monsoon	2022	2022-11-16	143-045	30	100

This excludes pixels of the mask and improves data quality for further analysis. To cover the large study area, through mosaicking images are stitched together to provide complete study area. Landsat 8 imagery has total 11 bands and each band contain the specific information. For the study, careful band selection is carried out and specific spectral bands like band 4 (red), band 5 (near-infrared (NIR)), and band 10 (the thermal infrared (TIR)) are extracted. The TIR band is used for estimating Land Surface Temperature (LST), while the reflectance of red and NIR bands are used to calculate Normalized Difference Vegetation Index (NDVI), which is utilized to estimate the vegetation cover. Equation 2 is used to calculate the NDVI index (Hutayanon and Somprasong, 2023). Later, NDVI is stacked as a new band in the image.

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (2)$$

Where; NIR: Reflectance of the NIR band; RED: Reflectance of the Red Band.

The value of NDVI ranges between -1 and +1. The non-positive NDVI value is indicative of a non-vegetated surface, while a positive value corresponds to the vegetated area (Garai et al., 2022). The increasing value of NDVI reflects greater vegetation density (Gandhi et al., 2015).

Equation 3 specifies the criteria to perform adaptive classification using NDVI values. Adaptive classification applies percentile-based thresholds to classify vegetation into categories such as no vegetation, sparse, moderate, and dense cover. The method allows context-sensitive interpretation that adjusts to each image's NDVI distribution.

$$C(x,y) = \begin{cases} C1 & \text{if } NDVI(x,y) \leq P_{10} \\ C2 & \text{if } P_{10} < NDVI(x,y) \leq P_{50} \\ C3 & \text{if } P_{50} < NDVI(x,y) \leq P_{85} \\ C4 & \text{if } NDVI(x,y) > P_{85} \end{cases} \quad (3)$$

Where; C(x,y): Classified output at pixel (x,y); NDVI(x,y): NDVI value at Pixel (x,y); P₁₀, P₅₀, P₈₅: 10th, 50th, 85th percentiles of the NDVI array; C1: No vegetation class, C2: Sparse vegetation Class, C3: Moderate vegetation Class, and C4: Dense vegetation class.

This NDVI value is further used for land use classification and classified the region in three classes namely Water, Vegetation and Built-up land. Equation 4 represents the classification function L(x,y).

$$L(x,y) = \begin{cases} 1 & \text{if } NDVI(x,y) < 0 \quad (\text{Water}) \\ 2 & \text{if } NDVI(x,y) > 0.2 \quad (\text{Built-up}) \\ 3 & \text{if } 0 \leq NDVI(x,y) \leq 0.2 \quad (\text{Vegetation}) \\ NaN & \text{if } NDVI(x,y) = \text{Undefined or masked value} \end{cases} \quad (4)$$

Where; NDVI(x, y) ∈ R denotes the NDVI at the spatial location (x, y). R is a set of real number. L(x, y) ∈ {1, 2, 3} ∪ {NaN}, denotes land use function where 1 represents water, 2 represents vegetation, 3 represents built-up / bare Land, NaN indicates undefined or masked values.

Further, the land surface temperature is calculated using the TIR band (García-Santos et al., 2018). The emitted thermal radiations are represented by the pixel-level digital numbers (DN) of this band. After calibration, these DNs are converted into the surface temperature values using a scale factor and additive offset. This transformation is applied using Equation 5.

$$LST_{KELVIN} = (T_B10 \times \text{Scale_Factor}) + \text{Offset} \quad (5)$$

Where; ST_B10: Landsat 8 satellite images's Band 10 pixel value represented as digital number. Scale_Factor=0.00341802; Offset =149.0.

The scale factor adjusts the magnitude of DN to align with radiometric calibration, while the offset corrects the baseline to reflect absolute temperature values. Once the temperature values in Kelvin are obtained, they are converted to degrees Celsius using Equation 6.

$$LST_{\text{Celsius}} = LST_{\text{KELVIN}} - 273,15 \quad (6)$$

To understand the correlation between various land covers and LST, correlation is calculated using Equation 7.

$$C_r = \frac{\text{Cov}(a,b)}{\sigma_a \sigma_b} \quad (7)$$

Where; a: the land class value array; b: LST value arrays; Cov(X,Y): the covariance between land cover class and LST; σ_a, σ_b : the standard deviations of land cover class and LST respectively.

The present study relies exclusively on data derived from the Landsat 8 satellite imagery. No in-situ temperature measurements, field-based vegetation assessments, or meteorological station records were available for direct validation of the NDVI and LST products used in this analysis. Hence to explore sensor or algorithm-dependent bias, a cross-sensor evaluation is carried out with MODIS land surface temperature products (Meshesha et al., 2024). The MODIS MOD11A2 data set provides 8 days composite daytime LST at 1 km spatial resolution, retrieved using a split-window algorithm, and was used as an independent reference to assess the robustness of the Landsat-derived LST estimates. LST of Landsat 8 was acquired from its thermal infrared band using a single-

channel method, then resampled and aggregated spatially to the MODIS scale (1 km) in order to minimize the differences caused by scales. A pixel-wise statistical comparison was carried out over the entire study area for a pre-monsoon period (May 2022). The corresponding Pearson correlation coefficient was 0.72, representing a strong positive linear relationship and the presence of high-level consistency in spatial temperature patterns among sensors. The average bias was 1.6°C point out a small systematic shift and Landsat-derived LST values are slightly higher on average. The RMSE of 2.4°C belongs to the uncertainties that are frequently reported for cross-sensor LST comparisons. Taken together, these statistics enforce that the LST estimates derived from Landsat data are not dominated by sensor or algorithm specific artifacts and provide confidence in their use for subsequent NDVI-LST relationship analysis.

3. RESULTS AND DISCUSSION

The first objective of this study is to analyse the vegetation dynamics from 2014 to 2022 using the vegetation index. Figure 3 represents the NDVI analysis for the study area for pre- and post-monsoon seasons.

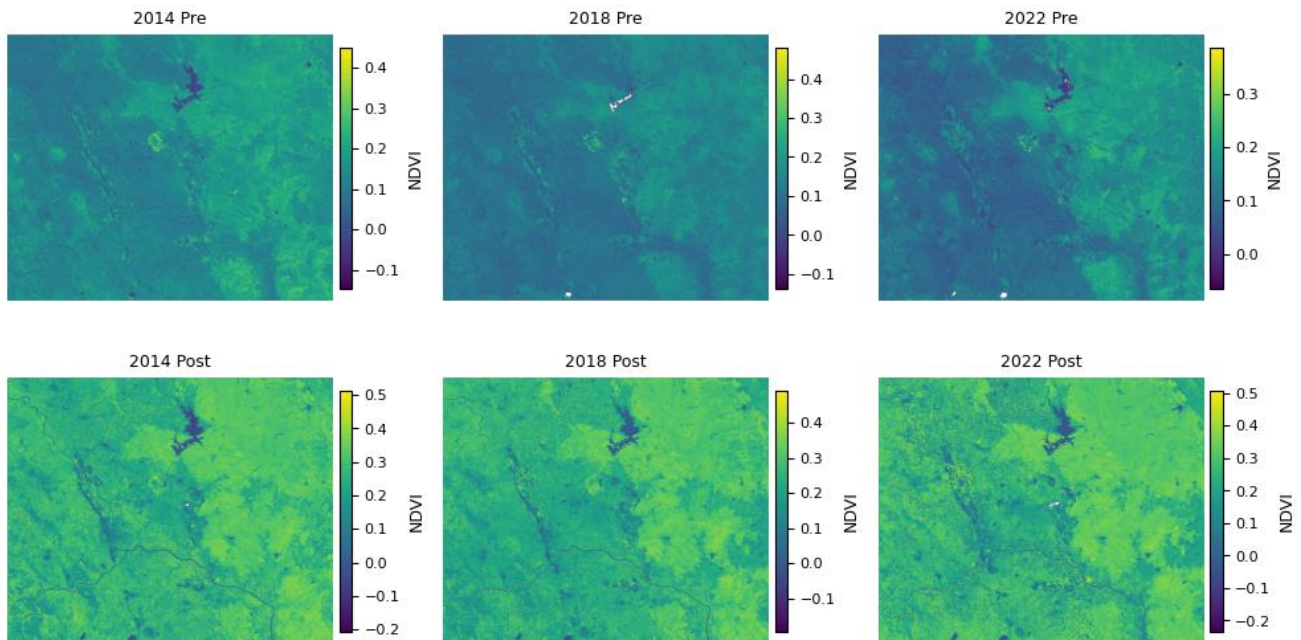


Figure 3. NDVI map for the study area for the year 2014, 2018, and 2022

The statistical NDVI information derived from remote sensing data for the post-monsoon and pre-monsoon periods for the years 2014, 2018, and 2022

is included in Table 2. For each year, the average, minimum, and maximum values for the pre- and post-monsoon periods are considered for further analysis.

The average NDVI value for the pre-monsoon was 0.145810 (range: -0.146479 to 0.450364) in 2014, and the average NDVI value for the post-monsoon was 0.264453 (range: -0.205797 to 0.5131). In 2018, the pre-monsoon NDVI mean was 0.121021 (range: -0.136576 to 0.480856), and the post-monsoon NDVI mean increased to 0.246208 (range: -0.194962 to 0.491923) similarly. In 2022, the NDVI value was averaged to 0.127531 (range: -0.064556 to 0.386672) during the pre-monsoon period and 0.255649 (range: -0.233793 to 0.508318) during the post-monsoon period. Across all three years, average NDVI values during post-monsoon are consistently higher than their pre-monsoon counterparts. This observation justifies the natural vegetation trend of a rise in the sprawl following the monsoon season.

Figure 4 give details about the temporal analysis of vegetation change dynamics based on average

NDVI value for years 2014, 2018, and 2022 during pre- and post-monsoon season.

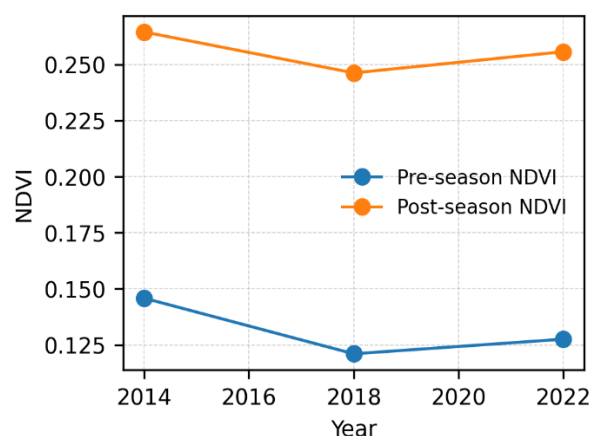


Figure 4. Average NDVI pre Vs post monsoon season analysis from 2014 to 2022

Table 2. Statistical comparison of pre- and post-monsoon NDVI values

Year	Pre-Monsoon				Post-Monsoon			
	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation
2014	0.450364	-0.146479	0.145810	0.049396	0.513100	-0.205797	0.264453	0.071778
2018	0.480856	-0.136576	0.121021	0.038752	0.491923	-0.194962	0.246208	0.066222
2022	0.386672	-0.064556	0.127531	0.045665	0.508318	-0.233793	0.255649	0.083301

The pre-season NDVI, representing vegetation conditions before the growing season, shows a noticeable decline in 2018, followed by a slight recovery in 2022. This trend suggests increasing environmental stress during this period. The post-season NDVI, indicating the status of vegetation after the monsoon season, exhibits a constant decline. Though post-season NDVI values are higher than pre-season values (in accordance with seasonal growth), the overall decrease in both indicates a decrease of vegetation productivity and health over time. Such a decline could be related to reasons like land degradation, climatic stress, and agricultural intensification. A decreasing trend in the difference between pre- and post-season NDVI implies decreasing seasonal vegetative cover recovery, which may affect ecosystem functions like soil retention, evapotranspiration, and carbon storage.

The adaptive NDVI percentile value-based classification maps for the years 2014, 2018, and 2022, shown in Figure 5, use a consistent colour scheme to highlight spatial and temporal patterns of

vegetation cover. Context-sensitive assessments of vegetation cover are possible using dynamic percentile thresholds (P10, P50, and P85) based on vegetation classification. Seasonal transitions are distinctly highlighted in all three years, where sparse to moderate vegetation dominates during pre-monsoon periods with considerable areas devoid of vegetation cover, which was predominant in 2014 and 2022. Post-monsoon maps show substantial increases in moderate and dense vegetation classes compared to pre-monsoon sparse vegetation dominance. Also, the landscape greening observed from pre- to post-monsoon periods is supported by significant rises in percentile value such as P50 and P85. As depicted in Figure 5, the extended range of dense vegetation compared to moderate vegetation observed in the 2022 map indicates improved vegetative health for that year, likely due to better land management. These maps emphasize interannual variability with intraseasonal change while demonstrating adaptive classification's advantages for monitoring dynamics of vegetation cover over time.

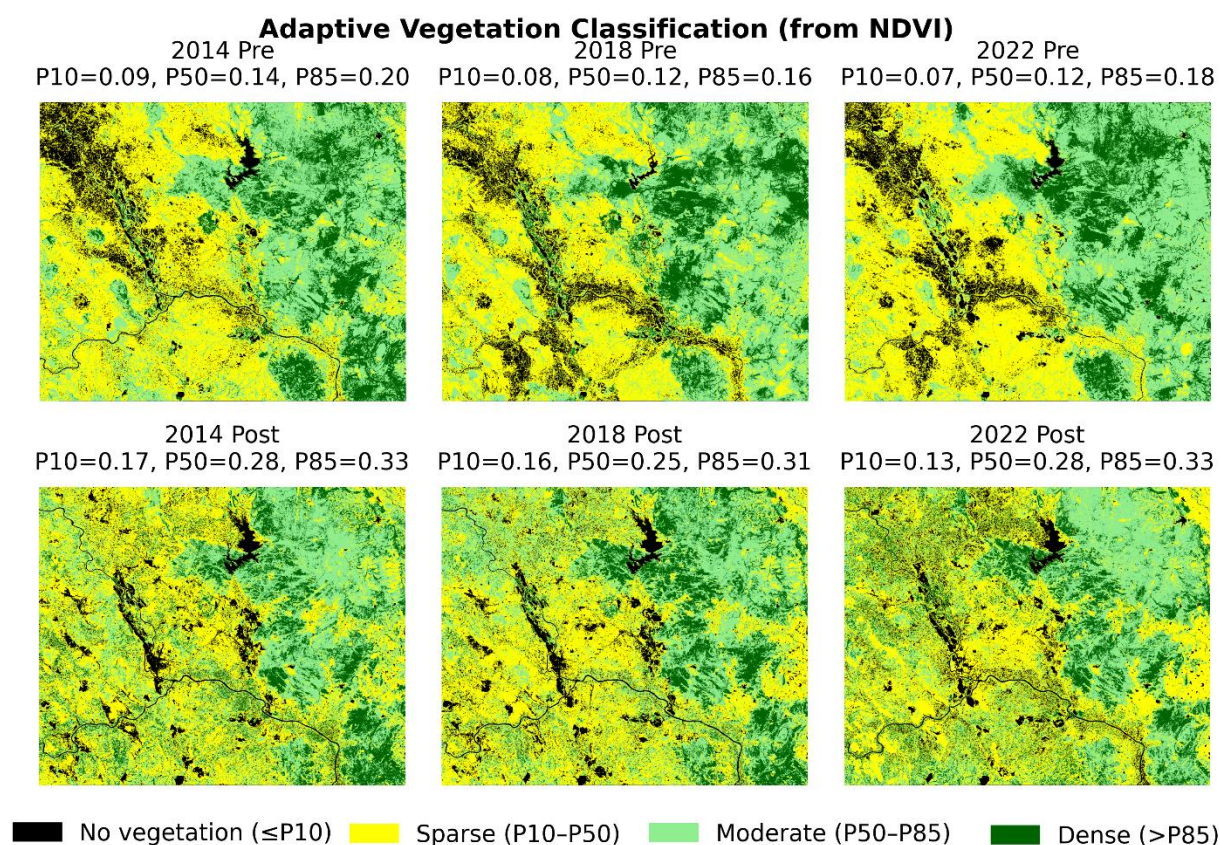


Figure 5. Vegetation distribution analysis using NDVI based adaptive classification for the years 2014, 2018, and 2022

This spatial interpretation of vegetation dynamics is further supported by the transition matrices shown in Figure 6. It quantifies changes in different vegetation classes from pre- to post-monsoon seasons. This helps in understanding the extent of vegetation cover change across years. For all three

years, the common pattern is followed where a large part of the low vegetation area during the pre-monsoon turns into a moderate vegetation area post-monsoon. In 2014, 47.0% of the region was converted from low to moderate vegetation.

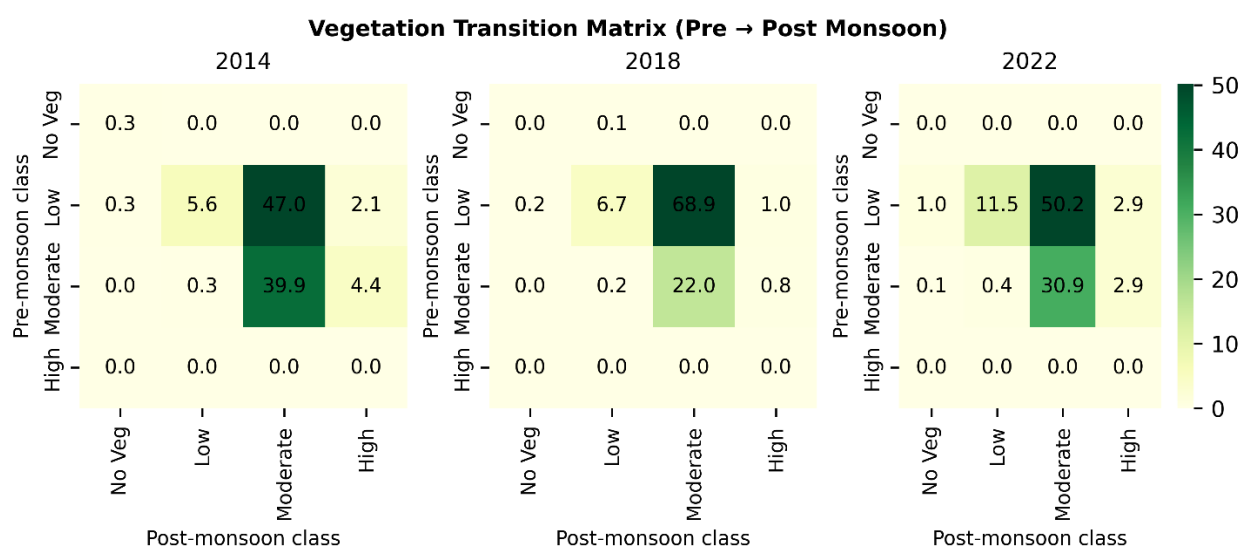


Figure 6. Year wise pre vs post monsoon transition matrix for different vegetation classes

The conversion level improved in 2018 and showed a 68.9% transition from low to moderate vegetation, representing a more intense greening effect. The year 2022 has also shown a strong low-to-moderate transition (50.2%) and an interesting appearance of 2.9% transitioning from moderate to high vegetation, which was very low in 2018. Overall, these matrices confirm the expected seasonal vegetation dynamics, where NDVI values increase after the monsoon, and also highlight an encouraging shift in 2022 toward higher vegetation classes.

To understand transition of vegetation class with other LULC classes, LULC classification is carried out. As mention in the [Table 3](#), overall accuracy of the LULC classification was 89.04% and Kappa coefficient was 0.86, indicating strong agreement. Vegetation and water classes are highly reliable, whereas the user's accuracy for the built-up class is lower indicating it's confusion with bare land and sparsely vegetated areas. This may add some noise to NDVI based classification but does not affect the general seasonal trend.

Table 3. Accuracy assessment for LULC classification

Class	User's accuracy (%)	Producer's accuracy (%)
Vegetation	88.70	90.21
Built up	84.64	87.01
Water	90.42	92.36
Overall accuracy (%)	89.04	
Kppa coefficient	0.86	

[Figure 7](#) presents pre- and post-monsoon LULC transitions for the years 2014, 2018, and 2022, expressed as a percentage change. A substantial proportion of built-up land areas identified during the pre-monsoon season transition to the vegetation class

in the post-monsoon period across all three years (68.95% in 2014, 75.27% in 2018, and 71.18% in 2022). This shift reflects a pronounced post-monsoon greening effect rather than actual anthropogenic land-cover change.

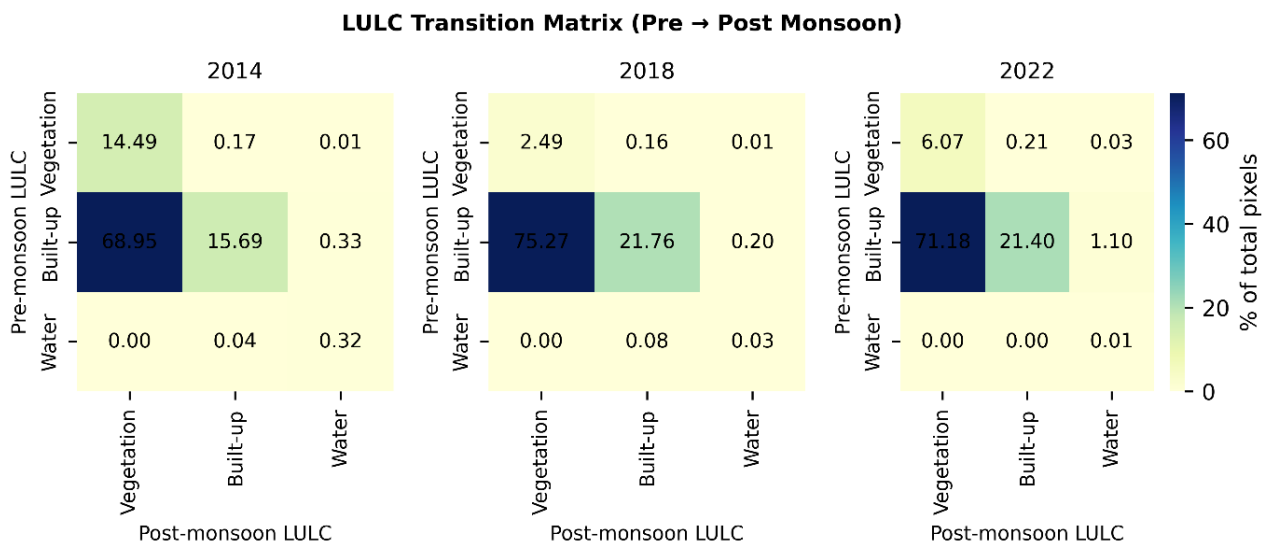


Figure 7. Year wise pre vs post monsoon transition matrix for different LULC classes

The overall vegetation analysis ascertains that in monsoon-influenced environments, seasonal vegetation growth over bare soils, mining spoils, road margins, and peri-urban vacant land increases surface greenness and leads to spectral mixing at the 30 m spatial resolution of Landsat. Consequently, mixed

pixels containing impervious surfaces partially obscured by seasonal vegetation are frequently misclassified as vegetation during the post-monsoon season. This phenomenon represents seasonality-driven vegetation obscuration of built-up surfaces and is a well-documented limitation in medium-resolution

optical remote sensing analyses (Arij et al., 2025). The low values for the Water class to/from status in all years indicate stable water bodies. The vegetation-to-vegetation class change is especially important, moving from 14.49% in 2014 to 2.49% in 2018, to then increase back to 6.07% in 2022, which suggests the temporal variability of the persistence of vegetal cover, probably. Investigations into the underlying climatic or anthropogenic factors responsible for the temporal pattern are therefore necessary.

The identified interannual trend in NDVI, for the period 2014-2018, is indicative of anthropogenic activity and other climatic drivers (Rahimi et al., 2025; Zhang et al., 2022). The increasing mining activities, industrial infrastructure and expanded urbanization have transformed the vegetated area into built-up and bare land. This observed a trend in study area has been regularly recorded in mineral-dominated and rapidly developing landscapes (Anbazhagan and Paramasivam, 2016). These changes of land cover decrease the grass cover, exposing the surface for

evapotranspiration and promote the rise in LST (Zhibin et al., 2015; Ferreira and Duarte, 2019). Moreover, frequent pre-monsoon heat stress limits the vegetation growth (Nassif et al., 2023; Sinha et al., 2019). This act as strong evidence for the finding for this study stating vegetation declination and LST rise in pre-monsoon season. Despite the fact that post-monsoon NDVI values are higher than pre-monsoon ones because of season-based greening, such a steady long-term decrease suggests a slow deterioration in vegetation productivity and ecosystem resilience (Psistaki et al., 2024). The partial recovery in 2022, especially in dense vegetation classes, might be owing to favourable monsoon conditions and local land administration practices but even such short-term improvements are not enough to counteract the long-term degradation (Gandhi et al., 2015; Ullah et al., 2023). Moreover, frequent pre-monsoon heat stress and enhanced variability in rainfall restrict growth of vegetation while keeping a check on the seasonal recovery as well (Nassif et al., 2023; Sinha et al., 2019).

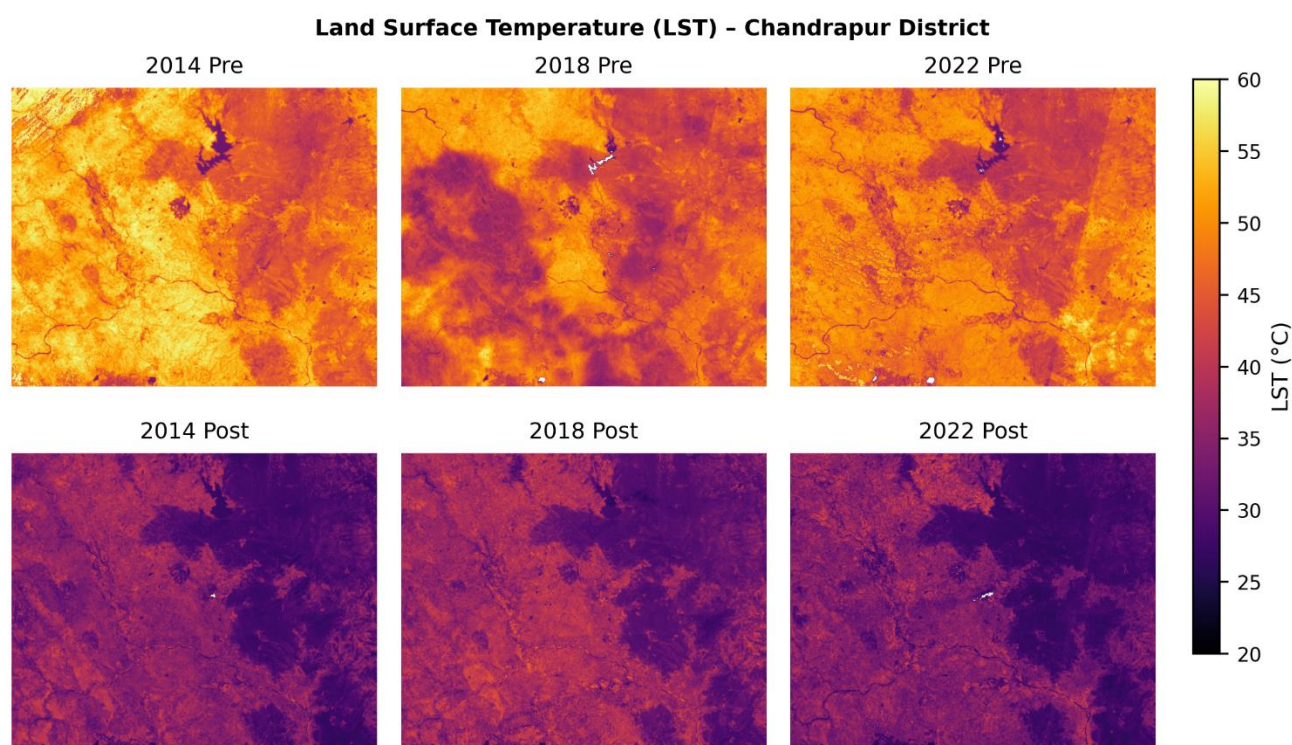


Figure 8. LST map for the study area for the years 2014, 2018, and 2022

The objective 2 focuses on computing LST. Figure 8 represents the LST map for the study area, while Table 4 presents statistics for the average, the minimum, and the maximum pre-monsoon-post-monsoon LST for 2014, 2018, and 2022. The average LST for the pre-monsoon in 2014 was 49.73 (range:

26.09-63.84) and for the post-monsoon average was lower than that, at 33.24°C (range: 23.91°C-48.42°C). In 2018 the same trend was followed: pre-monsoon mean LST was 44.70°C (range: 28.82°C-59.87°C), which reduced in post-monsoon to 35.20°C (range: 3.98°C-50.30°C). In 2022, the pre-monsoon mean was

46.91°C (range: 22.78°C-60.22°C), and post-monsoon decreased to 32.21 (range: 25.02°C-47.47°C). Between the three years, post-monsoon mean LST is

always less than pre-monsoon mean LST. This means there has been a significant decrease in LST following the monsoon season.

Table 4. Statistical comparison of pre- and post-monsoon LST values

Year	Pre-monsoon LST (°C)				Post-monsoon LST (°C)			
	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation
2014	63.84	26.09	49.73	4.86	48.41	23.91	33.24	3.66
2018	59.87	28.82	44.70	4.49	50.30	3.98	35.20	3.81
2022	60.22	22.78	46.91	3.93	47.47	25.02	32.21	3.68

Figure 9 shows a time series analysis of LST for 2014, 2018, and 2022 and depicts the comparison of the LST just before and just after monsoon. The pre-season LST in 2014 was high, hinting that the ground was much hotter than usual for that stage of the year. By 2018 that same early figure dropped, pointing to a brief cooling spell probably linked to kinder weather. Yet 2022 brought the pre-season LST back up, suggesting renewed heating likely caused by tree loss, spread of pavement, and other signs of growing development. The post-monsoon LST creeps up in both 2014 and 2018 before sliding down in 2022.

Even so, every year, the early-season temperature is still above the late-season figures by a healthy margin. That pattern fits what we expect—gaps in vegetation at the start of the season let sunlight warm the ground more, while denser post-season plants cool things down through evaporation. Oddly though, those post-season readings in 2014 and 2018 lingered a bit above the long-term average before the slight drop seen in 2022.

The third study objective is inclined toward investigating the potential relationship between vegetation change and land surface temperature fluctuation over the study period. Table 5 presents the relation between land cover classes and LST by considering the correlation of LST with land cover classes (water, vegetation, and built-up) and the overall correlation of NDVI-LST for the pre-monsoon and post-monsoon seasons for 2014, 2018, and 2022. Vegetation cover has a consistently moderate to strong negative relationship with LST, indicating the cooling effects due to evapotranspiration. The urban buildup and LST showed a positive correlation with higher surface temperatures in built-up areas, indicating the urban heat island effect. Water does exhibit weak negative correlations, which may result from localized extents or mixed pixels. The overall correlation of NDVI-LST is still strongly negative, indicating that increased vegetation density is correlated with reduced surface temperature.

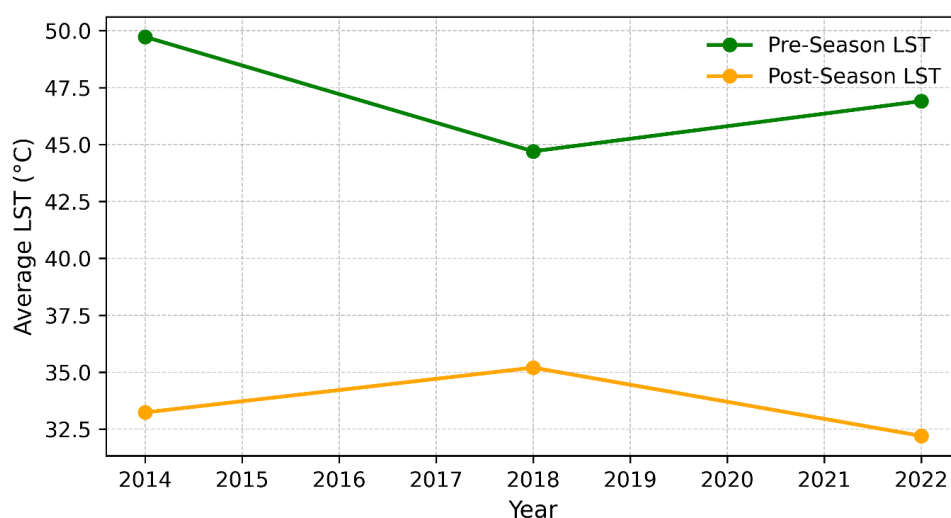


Figure 9. Average LST pre- Vs post-monsoon season analysis from 2014 to 2022

Table 5. LST Correlation between LULC classes and overall NDVI values for pre and post monsoon season

Season-year	Water vs. LST correlation	Vegetation vs. LST correlation	Built-up vs. LST correlation	Overall NDVI vs. LST correlation
Pre-monsoon 2014	-0.170594	-0.446206	0.470401	-0.603048
Post-monsoon 2014	-0.113006	-0.382907	0.414315	-0.557735
Pre-monsoon 2018	-0.060394	-0.143083	0.152460	-0.253942
Post-monsoon 2018	-0.058556	-0.411356	0.420279	-0.569535
Pre-monsoon 2022	-0.019580	-0.313470	0.314058	-0.513839
Post-monsoon 2022	-0.127817	-0.457682	0.500331	-0.530829

This observed inverse pattern does support the null hypothesis (H_0), which states that higher levels of vegetation lead to decreasing LST and vice versa. The results shows empirical evidence that the change in vegetation causes cooling of the surface temperature in the study area. We reject the alternative hypothesis (H_1), which says there is a positive relationship.

These findings have direct policy relevance, underscoring the need for vegetation-centered land-use planning, afforestation initiatives, mine reclamation strategies, and the integration of green infrastructure into regional development frameworks. The results provide a quantitative basis for promoting nature-based solutions aimed at mitigating heat stress and enhancing climate resilience in rapidly transforming landscapes.

4. LIMITATIONS AND FUTURE DISCUSSION

A key limitation of this study is the absence of ground-based or station-based validation data. NDVI and LST estimates were derived solely from Landsat 8 satellite imagery, and no site-specific land temperature observations, field-based vegetation measurements, or meteorological station records were available for direct verification. This limitation may introduce uncertainty in the absolute accuracy of the NDVI values. Despite this limitation, satellite-derived NDVI and LST products have been extensively validated in previous studies and are widely accepted for regional-scale environmental monitoring and trend analysis.

Future extensions of this work will aim to integrate meteorological station air temperature data, field-based vegetation indicators to further strengthen confidence in absolute estimates. The current study is based on the 30m spatial resolution imagery which may contribute to mixed pixels, and classification errors. In future finer spatial resolution can be used for better results.

5. CONCLUSION

The present study analysed vegetation dynamics and land surface temperature change taking place in Eastern Maharashtra during the period of 2014-2022 with the help of Landsat 8 imagery queried from Google Earth Engine. Inline to the first study objective, the results consistently reveal the higher average NDVI values of post-monsoon periods that yield lower LSTs than pre-monsoon periods, reconfirming the seasonally predictable growth patterns and the cooling nature of vegetation. Although a general pattern of negative vegetation productivity and health over the study period was observed, but as per the [Figure 5](#) a remarkable improvement of dense vegetation classes was observed in 2022, possibly a positive influence resulting from improved land management or favourable climatic conditions. Addressing Objective 2, the temporal assessment of LST revealed a clear seasonal and interannual variability over the study period. Consistent with objective 3, the correlation test supported the null hypothesis (H_0) and showed a negative moderate to strong relationship between NDVI and LST, thus emphasizing the important role of transpiration in mitigating surface temperatures. In contrast, the built-up land areas were positively correlated with LST, reflecting the urban heat island effects. The transition matrices were informative as to discovering land cover changes, although this did pose questions about possible spectral confusion. This study provides insight into the vegetation-thermal environment relationship at a regional scale in a tropical area, which gives important insights for environmental monitoring and management strategy in such regions. Future investigations could entail integrating more climatic variables, seeking out finer spatial-temporal scales, and conducting more localized studies to identify specific anthropogenic and natural drivers of observed changes.

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AUTHOR CONTRIBUTIONS

All authors agreed on the content of the study. Dipti Pawade (DP) and Sonali Patil (SP) conceptualized the initial research concept and plan of intervention. DP and SP cooperatively did the literature search and conceived the design and methodology of the study. DP carried out the data collection and did the analysis. DP and SP collectively interpreted the results as well as prepared, edited, reviewed, and approved the manuscript.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no competing interests.

REFERENCES

- Alademomi AS, Odumosu J, Okolie CJ, Daramola OE, Akinnusi SA, Adediran E, et al. The interrelationship between LST, NDVI, NDBI, and land cover change in a section of Lagos metropolis, Nigeria. *Applied Geomatics* 2022;14:299-314.
- Anbazhagan S. Paramasivam CR. Statistical correlation between land surface temperature (LST) and vegetation index (NDVI) using multi-temporal Landsat TM Data. *International Journal of Advanced Earth Science and Engineering* 2016;5:333-46.
- Arij N, Latifi H, Fakhri A, Esmaili R. Four decades of spatio-temporal trends in Miankaleh Wetland's water body and vegetation as revealed by remote sensing time series. *Ecological Informatics* 2025;91:Article No. 103374.
- Bandh SA, Shafi S, Peerzada M, Rehman T, Bashir S, Wani SA, et al. Multidimensional analysis of global climate change: A review. *Environmental Science and Pollution Research* 2021;28:24872-88.
- Ferreira LS, Duarte DHS. Exploring the relationship between urban form, land surface temperature and vegetation indices in a subtropical megacity. *Urban Climate* 2019;27:105-23.
- De Frenne P, Lenoir J, Luoto M, Scheffers BR, Zellweger F, Aalto J, et al. Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology* 2021;27:2279-97.
- Gandhi GM, Parthiban S, Thummalu N, Christy A. Ndv: Vegetation change detection using remote sensing and Gis - A case study of Vellore District. In: *Procedia Computer Science*, Vol. 57. Elsevier; 2015. p. 1199-210.
- Garai S, Khatun M, Singh R, Sharma J, Pradhan M, Ranjan A, et al. Assessing correlation between Rainfall, normalized difference Vegetation Index (NDVI) and land surface temperature (LST) in Eastern India. *Safety in Extreme Environments* 2022;4:119-27.
- García-Santos V, Cuxart J, Martínez-Villagrasa D, Jiménez MA, Simó G. Comparison of three methods for estimating land surface temperature from Landsat 8-TIRS Sensor data. *Remote Sensing (Basel)* 2018;10(9):Article No. 1450.
- Hutayanon T, Somprasong K. Application of integrated spatial analysis and NDVI for tree monitoring in reclamation area of coal mine. *Environmental Science and Pollution Research* 2023;32:13053-63.
- Islam S, Karipot A, Bhawar R, Sinha P, Kedia S, Khare M. Urban heat island effect in India: A review of current status, impact and mitigation strategies. *Discover Cities* 2024;1:Article No. 34.
- Kumar D, Shekhar S. Statistical analysis of land surface temperature-vegetation indexes relationship through thermal remote sensing. *Ecotoxicology and Environmental Safety* 2015;121:39-44.
- Kumar L, Mutanga O. Google Earth Engine applications since inception: Usage, trends, and potential. *Remote Sensing (Basel)* 2018;10:Article No. 1509.
- Li M, Bai Q, Du W. The world is different because of you: Global warming, technological progress and economic development. *Structural Change and Economic Dynamics* 2025;74:202-11.
- Li ZL, Wu H, Duan SB, Zhao W, Ren H, Liu X, et al. Satellite remote sensing of global land surface temperature: Definition, methods, products, and applications. *Reviews of Geophysics* 2023;61:e2022RG000777.
- Longobardi P, Montenegro A, Beltrami H, Eby M. Deforestation induced climate change: Effects of spatial scale. *PLoS One* 2016;11(4):e0153357.
- Meshesha KS, Shifaw E, Kassaye AY, Tsehayu MA, Eshetu AA, Agegnehu HW. Evaluating the relationship of vegetation dynamics with rainfall and land surface temperature using geospatial techniques in South Wollo Zone, Ethiopia. *Environmental Challenges* 2024;15:Article No. 100895.
- Nassif WG, Lagenean FHS, Al-Taai OT. Impact of vegetation cover on climate change in different regions of Iraq. *Caspian Journal of Environmental Sciences* 2023;21:333-42.
- Pawade D, Patil S. Environmental and socio-economic impacts of coal mining in India: A comprehensive analysis. In: *Advances in Emerging Technologies and Computing Innovations*. Cham: Springer Nature Switzerland; 2025. p. 371-9.
- Psistaki K, Tsantopoulos G, Paschalidou AK. An overview of the role of forests in climate change mitigation. *Sustainability (Switzerland)* 2024;16(14):Article No. 6089.
- Rahimi E, Dong P, Jung C. Global NDVI-LST correlation: Temporal and spatial patterns from 2000 to 2024. *Environments* 2025;12(2):Article No. 67.
- Sinha P, Nageswararao MM, Dash GP, Nair A, Mohanty UC. Pre-monsoon rainfall and surface air temperature trends over India and its global linkages. *Meteorology and Atmospheric Physics* 2019;131:1005-18.
- Ullah W, Ahmad K, Ullah S, Tahir AA, Javed MF, Nazir A, et al. Analysis of the relationship among land surface temperature (LST), land use land cover (LULC), and normalized difference vegetation index (NDVI) with topographic elements in the lower Himalayan Region. *Heliyon* 2023;9:e13322.
- Venkataramanan M, Smitha. Causes and effects of global warming. *Indian Journal of Science and Technology* 2011;4:226-9.
- Wei S, He Z, Zhai W, Zhao C, Li Y. How does vegetation influence surface temperature across various road types and urban morphology types? *Building and Environment* 2025;270:Article No. 112511.
- Yuxi W, Li P, Yuemin Y, Tiantian C. Global vegetation-temperature sensitivity and its driving forces in the 21st century. *Earths Future* 2024;12(2):e2022EF003395.
- Zhan W, Chen Y, Zhou J, Wang J, Liu W, Voogt J, et al. Disaggregation of remotely sensed land surface temperature: Literature survey, taxonomy, issues, and caveats. *Remote Sensing of Environment* 2013;131:119-39.

Zhang L, Yang L, Zohner CM, Crowther TW, Li M, Shen F, et al. Direct and indirect impacts of urbanization on vegetation growth across the world's cities. *Science Advances* 2022;8(27):eabo0095.

Zhibin R, Haifeng Z, Xingyuan H, Dan Z, Xingyang Y. Estimation of the relationship between urban vegetation configuration and land surface temperature with remote sensing. *Journal of the Indian Society of Remote Sensing* 2015;43:89-100.

Geological Analysis and Occupational Safety Risks in Traditional Oil Drilling in Ranto Peureulak, East Aceh, Indonesia

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ABSTRACT

Aceh has abundant natural resources, including oil and natural gas. One of these resources is located in Ranto Peureulak, East Aceh Regency. This area has abundant crude oil reserves. However, due to the lack of government permits, the local community relies on traditional oil drilling methods. The purpose of this study is to assess the impact of traditional oil drilling carried out by the local community in Ranto Peureulak, East Aceh, in terms of both occupational safety and environmental impact. This study was conducted at 20 drilling sites in Ranto Peureulak, East Aceh. Occupational safety risk data was obtained through direct observation and analysis. In addition, physicochemical analysis was also carried out by comparing the analysis results at the drilling sites with the standard quality values set by Government of Indonesia Regulation No. 22 of 2021. The results of this study indicate that traditional crude oil drilling poses an extreme level of risk to occupational safety and the environment. Physicochemical analysis shows that several drilling sites have test values exceeding the established thresholds. Therefore, it can be concluded that traditional oil drilling activities have a very serious impact, both on human health and the surrounding environment.

HIGHLIGHTS

- This study highlights the traditional crude oil drilling significantly degrades environmental quality
- Traditional oil drilling poses severe threats to both human health and environmental
- Occupational safety risk assessment reveals predominantly extreme risk levels

1. INTRODUCTION

Petroleum is one of the most important natural resources in Indonesia. Its utilization began approximately 5,000 years ago and has continued to evolve alongside modern technological advancements and the rapid growth of industries. As petroleum serves as a primary fuel for operating machinery in transportation and industrial sectors, consumer demand for oil remains constant and tends to increase annually (Olah et al., 2018).

Aceh is rich in oil and natural gas, which may possess one of the Indonesia's largest reserves (Budiana and Dalimi, 2021). One of the regions with abundant natural resources is East Aceh, which has extensive agricultural land, forests, marine resources, fisheries, plantations, and oil and gas deposits. Among

these, the most prominent natural resource is the oil reserves located in Peureulak. However, local communities still rely on drilling methods because they lack official government permits.

The drilling process involves inserting pipes encased in a protective casing, similar to drilling a clean water well. The community's drilling apparatus requires at least 60 pipe sections to extract crude oil (Kroepsch et al., 2019). From a well, residents can produce between 5 and 20 large barrels of oil per day.

Oil plays a significant role in the local economy; however, accidents frequently occur during production. The primary cause is the community's inadequate skills in managing oil and gas resources properly and accurately (Mahmood et al., 2023). Numerous incidents of fire and explosion during

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drilling have been reported in the media. One such incident occurred in Peureulak on April 25, 2018. Explosions occurred at 10 illegal oil wells, causing significant material losses and potentially endangering the safety of residential areas around the location. This case exemplifies the severe consequences of oil production conducted without proper extraction techniques for petroleum and natural gas (Khaidir et al., 2024).

Drilling not only poses occupational safety risks but also negatively impacts the environment. The area is known for its oil drilling activities due to frequent mixing of oily and clean water, leading to the continuous expansion of traditional extraction and processing. The mixture of water and drilling mud is hazardous if ingested, and the contaminated mud pollutes the soil. Given the environmental and safety

risks associated with drilling in Peureulak, research is needed to map the distribution of oil wells in the region. Such mapping will help estimate the potential scale of disasters and environmental impacts resulting from extraction activities.

2. METHODOLOGY

2.1 Research location

This research was conducted in Ranto Peureulak, East Aceh, Indonesia. This area has many drilling activities and small-scale oil processing. Samples were collected from 20 locations, as shown in Figure 1. This study was conducted from September 1 to 10, 2023. Sample collection was carried out between 08:00 and 18:00 WIB under relatively clear weather conditions.

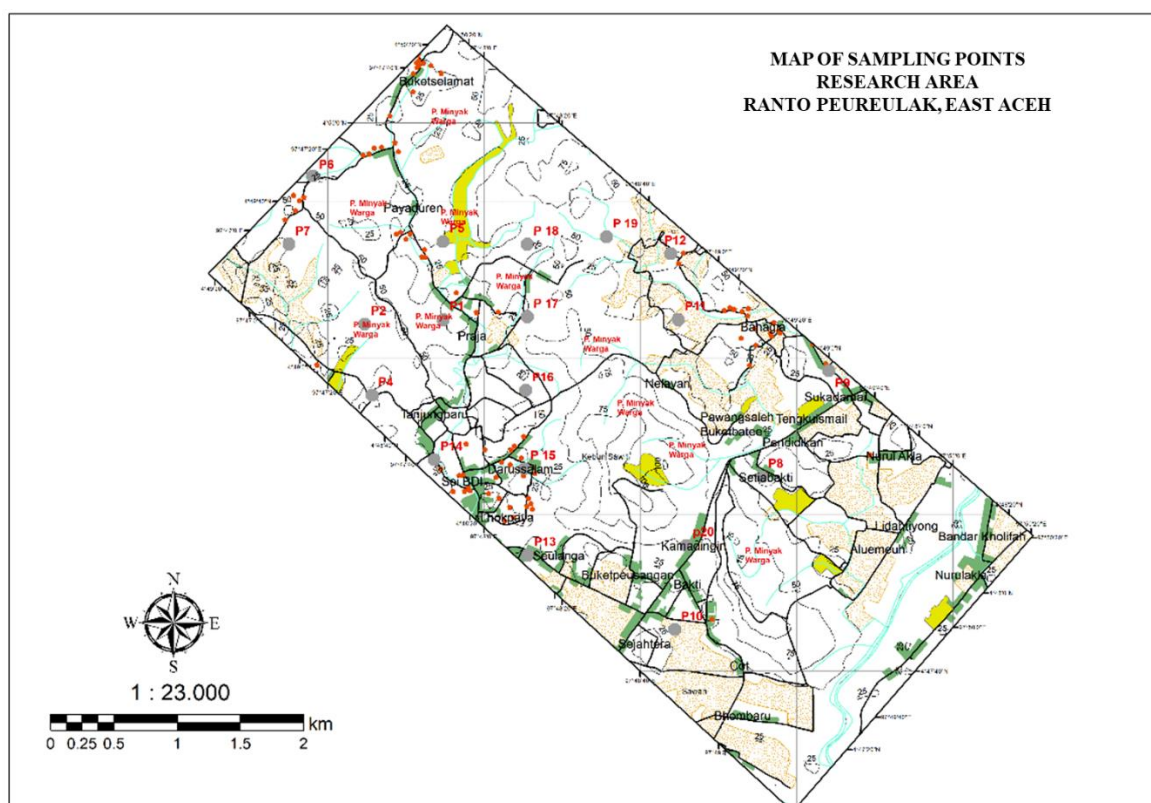


Figure 1. Sample point map of Ranto Peureulak

The research was conducted by visiting oil drilling locations marked on the map above. In addition, wells at the research locations varied in depth and were predominantly water wells. The coordinates of traditional oil drilling sites in Ranto Peureulak are shown in Table 1.

2.2 Hazard risk analysis in traditional oil drilling

The identification of hazards in traditional oil drilling activities is carried out by looking at several types of hazards to humans, materials, and the environment in the traditional oil drilling process, as presented in Table 2.

Table 1. The coordinates of traditional oil drilling sites in Ranto Peureulak

No	Locations		Conditions	Wells depth	
	X	Y		Water well	Oil well
P1	4 49' 14"	97 47' 43"	Close to residential areas	20 m (drilled well)	480 m
P2	4.81'8886	97.79398	Open land and far from residential areas	15 m	480 m
P3	4.82445	97.79024	Close to residential areas		300 m
P4	4.81353	97.79858	Open land adjacent to residential areas	Flowing water	98 m
P5	4 49' 32"	97 47' 42"	Rubber tree plantations adjacent to residential areas	20 m (drilled well)	
P6	4 49' 46"	97 47' 20"	Open land with oil palm vegetation adjacent to residential areas	Flowing water	180 m
P7	4 49' 37"	97 47' 13"	Rice fields adjacent to residential areas	Flowing water	480 m
P8	4.80958	97.81806	Close to residential areas	20 m (drilled well)	
P9	4.81621	97.82506	Close to residential areas	12 m	
P10	4.79966	97.8148	Open land with oil palm vegetation adjacent to residential areas	288 m (former oil well)	240 m
P11	4.81887	97.81636	Rice field area	8 m	
P12	4 49' 18"	97 48' 48"	Rice field area	12 m	
P13	4 47' 57"	97 48' 13"	Open land with sedimentary rock conditions and adjacent to residential areas	Flowing water	
P14	4 48' 32"	97 47' 33"	Open land with sedimentary rock conditions and adjacent to residential areas	7 m	
P15	4 48' 37"	97 48' 9"	Open land with sedimentary rock conditions	20 m (drilled well)	300 m
P16	4 48' 55"	97 48' 14"	Open land with oil palm vegetation	18 m	372 m
P17	4 49' 3"	97 48' 7"	Open land with sedimentary rock conditions	Flowing water	500 m
P18	4 49' 22"	97 48' 14"	Open land with sedimentary rock conditions	24 m	
P19	4 48' 37"	97 48' 9"	Open land with sedimentary rock conditions	Flowing water	
P20	4 48' 20"	97 48' 57"	Close to residential areas	25 m	480 m

Table 2. Hazard identification in traditional oil drilling

Activity	Sources	Emerging hazards
Traditional oil drilling	Humans	Smoking while working
	Environmental	Slippery and wet ground due to oil drilling residue
	Materials	Direct exposure to crude oil on workers' bodies
	Humans	Performing tasks that generate flames near crude oil drilling activities
	Humans	Operating oil pipes
	Tools	Condition of the drilling rig structure
	Environmental	Flowing waste fluid from drilling activities

This analysis uses a matrix to assess the likelihood of risk occurrence and the resulting impact. The risk levels can be seen in [Table 3](#).

2.3 Analysis of risk assessment and risk level in Ranto Peureulak

The risk assessment method used in this study is a qualitative risk assessment. Qualitative risk

assessment results from multiplying the consequence/impact level parameter by the likelihood parameter for occupational risks in Drilling areas. The risk levels based on this analysis are grouped into four categories: extreme, high, medium, and low.

2.4 Analysis of water and soil at traditional oil drilling in Ranto Peurelak

The analysis conducted involved measuring the supporting physical and chemical parameters tested in this study, including depth analysis, water temperature, water and soil pH, salinity, TDS, COD,

BOD, DO, oil and grease, lead (Pb), NH_4 , NO_2 , alkaline hardness (CaCO_3), and total organic matter.

Total Dissolved Solids (TDS) in Ranto Peurelak, East Aceh Regency, were analyzed using the gravimetric method in accordance with SNI 6989.27:2019. Chemical Oxygen Demand (COD) was determined according to SNI 6989.2:2009, using the UV-Vis spectrophotometry method for analysis. While Biochemical Oxygen Demand (BOD) was measured by the titrimetric method, specified in SNI 6989.72:2009. Dissolved oxygen (DO) determined by the Winkler titration based on SNI 06-6989.14.

Table 3. Risk levels

Risk	Effects				
	Insignificant	Minor	Moderate	Major	Catastrophe
Opportunity	1	2	3	4	5
Almost certain	5	Medium	High	Extreme	Extreme
Likely	4	Low	Medium	High	Extreme
Possible	3	Low	Medium	High	Extreme
Unlikely	2	Low	Medium	High	Extreme
Rare	1	Low	Medium	High	High

Oil and grease concentration were analyzed gravimetrically extracting water-soluble oils and fats with organic solvents, such as n-hexane in accordance with SNI 6989.10:2011. Lead (Pb) concentration in water samples were measured using Atomic Absorption Spectrophotometry (AAS) following SNI 6989.46-2009. Nitrite (NO_2) concentrations were analyzed by spectrophotometry using SNI 06-6989.9-2004, while Ammonium (NH_4) was determined by spectrophotometry using the Fenat method according

to SNI 06.6989.30-2005. Alkalinity was measured by the titrimetric method as specified in SNI 06-2420-1991, and total organic matter (TOM) was determined by potassium permanganate (KMnO_4) titration following SNI 06.6989.22-2004.

The physicochemical analysis was conducted in accordance with the quality standards stipulated in Government Regulation No. 22 of 2021, which are listed in [Table 4](#).

Table 4. The quality standards stipulated in Government Regulation No. 22 of 2021

No	Parameters	Quality standards
1	Water temperature	26-31°C
2	Water pH	6-9
3	Soil pH	6-9
4	Total dissolved solids (TDS)	1,000 mg/L
5	Chemical oxygen demand (COD)	25 mg/L
6	Biochemical oxygen demand (BOD)	3 mg/L
7	Dissolved oxygen (DO)	4-10 mg/L
8	Oil and grease	1 mg/L
9	Lead content (Pb)	0.03 mg/L
10	NO_2 concentration (Nitrite)	0.06 mg/L
11	NH_4 (Ammonium)	0.2 mg/L
12	Alkalinity	500 mg/L
13	Total organic matter (TOM)	10 mg/L

3. RESULTS

3.1 Hazard risk analysis in traditional oil drilling

The risk value is determined by the frequency of the work and its impact on workers. The risk assessment and the percentage of danger, ranging from low to extreme, are shown in Table 5 below.

Based on traditional oil drilling operations, the risk associated with drilling activities is shown in Figure 2.

After hazard identification, risk assessment is carried out, and the risk level for each hazard is determined. The risk level assessment analysis is presented in Table 6.

Table 5. Risk assessment in traditional oil drilling in Ranto Peureulak

No	Potential hazards	Potential risks	Risk assessments		Risk matrixs
			L	S	
P1	Waste from crude oil drilling operations	Environmental pollution	5	1	M
P2	Slippery and wet work floors	Slipping or sprains	5	1	M
	Drilling rig foundations	Collapse and potential injury to workers	5	5	E
P3	Drilling rig foundations	Collapse and potential injury to workers	5	5	E
	Exposure to crude oil	Symptoms of bumps on exposed areas, and if it gets in the eye, it causes stinging.	5	2	H
P4	Well no longer producing				
P5	Waste from crude oil drilling operations	Environmental pollution	5	1	M
P6	Waste from crude oil drilling operations	Environmental pollution	5	1	M
P7	Waste from crude oil drilling operations	Environmental pollution	5	1	M
P8	Slippery and wet work floors	Slipping or sprains	5	1	M
	Exposure to crude oil	Symptoms of bumps on exposed areas and if it gets in the eye, it causes stinging.	5	2	H
	Operating drilling equipment	Collapse and potential injury to workers	3	5	E
	Smoking while working	Fire hazard	5	5	E
P9	Well no longer producing				
P10	Waste from crude oil drilling operations	Environmental pollution	5	1	M
	Drilling rig foundations	Collapse and potential injury to workers	5	5	E
P11	Operating drilling equipment	Potential injury to workers	3	5	E
P12	Well no longer producing				
P13	Well no longer producing				
P14	Well no longer producing				
P15	Well no longer producing				
P16	Waste from crude oil drilling operations	Environmental pollution	5	1	M
P17	Well no longer producing				
P18	Well no longer producing				
P19	Well no longer producing				
P20	Exposure to crude oil	Symptoms of bumps on exposed areas	5	2	H
	Slippery and wet work floors	Slipping or sprains	5	1	M
	Smoking while working	Fire hazard	5	5	E
	Operating drilling equipment	Potential injury to workers	3	5	E

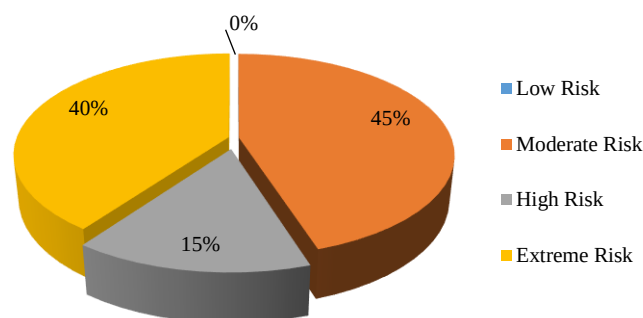


Figure 2. Percentage of risk levels in traditional oil drilling activities

Table 6. Risk assessment analysis results

No	Activities/conditions	Risks	L	S	Risk value	Risk level
1.	Oil spills or other hazardous material leaks	Environmental pollution	5	4	20	Extreme
2.	Air and water pollution caused by drilling activities	Environmental pollution	4	3	12	High
		Health issues	4	4	16	High
3.	Gas or oil leaks leading to explosions and fires	Explosions and fires	4	5	20	Extreme
4.	Extreme weather conditions near drilling areas	Environmental damage	3	3	9	Medium
5.	Noise pollution from drilling machinery	Health issues	5	4	20	Extreme
6.	Community activities near drilling sites	Disruptions to community life	4	4	16	High
7.	Soil erosion	Environmental damage	4	4	16	High
8.	Residential areas located near drilling sites	Health issues	3	3	9	Medium
9.	Oil refining operations near residential areas	Health issues	3	3	9	Medium
		Environmental damage	3	4	12	High
10.	Community Environment Located Far from the Drilling Area	Environmental pollution	2	2	4	Low

Based on the risk assessment results, the overall distribution of risk levels in the drilling area is shown in [Figure 3](#).

3.2 Results of physicochemical analysis

The results of physicochemical parameter measurements are presented in [Table 7](#). Based on the analysis results, the water temperature at the study site ranged from 29 to 34°C. Furthermore, water pH measurements indicated that the site's water ranged from 6.3 to 8.9. Meanwhile, the soil pH value ranged from 4.2-8.0. [Table 3](#) shows that several locations do not meet the quality standards, namely P2, P3, P4, P5, P6, P7, P8, P9, P12, P14, P15, P16, and P17. These results suggest that the northern part of the study area is predominantly acidic. According to [Singh et al. \(2022\)](#), low pH levels in water bodies increase the

toxicity of heavy metals. This interpretation is also supported by the salinity analysis data, which show that the sample locations have high salinity values, ranging from 4,606.76 to 5,115.28 ppm.

The TDS analysis conducted shows that the TDS value meets the Class IIm quality standard of 1,000 mg/L. However, there were three samples with the highest TDS values, namely P2, P7, and P17, at 4968 mg/L, 3151 mg/L, and 2461 mg/L, respectively, which exceeded the permissible quality standard. Meanwhile, the Chemical Oxygen Demand (COD) values obtained showed that there were two samples with high COD values, namely samples P4 and P6. BOD analysis showed that samples P13, P20, P6, and P4 exceeded the established quality standard of 3 mg/L.

Table 7. Sample data and water and soil quality parameters

Labels No.	Parameters													
	Water temperature (°C)	Water pH	Salinity (µS/cm)	TDS (mg/L)	Soil pH	COD (mg/L)	Oil and grease (mg/L)	DO (mg/L)	BOD (mg/L)	Pb content (mg/L)	NH4 (mg/L)	NO2 (mg/L)	Alkalinity (mg/L)	Total Organic Matter (mg/L)
P1	31	8.4	524/0.05%	524	7	0.9	2.8	5.2	2.4	4.87	1.01	0.01	448	7
P2	34	7.55	5,117/0.51%	4,968	4.5						3.14	0.01	1392	61
P3	31	7.5	950/0.09%	950	5.5						1.16	0.02	312	6
P4	30	7.82	555/0.05%	555	5.5	68.9	7.4	5.7	6.7	<0.0002	1.01	0.04	568	91
P5	29	7.18	468/0.04%	468	5.5						1.16	0.04	312	6
P6	31.5	7.87	894/0.09%	894	5	38	2.7	5.4	5.1	0.83	0.22	0.01	204	48
P7	33.8	8.96	3,245/0.32%	3,151	5.2						0.23	0.08	1100	87
P8	32.4	7.97	423/0.04%	423	5.5	6.6	1.2	5.8	2.4	<0.0002	0.25	0.02	180	6
P9	31	7.58	493/0.05%	493	5.2						0.12	1.90	180	65
P10	30.5	8.19	601/0.06%	601	6	1.1	1.8	5.3	2.5	1.37	0.22	0.01	1104	7
P11	31.7	7.34	239/0.02%	239	6						1.07	0.13	152	24
P12	30	6.69	84/0.0001%	84	5.5	1.4	0.4	5.2	2.5	<0.0002	0.14	0.01	36	2
P13	29	8.6	191/0.01%	191	7	21.7	1.6	5.4	3.1	8.61	0.44	0.22	70	48
P14	30.6	7.76	439/0.04%	439	4.5	5.5	1.2	5.9	2.7	2.49	0.20	0.98	356	12
P15	31	7.23	883/0.09%	883	4.5						0.14	0.01	408	9
P16	31	6.92	961/0.09%	961	5.8	0.8	2.5	5.7	2.5	2.07	0.12	0.01	412	10
P17	31	7.93	2,461/0.24%	2,461	4.2						4.81	0.05	552	98
P18	29	8.3	540/0.05%	540	8	1.2	1.1	5.2	2.5	<0.0002	0.64	0.01	364	10
P19	30.3	6.3	30/0.0001%	30	6.8						0.24	0.10	36	55
P20	30	7.23	30/0.0001%	30	8	1.7	0.8	5.1	3.1	<0.0002	0.17	0.03	32	16

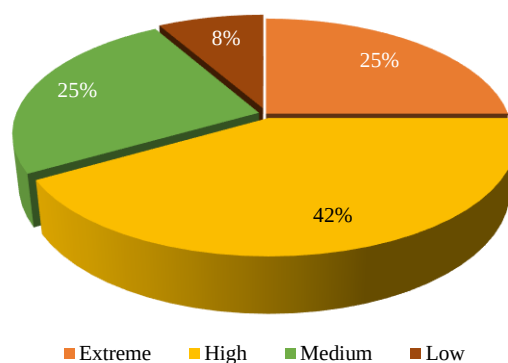


Figure 3. Percentage of risk level

DO shows values that meet the quality standards set by Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management, namely a Class II quality standard of 3 mg/L. According to Government Regulation of the Republic of Indonesia No. 22 of 2021 on Environmental Protection and Management, the oil and grease standard for Class II water bodies is 1 mg/L. A total of 11 out of 20 samples contained detectable levels of oil and grease. Based on the test results for Pb, only 5 out of 20 samples had detectable Pb levels. The Pb concentrations in samples P4, P8, P12, P18, and P20 were <0.0002 mg/L, indicating that these values are below the regulatory threshold set by Government Regulation of the Republic of Indonesia No. 22 of 2021, which establishes a Class II Pb water quality standard of 0.03 mg/L. 20 sample data points, only 14 samples showed measurable NO₂ levels. The NO₂ concentrations in samples P1, P2, P4, P3, P5, P6, P8, P10, P12, P15, P16, P17, P18, and P20 complied with the Class II quality standard of 0.06 mg/L. Based on the results of the NH₄ analysis, the lowest NH₄ concentrations were found in samples P9, P12, P16, P15, P20, and P14, all of which remained below the quality standard stipulated in Government Regulation No. 22 of 2021 on Environmental Protection and Management. The Class II quality standard for NH₄ is 0.2 mg/L. Alkalinity levels in samples P12, P19, P13, P11, P9, P8, P6, P3, P5, P14, P18, P15, P16, and P1 met the established quality standard of 500 mg/L. However, higher alkalinity values were recorded in samples P17, P4, P7, P10, and P2, exceeding the permissible limit. Meanwhile, Total Organic Matter analysis showed that samples P14, P20, P6, P13, P19, P2, P9, P7, P4, and P17 exceeded the established quality standard of 10 mg/L.

4. DISCUSSION

This research was conducted at the oil production well drilling site in Ranto Peureulak, East Aceh, Aceh. Based on the hazard identification results at each stage of traditional oil drilling activities, several factors contribute to workplace accidents, including human factors, machinery and equipment, materials, and environmental conditions (Benson et al., 2021). Therefore, raising awareness of potential risks, developing more effective control measures, and enhancing operational safety in drilling activities are crucial. After identifying hazards and the risks they pose, the next step was to assess the level of risk. In this study, the assessment method is qualitative. The method of determining control in Ranto Peureulak was to manage and take corrective actions on existing risks. Risk control in traditional oil drilling areas follows SNI ISO 3100:2018 on risk management and SNI ISO 45001:2018 on occupational health and safety management systems.

The physicochemical analysis conducted shows that certain locations do not meet the quality standards set out in Government Regulation No. 22 of 2021. This may be influenced by the weather or season at the time the samples were taken, the interaction between air and water, cloud conditions, wind gusts, and the geographical location of a well. In addition, high sunlight intensity can affect the temperature in the well. This is in line with the location of the water sampling, which is an open space and very accessible to sunlight entering the water body. Sunlight exposure is a major factor that affects temperature changes in water bodies (Nimma et al., 2025).

Based on the results of this study, soil samples from the study site were predominantly acidic or failed to meet the quality standard. Low pH values can be

influenced by the presence of microorganisms or heavy metal contamination in the samples. This aligns with [Singh et al. \(2022\)](#), who found that low pH levels in water bodies increases the toxicity of heavy metals, making them more bioavailable and hazardous to aquatic life. Metallic elements dissolved in the soil can also cause low TDS values. Such conditions are likely due to the proximity of residential areas to and underground water contaminated with oil, both of which negatively affects water quality. Additionally, the use of fertilizers and pesticides in agriculture may also contribute to TDS levels. According to [Mushtaq et al. \(2020\)](#), the primary sources of TDS in water bodies include runoff from agricultural activities, household wastewater, and industrial effluents. When a water source exhibits high TDS levels, it can be classified as contaminated ([Mushtaq et al., 2020](#)).

Based on observations at the research site, samples with high COD values were collected from locations with various community activities that generated organic waste. The organic waste produced caused low oxygen concentrations in the water ([Amoatey and Baawain, 2019](#)). This finding aligned with [Byliński et al. \(2019\)](#), who stated that COD levels can indicate the extent of organic pollutants present in a well. Therefore, immediate actions are required to reduce COD, restore groundwater quality to normal levels, and ensure the surrounding community can safely use it. In addition to organic waste, the extensive agricultural land surrounding these wells contributed to water contamination, reducing water quality. According to [Jiao et al. \(2021\)](#), low dissolved oxygen levels in water suggested that organic matter in the water requires a high oxygen demand due to increased oxygen consumption.

Low oxygen concentrations in water also affect DO values. DO values in this study tended to be low or close to the minimum quality standards set. These low DO levels are likely due to water flow during the dry season, which lowers water quality. Additionally, the presence of settlements and agricultural activities around the wells may further contribute to pollution through. Waste disposal and runoff according to [Breitburg et al. \(2018\)](#), a decrease in DO levels in water indicates a decline in water quality.

The oil and fat content on the water surface can also reduce dissolved oxygen concentration by inhibiting oxygen fixation ([Saravanan et al., 2021](#)). Based on the results of the study, almost all well locations had oil and fat levels exceeding established quality standards and had the potential to cause water

pollution. In addition, based on test results from oil wells in Ranto Peureulak, Pb metal pollution has already occurred. This pollution was caused by untreated drilling mud that was piled up. To address this drilling mud waste, it was necessary to treat it using specific techniques. [Katipana \(2015\)](#) stated that aquatic plants can contribute approximately 0.200 to 0.553 ppm of lead (Pb) content in water. In addition, household waste, such as peeling residues from cookware and paint from water pipes can increase lead contamination in water bodies ([Kumar et al., 2020](#)).

The results of NO₂ testing showed that the average sample NO₂ values remained within the quality standard threshold. According to [Tadesse et al. \(2018\)](#), NO₂ levels in aquatic environments are typically low, with natural waters generally containing around 0.001 mg/L. Ideally, the NO₂ concentration should not exceed 0.06 mg/L to maintain environmental safety. However, several locations had NO₂ levels exceeding the permissible quality standards. These elevated NO₂ levels are thought to originate from agricultural activities, especially the fertilization process, in which water in the area flows out at the outlet or observation point.

NH₄ testing showed that locations near residential areas have higher NH₄ levels. According to [Yang et al. \(2025\)](#), ammonium in water comes from the reaction between household organic waste and organisms. High concentrations of NH₄⁺ (ammonium) in water can cause an unpleasant taste and adverse effects on humans. Ammonia in water can affect is vertebrates, invertebrates, algae, and microbes, potentially altering the structure and function of aquatic ecosystems ([Zhang et al., 2018](#)).

Alkalinity analysis showed high values in locations with sedimentary rock conditions. The elevated alkalinity may be due to contamination of the wells in Ranto Peureulak, which caused minerals to seep into the soil, and increasing water hardness. In addition, the soil in this area contained minerals that caused hardness, such as limestone and magnesium. This interpretation is in line with what [Ahn et al. \(2018\)](#) that water will have high hardness levels when it encounters limestone in the soil layer.

Furthermore, total organic matter values exceeding quality standards were observed in open areas with sedimentary rocks and adjacent to residential areas. The elevated organic matter levels are attributed to liquid, solid, and gaseous waste discharges from human activities, industrial operations, agriculture/forestry, transportation, and

mining, among others. Excessive or insufficient total organic matter can affect the fertility of aquatic environments. Good water is characterized by organic material concentrations that meet established water quality standards. This characterization aligns with the statement by Rahmawati et al. (2023), who argue that an excess of organic material can lead to eutrophication, which is the excessive growth of aquatic organisms. Eutrophication, in turn, can negatively affect aquatic life and overall water quality.

5. CONCLUSION

Based on qualitative hazard and risk assessments in the transitional oil drilling area, the risk level is classified as extreme. This activity has a serious impact on the environment, human health, and the lives of communities around the site. Quantitative analysis of water and soil showed that the physicochemical parameters at several drilling sites exceed the quality standards set out in Regulation No. 22 of 2021. These exceedances may occur due to community activities that produce organic waste, agricultural activities, and mineral content from sedimentary rocks that seep into the soil. Therefore, the government needs to conduct regular monitoring and further improve waste management to reduce pollution.

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AUTHOR CONTRIBUTIONS

Each author contributed significantly to the concept and development of the present paper. Muchlis.: Supervision, Conceptualization, Investigation, Methodology, Experiment, Validation, Formal Analysis, Visualization, Writing Original manuscript, Writing - Revise and Editing. Aflah, N.: Supervision, Investigation, Methodology, Experiment, Validation, Formal Analysis, Visualization. Lubis, M.R.: Conceptualization, Investigation, Methodology, Experiment, Visualization.

DECLARATION OF CONFLICT OF INTEREST

We state that they have no conflicts of interest.

REFERENCES

Ahn MK, Chilakala R, Han C, Thenepalli T. Removal of hardness from water samples by a carbonation process with a closed pressure reactor. *Water* 2018;10(1):Article No. 54.

Amoatey P, Baawain MS. Effects of pollution on freshwater aquatic organisms. *Water Environment Research* 2019;91(10):1272-87.

Benson C, Dimopoulos C, Argyropoulos CD, Mikellidou CV, Boustras G. Assessing the common occupational health hazards and their health risks among oil and gas workers. *Safety Science* 2021;140:Article No. 105284.

Breitbart D, Levin LA, Oschlies A, Grégoire M, Chavez FP, Conley DJ, et al. Declining oxygen in the global ocean and coastal waters. *Science* 2018;359(6371):eaam7240.

Budiana D, Dalimi R. The economics comparison of power plants fuelled by wellhead gas and liquefied natural gas in Aceh Province. *IOP Conference Series Materials Science Engineering* 2021;1041:Article No. 012019.

Byliński H, Gębicki J, Namieśnik J. Evaluation of health hazard due to emission of volatile organic compounds from various processing units of wastewater treatment plant. *International Journal Environmental Research Public Health* 2019;16(10):Article No. 1712.

Jiao N, Liu J, Edwards B, Lv Z, Cai R, Liu Y, et al. Correcting a major error in assessing organic carbon pollution in natural waters. *Science Advances* 2021;7(16):eabc7318.

Katipana D. Testing for lead (Pb) content in water spinach (*Ipomoea aquatica* F) at Pattimura University. *Biopendix: Jurnal Biologi, Pendidikan dan Terapan* 2015;1(2):153-9.

Khaidir M, Matsyah A, Dayyan M. Legality of traditional oil mining exploration in Ranto Peureulak, East Aceh. *JURISTA: Jurnal Hukum dan Keadilan* 2024;8(2):435-54.

Kumar A, Kumar A, MMS Cabral-Pinto, Chaturvedi AK, Shabnam AA, Subrahmanyam G, et al. Lead toxicity: Health hazards, influence on food chain, and sustainable remediation approaches. *International Journal Environmental Research and Public Health* 2020;17(7):Article No. 2179.

Kroepsch AC, Maniloff PT, Adgate JL, McKenzie LM, Dickinson KL. Environmental justice in unconventional oil and natural gas Drilling and production: A critical review and research agenda. *Environmental Science Technology* 2019;53(12):6601-15.

Mahmood Y, Afrin T, Huang Y, Yodo N. Sustainable development for oil and gas infrastructure from risk, reliability, and resilience perspectives. *Sustainability* 2023;15(6):Article No. 4953.

Mushtaq N, Singh DV, Bhat RA, Dervash MA, Hameed OB. Freshwater contamination: Sources and hazards to aquatic biota. In: *Fresh Water Pollution Dynamics and Remediation*. Singapore: Springer Singapore; 2020. p. 27-50.

Nimma D, Devi OR, Laishram B, Ramesh JVN, Boddupalli S, Ayyasamy R, et al. Implications of climate change on freshwater ecosystems and their biodiversity. *Desalination Water Treat* 2025;321:Article No. 100889.

Olah GA, Goepfert A, Prakash GKS. *Beyond Oil and Gas: The Methanol Economy*. John Wiley and Sons; 2018.

Rahmawati SD, Ain C, Sabdaningsih A. Water quality and trophic status in Jatibarang Reservoir, Semarang. *Saintek Perikanan: Indonesian Journal of Fisheries Science and Technology* 2023;19(3):152-8.

Saravanan A, Senthil Kumar P, Jeevanantham S, Karishma S, Tajsabreen B, Yaashikaa PR, et al. Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. *Chemosphere* 2021;280:Article No. 130595.

- Singh A, Sharma AK, Verma RL, Chopade RP, Pandit P, Nagar V, et al. Heavy metal contamination of water and their toxic effect on living organisms. In: Dorta DJ, de Oliveira DP, editor. *The Toxicity of Environmental Pollutants*. London: IntechOpen; 2022. p. 49.
- Tadesse M, Tsegaye D, Girma G. Assessment of the level of some physico-chemical parameters and heavy metals of Rebu River in Oromia Region, Ethiopia. *MOJ Biology and Medicine* 2018;3(3):99-118.
- Yang J, Zhang J, Du X, Gao T, Cheng Z, Fu W, et al. Ammonia inhibition in anaerobic digestion of organic waste: A review. *International Journal of Environmental Science and Technology* 2025;22(5):3927-42.
- Zhang L, Xu EG, Li Y, Liu H, Vidal-Dorsch DE, Giesy JP. Ecological risks posed by ammonia nitrogen (AN) and unionized ammonia (NH₃) in seven major river systems of China. *Chemosphere* 2018;202:136-44.

Quantifying Decadal Recovery in Small Scale Community-Based Mangrove Management (SSCM) in East Java, Indonesia, using Integrated Remote Sensing and Ecological Assessments

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ABSTRACT

This study examines ecological outcomes of small-scale community-based mangrove management (SSCM) in three locations in East Java: Clungup Mangrove Conservation (CMC, south coast), Penunggul (north coast) and Hijau Daun (small island). The primary objective is to evaluate the impacts of local community initiatives on mangrove ecosystem recovery over the past decade. Methodology combined remote sensing and field-based approaches. Machine learning google earth engine (GEE) was applied to assess past decade vegetation recovery using Normalized Difference Vegetation Index (NDVI), while raster analysis processed using R software to obtain net value change. To ensure compatibility between datasets, spatial harmonization was performed by resampling and aligning Sentinel-2 imagery to match Landsat 7 resolution using QGIS software. Field observations were conducted to assess the current ecological metrics, and descriptive analysis was carried out to connect restoration outcomes with management practices. Research findings indicate notable increases in net value change, with CMC showing the most substantial recovery (0.2-0.3), shifted from predominantly open or sparse areas to moderate or dense vegetation. Mangrove in Daun and Penunggul have ΔNDVI of 0-0.1, reflecting mild improvement in vegetation cover. Ecological assessments further revealed variation among sites. In Penunggul, diameter at breast height (DBH) of mangrove ranged from 2-16 cm (mean 7.70 ± 3.34 cm), with average tree density of 2,300 ind/ha. CMC has mangrove density from 1,200-3,600 ind/ha and mean DBH 5.70 ± 2.20 cm (range from 3.00-10.00 cm). Hijau Daun exhibited the lowest average density at 1,333 ind/ha, with DBH range from 2.00-37.00 cm (mean 9.27 ± 7.24 cm).

HIGHLIGHTS

Small scale community-based initiatives (SSCM) are creating sustainable mangrove management models. GEE-based NDVI analysis and net value change indicate increasing vegetation cover and density in restored areas, while field surveys show enhancements in terms of mangrove ecological quality. However, lacks of seaward expansion in most restoration sites despite decadal consistent management, highlights limitations in biophysical support. This should be considered by government and stakeholders when proposing mangrove restoration programs.

1. INTRODUCTION

Indonesia has 3.44 Mha of mangrove (Ministry of Forestry, 2021), representing one-fifth global mangrove areas, as well as the most diverse mangrove species (Arifanti et al., 2022b). This ecosystem

provides at least 26 ecosystem services: supporting, provisioning, regulating, and cultural services (Bimrah et al., 2022). Mangrove also plays an important role in carbon sequestration in marine systems (Kathiresan and Bingham, 2001; Donato et

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al., 2011; McLeod et al., 2011), forming the foundation of “Nature-based Solutions (NbS)” (Cohen-Shacham et al., 2016).

East Java has 27,221 ha of mangrove (Ministry of Forestry, 2021), making it the largest in Java, most populated Island in Indonesia. Majority mangrove in East Java categorized as converted mangrove, located in high intensity use of coastal areas. North coast of East Java provides an ideal habitat for mangrove, dominated by *Avicennia* and *Sonneratia* spp. (Asadi et al., 2019; Saputra et al., 2022b). South coast is geologically uplifted region dominated by sand and carbonate deposits. Lagoon mangrove in this region are found in river mouths affected by tides, behind sandy coastlines, protecting vegetations from high wave energy of the Indian Ocean (Saputra et al., 2020; Winarso et al., 2023; Sidik et al., 2025). Mangrove in East Java are utilized in various ways, providing a range of services that can be categorized into provisional, regulatory, and socio-cultural functions.

- Provisional function: mangrove-associated fish (Harahab, 2009; Saputra et al., 2022a) and various derivative products (functional-food, medicine and natural dyes for clothing) (Hardoko et al., 2015; Hardoko et al., 2020).
- Regulatory function: blue carbon ecosystem (Donato et al., 2011; Alongi, 2012; Asadi et al., 2018), protect coastal settlements and aquaculture from damaging storm, waves, and floods (Bimrah et al., 2022).
- Socio-cultural function: recreational sites (Hakim et al., 2017; Harahab and Setiawan, 2017; Arsad et al., 2021; Intyas et al., 2021; Abidin et al., 2023).

In contrast, mangrove ecosystems are among the most vulnerable habitats in Indonesia, with total net deforestation or the net loss of mangrove forest area from 2001-2020 at 193.37 ha (Sasmito et al., 2023), contributing CO₂ emission factor (EF) of 24.0±5.4 - 92.3±15.7 Mg CO₂e/ha/year (Arifanti et al., 2022a). Over decades, mangrove deforestation is estimated at around 637,000 ha or 10-33% of total mangrove area (Arifanti et al., 2022b), including mangrove in East Java (Saputra et al., 2022a).

Local communities play a pivotal role in the success of sustainable mangrove management (Susilo et al., 2015; Arifanti et al., 2022b; Quevedo et al., 2023). In East Java (outside national parks), existing mangrove stands outside national parks largely result from local conservation and restoration initiatives by local community (Susilo et al., 2015; Hakim et al.,

2017). Mangrove in East Java is the prime examples of how small scale community-based mangrove management (SSCM) efforts become backbone to mangrove existence. SSCM is closely related to community based mangrove management terms (Tacconi, 2007), aimed at restoring important services and conserving biodiversity, with heavy involvement of local communities in various forest activities such as planting, monitoring and nursery establishment. Despite these promising results, there is a research gap in understanding the impacts of SSCM on the ecological and socio-economic outcomes of mangrove ecosystems. Comprehensive research focusing specifically on East Java is still lacking.

The advancement of technology provides new opportunities to evaluate SSCM initiatives. Combination of ecological assessment (plot-based field measurement) and remote sensing provides key information related to SSCM results. This study aims to (1) Quantify current mangrove condition after more than one decade of restoration, (2) Identify long-term changes in mangrove cover using multi-temporal satellite data, and (3) Integrate both approaches to evaluate SSCM effectiveness in East Java.

2. METHODOLOGY

This research covers primary SSCM areas, representing all geomorphological regions in East Java. South coast of East Java represented by CMC (Clugup Mangrove Conservation) in Malang, north coast of East Java represented by Penunggul in Pasuruan, while small islands represented by Mangrove Hijau Daun in Bawean Island, 60 nautical miles from Gresik Regency (Figure 1). A total of 15 plots 10×10 m were deployed using stratified random sampling to obtain community structure data. Field observations carried out in 2023-2024 for each location.

2.1 Temporal analysis of mangrove cover

Change in mangrove cover within last decade (2012-2024) processed using google earth engine (GEE), which supports geospatial processing, cloud computing and provides vast number of satellite datasets (Gorelick et al., 2017). Landsat 7 Collection 2 Level-2 imagery was filtered for the period Jan 1 - Dec 31, 2012, while Sentinel-2 Surface Reflectance imagery was filtered for the period Jan 1 - Dec 31, 2024. Both satellite imageries prepared with a max cloud cover of 20%. Median composite imagery was generated to minimize the influence of atmospheric conditions and

ensure high data quality. Due to Landsat 7 SLC failure (which affecting up to 22% results), gap filling

algorithms were implemented during median composite processing (Chen et al., 2011).

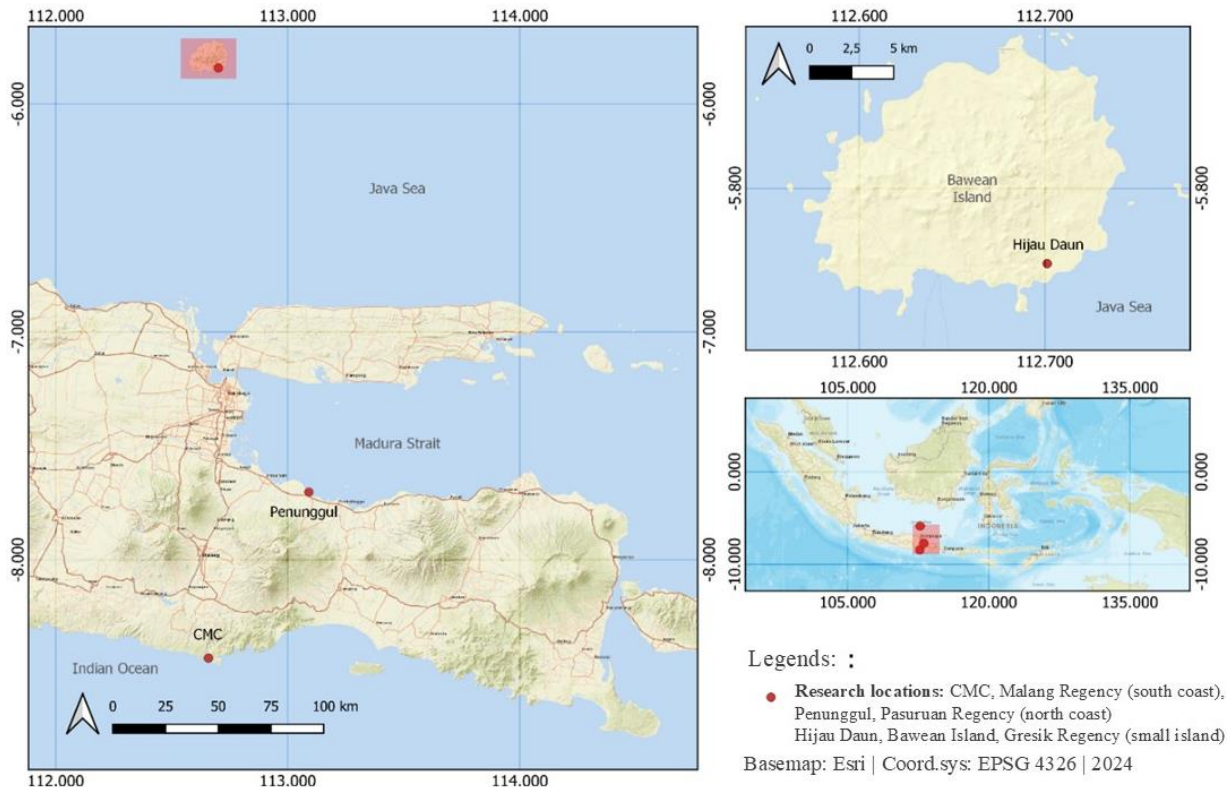


Figure 1. Map of research locations

NDVI values were computed using the (normalized Difference) function in GEE. NIR represents the near-infrared reflectance (Landsat 7: Band 4, Sentinel-2: Band 8), and RED represents the red reflectance (Landsat 7: Band 3, Sentinel-2: Band 4). Normalized Difference Vegetation Index (NDVI) was calculated for each year using the following formula (Pettorelli et al., 2005):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

NDVI rasters derived from Landsat 2012 and Sentinel 2024 satellite imagery. To ensure compatibility between datasets, spatial harmonization were performed to obtain comparable pixels. Sentinel-2 NDVI raster was resampled and aligned to Landsat 7 (30 m resolution) using Qgis software. The NDVI values for 2024 and 2012 then compared on a pixel-by-pixel basis to assess temporal changes in vegetation cover. This comparison was performed using the QGIS raster calculator, with the net NDVI value change ($\Delta NDVI$) calculated as:

$$\Delta NDVI = NDVI_{2024} - NDVI_{2012}$$

Positive values of $\Delta NDVI$ represent increase in vegetation cover, while negative values suggest a decrease. The resulting raster file was exported in GeoTIFF format and imported into R software using Terra package (Hijmans, 2020). $\Delta NDVI$ was derived by subtracting baseline from recent NDVI, which theoretically ranges between -2 and 2. For classification and visualization, $\Delta NDVI$ values were normalized to a 0-1 scale. $\Delta NDVI$ values were further reclassified into predefined ranges (0-1) to facilitate a deeper understanding of vegetation dynamics as a result of rehabilitation efforts.

2.2 Present ecological mangrove condition

Mangrove ecological quality consists of mangrove density, important value index (IVI) and mangrove health index (MHI). Field data collection was carried out at three locations, namely Penunggul, CMC and Hijau Daun. Primary variable of community structure represented by mangrove DBH size (cm) at 1.3 m height, mangrove density (ind/ha) and IVI. IVI

is widely used to explain ecological dominance of a species within forest community (Darmawan and Pramudji, 2017). It is calculated using the relative density (RD), relative frequency (RF) and relative dominance (RD), as explained from following equations:

$$RD_i = \left(\frac{N_i}{N_{tot}} \right) \times 100$$

$$RF_i = \left(\frac{F_i}{F_{tot}} \right) \times 100$$

$$RDom_i = \left(\frac{BA_i}{BA_{tot}} \right) \times 100$$

$$BA_i = \pi \left(\frac{DBH_i}{2} \right)^2$$

$$IVI = RD_i + RF_i + RDom_i$$

MHI model was generated by combination of vegetation indices algorithms (NBR, GCI, SIPI, and ARVI) (Nurdiansah and Dharmawan, 2021). Mangrove health index (MHI) represents the condition of healthy and productive mangrove ecosystem, supported by adequate natural regeneration to ensure the sustainability of the mangrove community. It calculated from canopy cover, sapling density and sapling-tree diameter (Nurdiansah and Dharmawan, 2021). MHI categorized mangrove condition into three categories: Poor ($MHI \leq 33.33\%$), Moderate ($33.33\% < MHI \leq 66.67\%$) and Excellent ($MHI > 66.67\%$). MHI values were used to determine the placement of sampling plots for field sampling, representing the poor, moderate, and excellent categories.

2.2 Stakeholder analysis

Semi-structured interviews were conducted with key local stakeholders in the study areas to obtain information related to motivations, activities and challenges of their initiatives. A descriptive analysis was performed to understand the impact of SSCM activities on mangrove ecosystem quality. This analysis can inform the development of strategies for mangrove conservation and restoration.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Temporal changes of mangrove cover

In the 1980s, coastal area of Penunggul Village experienced significant degradation due to land conversion. In response, local community initiated voluntary mangrove replanting in 1985, using propagules of *Rhizophora* spp. (Sofian et al., 2012). Restoration site focused in abandoned farms and sedimentation zone surrounding Lewean rivermouth. This initiative marked the beginning of small-scale, community-based mangrove restoration in East Java.

Existing mangrove area in Penunggul Village spans approximately 31 ha, with a stable shoreline trend observed in the restored mangrove area, while the Lewean rivermouth continues to expand seaward. Temporal analysis using NDVI over the past decade (Figure 2) shows increase in maximum NDVI values (from 0.42 in 2012 to 0.60 in 2024) and a reduction in open areas, particularly in former abandoned farms. This reflects improvement in vegetation cover, driven by both replanting efforts and natural mangrove regeneration.

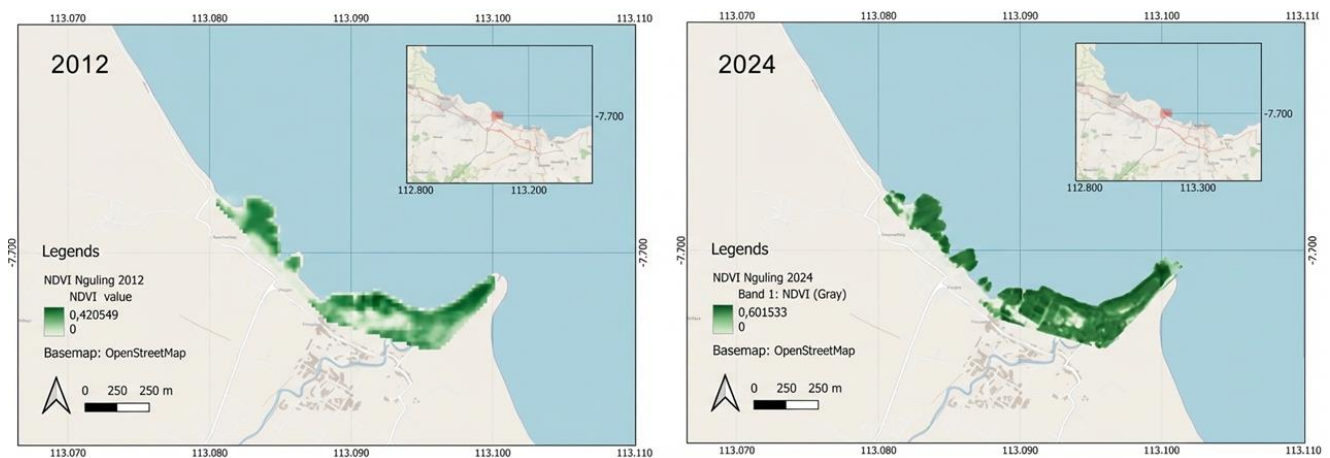


Figure 2. Temporal change of mangrove area in Penunggul, Pasuruan

Clungup mangrove conservation (CMC) represents inland mangrove in uplifted region, south coast of Malang. This area experienced severe deforestation from 1998 to early 2000s. Started in 2012, small-scale restoration initiatives were initiated voluntarily by local community (Antyo et al., 2018). The establishment of the Supervisory Community Group (POKMASWAS) GOAL played a pivotal role

in enhancing the restoration efforts. From 2012-2024, CMC gradually experienced significant improvements in mangrove cover. NDVI analysis revealed notable changes. In 2012, NDVI scores ranged from 0-0.4, representing majority of open areas and sparse vegetation cover. By 2024, NDVI values mostly range between 0.3-0.6, indicates moderate to dense vegetation cover (Figure 3).

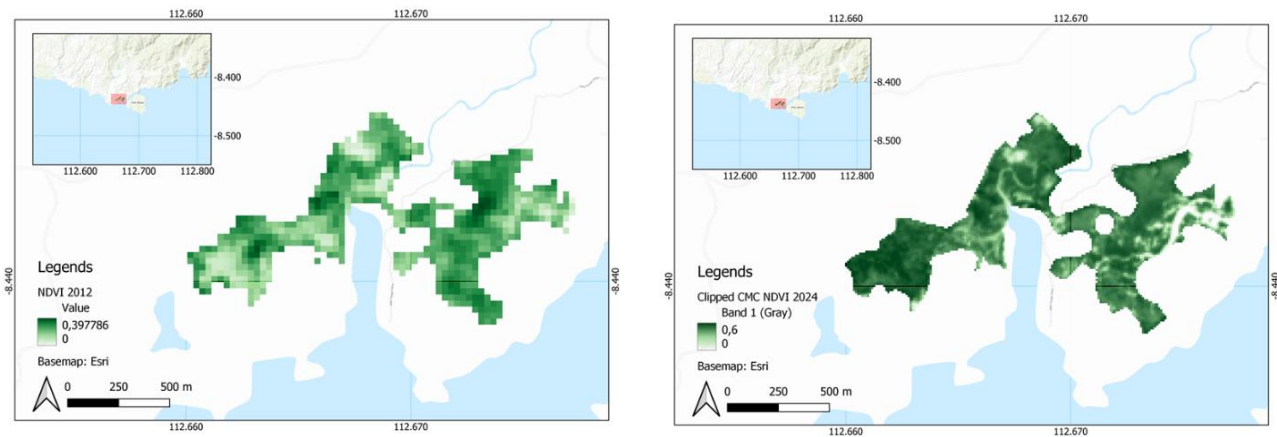


Figure 3. Temporal change of mangrove area in CMC, Malang

Hijau Daun in Bawean Island has a coastal area dominated by fringing mangroves, with a tidal inlet that drains the tides into the back mangroves, protecting vast area of rice fields behind mangrove stands. In the 1990s, mangrove along the coast of Hijau Daun, Bawean, suffered extensive damage due to overharvesting for firewood and the use of destructive fishing. These activities led to 43 ha coastal erosion in 2004, inundating productive rice-fields and severely affected the village's economy (Saputra et al., 2024). In response, a local youth group in 2008 initiated voluntary activities to restore

mangrove ecosystem. Temporal analysis using NDVI revealed significant shifts in vegetation cover classes during last decade. In 2012, NDVI values ranged from 0-0.44, indicating the dominance of sparse to moderate vegetation cover. By 2024, NDVI values had shifted to 0.30-0.66, signifying a majority of moderate to dense categories (Figure 4). However, there has been no significant seaward mangrove expansion due to the characteristics of small island beaches, which receive minimal sediment input from terrestrial sources.

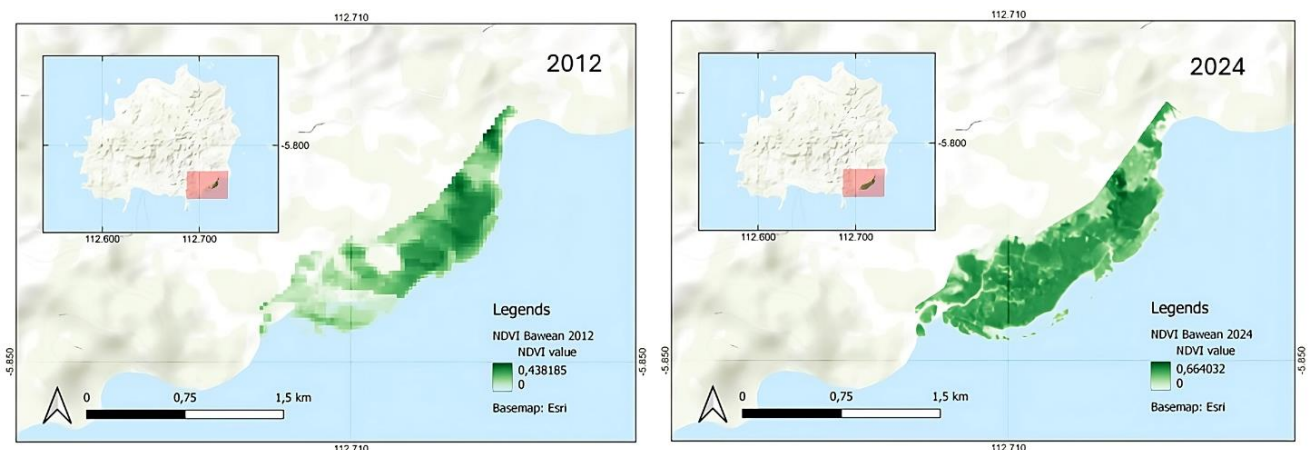


Figure 4. Temporal change of mangrove cover in Hijau Daun, Bawean Island

Analysis of NDVI value change (Δ NDVI) performed by reclassifying pixel value 0-1, divided into equal interval. With the temporal observation spanning over one decade, value Δ NDVI less than 0.3 can be categorized as mild improvement in mangrove cover, while more than 0.4 considered as significant change. Based on pixel count of Δ NDVI, Bawean and Penunggul has the highest pixel count within 0-0.1 class, while CMC has the most value in 0.2-0.3 class. This difference can be attributed to the varying starting points of rehabilitation efforts. Penunggul began its rehabilitation activities since 1980s, allowing ample time for vegetation to recover and establish in early

decade of restoration. Similarly, Hijau Daun in Bawean Island initiated its rehabilitation efforts in 2008, benefiting from over a decade of both replantation and natural regeneration. Moreover, both locations using fast growing *Rhizophora* spp. as primary replanted species, which will produce significant canopy density after five years of plantation. In contrast, CMC started rehabilitation initiatives in 2012, which consequently, temporal analysis spanning last 10 years reflects significant changes in vegetation cover, encompassing almost entire CMC area (Figure 5).

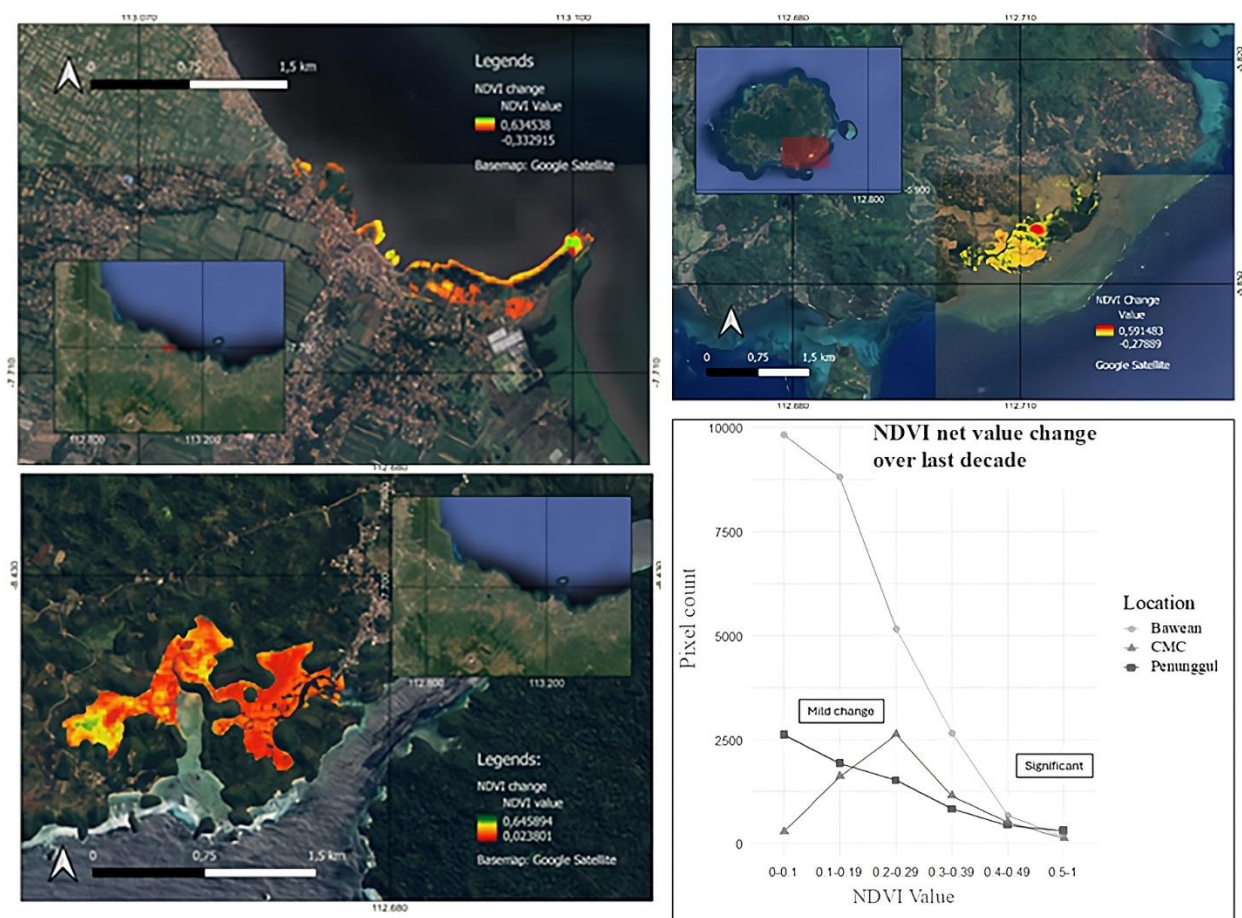


Figure 5. Net change of NDVI values (Δ NDVI) from each location over the last decade

Mangrove in Penunggul supported by favorable coastal characteristic that naturally promote mangrove growth (muddy substrate and high sediment input, particularly surrounding Lewean rivermouth in Penunggul). In contrast, CMC (uplifted south coast) and Hijau Daun (carbonate small island) tend to stable. These two locations faces biophysical limitations due to its predominantly sandy substrate and the lack of organic matter input from terrestrial sources.

3.1.2 Present ecological status of mangrove

After more than one decade, restoration initiatives by local communities shows clear ecological recovery. Sampling plots in Penunggul dominated by tree category (mean DBH 7.70 ± 3.34 cm), dominated by *Rhizophora* spp. In CMC, restoration in the karstic environment produced diverse species and mangrove stands. There are eight species recorded within plot, with mean DBH is

5.70±2.20 cm. Plots in Hijau Daun, Bawean, consists of six mangrove species with various DBH size. Mixed replanted *Rhizophoraceae* combined with old natural *Sonneratia* stands contribute wide DBH range (2-37 cm) with mean of 9.27±7.24 cm. All three sites

has average density more than 1,000 ind/ha, categorized as moderate to good condition, according to Ministry of Forestry standard (Darmawan and Pramudji, 2017). DBH distribution and mangrove density presented in Figure 6.

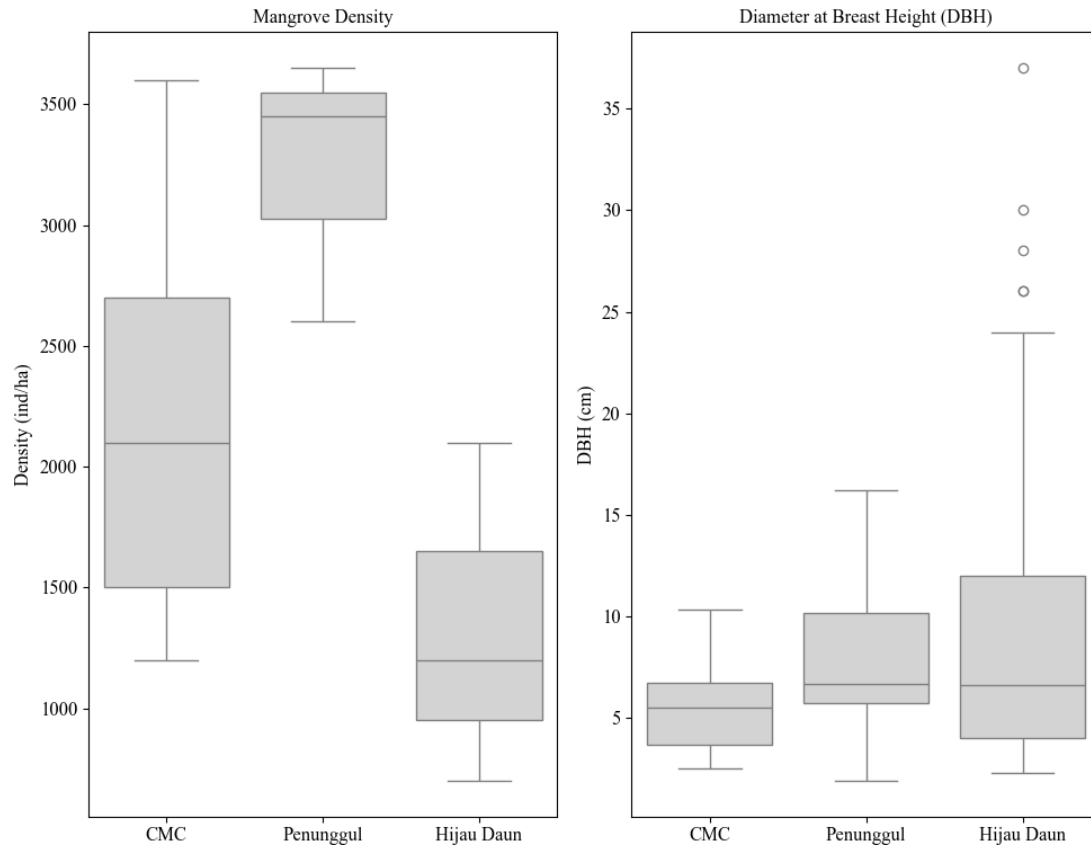


Figure 6. DBH distribution and mangrove density from each location

Most of mangrove area in CMC categorized as excellent MHI (38.4 ha, represents 69.3% of total area), while most of mangrove areas in Penunggul and Hijau Daun, dominated by moderate class of MHI. Penunggul has 12.5 ha of mangrove in moderate category (represents 57.5% of total area), while Hijau Daun has 61.5 ha of mangrove within moderate

category (62.2% of total area). All three locations have less than 10% of “poor” category MHI (Figure 7).

Present ecological condition of the three SSCM sites are summarized in Table 1. Ecological variables determine mangrove status under Min. Decree of Indonesia No. 201/2004.

Table 1. Present ecological condition as resulted from SSCM initiatives

RestorationSite	Dominant species (IVI)	DBH (cm)/ mean±SD	% Trees (DBH≥5 cm)	Density (ind/ha, mean±range)	Category
Penunggul (Pasuruan)	<i>R. mucronata</i> (155.63), <i>R. apiculata</i> (144.37)	2-16/7.70±3.34	87.5%	2,300 (low variability)	Good
CMC (Malang)	<i>R. apiculata</i> (196.99-231.66), <i>C. tagal</i> (208.81-300), <i>S. alba</i> , <i>B. gymnorrhiza</i>	3-10/5.70±2.20	66.7%	2,155 (1,200-3,600)	Good
Hijau Daun (Bawean Island)	<i>R. stylosa</i> (151.94), <i>A. marina</i> (91.84), <i>S. alba</i> (123.58)	2-37/9.27±7.24	70.9%	1,333 (700-2,100)	Moderate

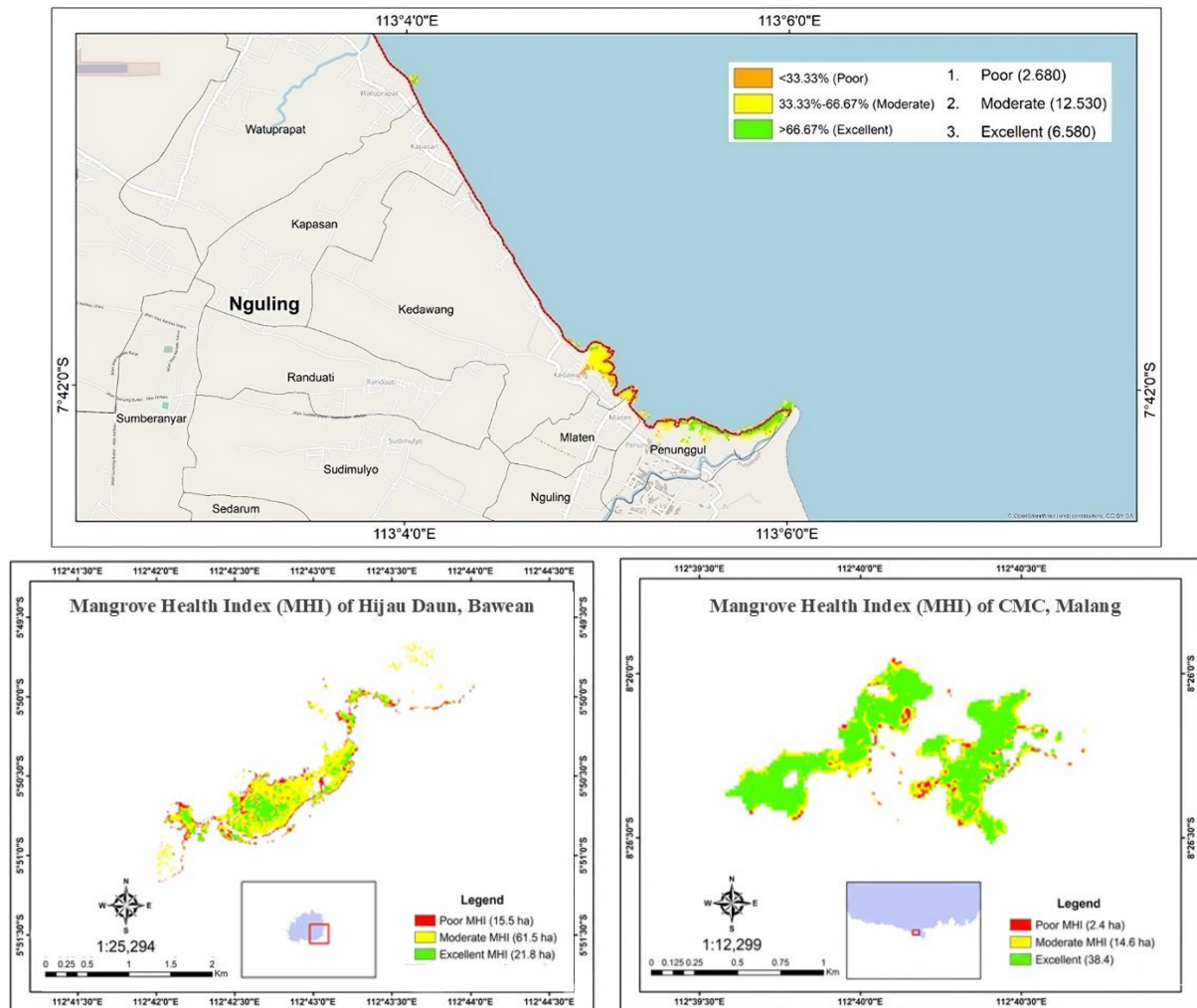


Figure 7. MHI value shows good condition of restored mangrove areas

4. DISCUSSION

Δ NDVI analysis confirms that SSCM increased canopy cover significantly at all sites. CMC, rehabilitated since 2012, has the highest Δ NDVI (0.2-0.3), which suggests rapid change due to fast-growing *Rhizophora* spp. Penunggul (since the 1980s) and Bawean (since 2008) both have small Δ NDVI (0-0.1). Penunggul indicates old stable maturity stands, where biophysical constraints in Bawean limit the mangrove growth. Restoration age thus controls canopy dynamics considerably, such that early-stage restoration exhibits fast increases, whilst older systems register stability more than growth (Lovell and Brown, 2019; Sasmito et al., 2019; Sasmito et al., 2023; Howard et al., 2023).

A single NDVI reading can't solely determine restoration effectiveness. Negative results can signify conversion for agriculture or aquaculture uses. Static change in NDVI values can be a sign of location-specific biophysical constraints, and drastic NDVI

improvement can sometimes be indicative of invasive species growth. Other algorithms (Baloloy et al., 2020; Nurdiansah and Dharmawan, 2021; Winarso et al., 2023) and in-field ecological information are needed for proper assessment.

Stakeholder interviews highlight community motivation as the key driver for long-term success. Many villagers who, since childhood, had witnessed mangrove decline, were deeply motivated to restore them. Early restoration efforts were carried out voluntarily, despite social tensions, lack of funding and technological constraints. Sustained efforts over more than five years led to ecological recovery, the return of bird populations, and increased productivity of mangrove crab and fisheries. This strong community incentive distinguishes SSCM from large-scale restoration programs, which are often driven by regulatory objectives (Arifanti et al., 2022b; Friess et al., 2022; Quevedo et al., 2023). On the densely inhabited coast of Java, there is very limited space

available for large-scale restoration (Worthington and Spalding, 2018), as many biophysically suitable areas area already used for fisheries and coastal activities (Saputra et al., 2022b; Saputra, 2023). Tenure conflicts regarding the land contribute to another barrier (Lovelock and Brown, 2019). In contrast, small-scale conservation of existing mangrove stands is often more feasible and cost-effective. SSCM, when adapted to the local conditions, provides pragmatic and sustainable solutions (Sasmito et al., 2023).

Another benefit of SSCM is a strong connection with local livelihoods. Ecotourism and aquaculture activities generate income that complements conservation efforts. For example, Penunggul and CMC programs promote ecotourism (Sofian et al., 2012; Harahab and Setiawan, 2017), while in Bawean, restoration with crab aquaculture (Saputra et al., 2024). Such activities help alleviate poverty while strengthening local ownership of conservation outcomes.

5. CONCLUSION

This study reveals that SSCM has effectively enhanced mangrove canopy cover and ecosystem quality over the past decade. Change detection analysis using Δ NDVI shows positive trends across all three sites, with CMC recording the most Δ NDVI values in the 0.2-0.3 range, reflecting rapid recovery due to its early restoration phase. In contrast, Penunggul and Hijau Daun-both with longer restoration histories-display smaller Δ NDVI changes (0-0.1), reflecting their mature and stable ecosystems. However, Δ NDVI alone cannot fully capture restoration success, as it is shaped by factors such as biophysical conditions, invasive species, and land-use changes. All sites demonstrated improved ecological quality, indicated by increased mangrove density and mangrove health index (MHI) values. Our findings demonstrate strong relations between SSCM interventions and the observed improvements in vegetation cover and ecological quality. The temporal alignment between restoration activities and positive Δ NDVI trends, combined with field evidence of improved mangrove condition, supports this interpretation. Overall, the results highlight the value of SSCM as a practical and adaptive approach to mangrove conservation and recovery.

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AUTHOR CONTRIBUTIONS

The contribution of each author as follow, DKS; collected the data, performed data processing and analysis and drafted the manuscript. SS, AT, ES, HH, UZ, MM, AS, YEP; devised the main conceptual ideas and critical revision of the article. AY, SSR, MAA, MAZF; concepting, provide additional data and supervising of the analysis. All authors discussed the results and contributed to the final manuscript.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Abidin Z, Nuryani FE, Saputra DK, Fattah M, Harahab N, Kusumawati A. Mangrove potential assessment for determining ecotourism attraction and strengthening destination branding and marketing: "Gunung Pitihing Mangrove Conservation", Indonesia. *Geojournal of Tourism and Geosites* 2023;47(2):388-96.
- Alongi DM. Carbon sequestration in mangrove forests. *Carbon Management* 2012;3(3):313-22.
- Antyo F, Riniwati H, Nugroho I. The role of volunteer for the management of conservation-based ecotourism in Clungup Mangrove Conservation Tambakrejo Village, Sumbermanjing Wetan Sub-District, Malang Studies. *Journal of Indonesian Tourism and Development Studies* 2018;6(3):187-93.
- Arifanti VB, Kauffman JB, Subarno, Ilman M, Tosiani A, Novita N. Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia. *Global Change Biology* 2022a;28(15):4523-38.
- Arifanti VB, Sidik F, Mulyanto B, Susilowati A, Wahyuni T, Yuniarti N, et al. Challenges and strategies for sustainable mangrove management in Indonesia: A review. *Forests* 2022b;13(5):Article No. 695.
- Arsad S, Daryanto AO, Sari LA, Saputra DK, Pratiwi FD. Community-based ecotourism and its impact on the social and economic conditions: A case study in Blekok, Situbondo Regency, Indonesia. *Journal of Environmental Management and Tourism* 2021;12(3):797-807.
- Asadi M, Semedi B, Rahardani A, Soegianto A. Carbon storage of mangrove ecosystems in Pasuruan and Probolinggo Regency, East Java, Indonesia. *Ecology, Environment and Conservation* 2019;25:161-7.
- Asadi MA, Yona D, Fikri MZ. Comparing carbon in sediment of primary and artificially generated mangrove forests. *Disaster Advances* 2018;11(11):18-26.
- Baloloy AB, Blanco AC, Sta. Ana RRC, Nadaoka K. Development and application of a new mangrove vegetation index (MVI) for rapid and accurate mangrove mapping. *ISPRS Journal of Photogrammetry and Remote Sensing* 2020;166:95-117.
- Bimrah K, Dasgupta R, Hashimoto S, Saizen I, Dhyani S. Ecosystem services of mangroves: A systematic review and synthesis of contemporary scientific literature. *Sustainability (Switzerland)* 2022;14(19):Article No. 12051.

- Chen J, Zhu X, Vogelmann JE, Gao F, Jin S. A simple and effective method for filling gaps in Landsat ETM+ SLC-off images. *Remote Sensing of Environment* 2011;115(4):1053-64.
- Cohen-Shacham E, Walters G, Janzen C, Maginnis S, editors. *Nature-Based Solutions to Address Global Societal Challenges*. Gland: IUCN; 2016.
- Darmawan IWE, Pramudji S. *Mangrove Community Monitoring Guide (P20-LIPI)*. Jakarta: Lembaga Ilmu Pengetahuan Indonesia; 2017 (in Bahasa).
- Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 2011;4:293-7.
- Friess DA, Gatt YM, Ahmad R, Brown BM, Sidik F, Wodehouse D. Achieving ambitious mangrove restoration targets will need a transdisciplinary and evidence-informed approach. *One Earth* 2022;5(5):456-60.
- Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. Google earth engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* 2017;202:18-27.
- Hakim L, Siswanto D, Makagoshi N. Mangrove conservation in East Java: The ecotourism development perspectives. *Journal of Tropical Life Science* 2017;7(3):277-85.
- Harahab N. The influence of mangrove forest ecosystems on capture fisheries production (A case study in Pasuruan Regency, East Java). *Jurnal Perikanan (J Fish Sci)* 2009;11(1):100-6 (in Bahasa).
- Harahab N, Setiawan S. Suitability index of mangrove ecotourism in Malang Regency. *Economic and Social of Fisheries and Marine Journal* 2017;4(2):153-65.
- Hardoko ES, Puspitasari YE, Amalia R. Study of ripe *Rhizophora mucronata* fruit flour as functional food for antidiabetic. *International Food Research Journal* 2015;22:953-9.
- Hardoko M, Sasmito BB, Fitriani EN. Studi aktivitas antidiabet cuka buah mangrove pedada (*Sonneratia alba*) secara in vivo. *Journal of Fisheries and Marine Research* 2020;4(3):399-407.
- Hijmans RJ. Terra: Spatial data analysis [Internet]. 2020 [cited 2025 Apr 4]. Available from: <https://CRAN.R-project.org/package=terra>.
- Howard J, Sutton-Grier AE, Smart LS, Lopes CC, Hamilton J, Kleypas J, et al. Blue carbon pathways for climate mitigation: Known, emerging and unlikely. *Marine Policy* 2023;156:Article No. 105788.
- Intyas CA, Primyastanto M, Tjahjono A, Yustinaningrum D. Activities mapping in the three mangrove ecotourism in East Java. *EM International* 2021;27:115-21.
- Kathiresan K, Bingham BL. Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology* 2001;40:81-251.
- Lovelock CE, Brown BM. Land tenure considerations are key to successful mangrove restoration. *Nature Ecology and Evolution* 2019;3(8):Article No. 1135.
- McLeod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, et al. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment* 2011;9(10):552-60.
- Ministry of Forestry. *National Mangrove Map (Peta Mangrove Nasional)*. Jakarta: PDASRH, KLHK; 2021. (in Bahasa)
- Nurdiansah D, Dharmawan IWE. Community structure and mangrove health conditions on Middlebur Island (Struktur Komunitas dan Kondisi Kesehatan Mangrove di Pulau Middlebur). *Jurnal Ilmu dan Teknologi Kelautan Tropis* 2021;13:81-96 (in Bahasa).
- Pettorelli N, Vik JO, Mysterud A, Gaillard JM, Tucker CJ, Stenseth NChr. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology and Evolution* 2005;20(9):503-10.
- Quevedo JMD, Lukman KM, Ulumuddin YI, Uchiyama Y, Kohsaka R. Applying the DPSIR framework to qualitatively assess the globally important mangrove ecosystems of Indonesia: A review towards evidence-based policymaking approaches. *Marine Policy* 2023;147:Article No. 105354.
- Saputra DK. *Small-Scale Rehabilitation for Sustainable Mangrove Management in East Java (Rehabilitasi Skala Kecil untuk Pengelolaan Mangrove Berkelanjutan di Jawa Timur)* (Short policy brief). Brawijaya University. Policy Brief No.1. 2023. (in Bahasa).
- Saputra DK, Darmawan A, Silitonga N, Asadi MA, Aliviyanti D, Arif M, et al. Shoreline evolution and mangrove landscape transition in Probolinggo, East Java, Indonesia. *Ecology Environment and Conservation* 2022a;28(1):105-12.
- Saputra DK, Maftuch, Riyanto FAD, Septiani A, Luqmania D, Anjum, et al. *Om Budi: Integrated Sustainable Aquaculture in Daun Village, Bawean Island (Om Budi: Budidaya Perikanan Berkelanjutan Terintegrasi Desa Daun, Pulau Bawean)*. Indonesia: MNC Publishing; 2024 (in Bahasa).
- Saputra DK, Semedi B, Darmawan A, Luthfi OM, Handayani M, Arsad S. Habitat management based on mangrove sensitivity assesment in Tulungagung Coastal Area. *Economic and Social of Fisheries and Marine Journal* 2020;007(02):258-67.
- Saputra DK, Semedi B, Yamindago A, Dewi CSU, Asadi MA, Isdianto A, et al. Characteristics of mangrove fisheries in Essential Ecosystem Area Ujungpangkah, Indonesia. *Journal of Environmental Management and Tourism* 2022b;13(3):812-20.
- Sasmito S, Basyuni M, Kridalaksana A, Saragi-Sasmito M, Lovelock C, Murdiyarso D. Proper restoration of Indonesia's mangrove forests can contribute to the achievement of the Sustainable Development Goals (SDGs). (Merestorasi hutan mangrove Indonesia dengan benar dapat membantu pencapaian Sustainable Development Goals (SDGs)). University North Sumatera. Policy Brief. 2023 (in Bahasa).
- Sasmito SD, Taillardat P, Clendenning JN, Cameron C, Friess DA, Murdiyarso D, et al. Effect of land-use and land-cover change on mangrove blue carbon: A systematic review. *Global Change Biology* 2019;25(12):4291-302.
- Sidik F, Saputra D, Ulumuddin YI, Suarez E. IUCN Red List of Ecosystems, Mangroves of the Java Transitional. *EcoEvoRxiv*; 2025.
- Sofian A, Harahab N, Marsoedi. The condition and direct benefits of the mangrove forest ecosystem in Penunggul Village, Nguling District, Pasuruan Regency (Kondisi Dan Manfaat Langsung Ekosistem Hutan Mangrove Desa Penunggul Kecamatan Nguling Kabupaten Pasuruan). *El-Hayah: Jurnal Biologi* 2012;2(2):56-63 (in Bahasa).
- Susilo E, Purwanti P, Lestariadi RA. The sustainability of “Kejung Samudra” in the management and utilization of mangrove resources in Pancer Cengkong and Damas, Prigi Beach, Trenggalek (Keberlanjutan “Kejung Samudra” Dalam Pengelolaan Dan Pemanfaatan Sumberdaya Mangrove Di Pancer Cengkong Dan Damas, Pantai Prigi, Trenggalek). *Jurnal Kebijakan Sosek KP* 2015;5(2):19-25 (in Bahasa).

- Taconi L. Decentralization, forests and livelihoods: Theory and narrative. *Global Environmental Change* 2007;17(3):338-48.
- Winarso G, Rosid MS, Kamal M, Asriningrum W, Margules C, Supriatna J. Comparison of mangrove index (MI) and normalized difference vegetation index (NDVI) for the detection of degraded mangroves in Alas Purwo Banyuwangi and Segara Anakan Cilacap, Indonesia. *Ecological Engineering* 2023;197:Article No. 107119.
- Worthington T, Spalding M. Mangrove restoration potential: A global map highlighting a critical opportunity [Internet]. 2018 [cited 2025 Jan 17]. Available from: <https://www.repository.cam.ac.uk/handle/1810/292000>.

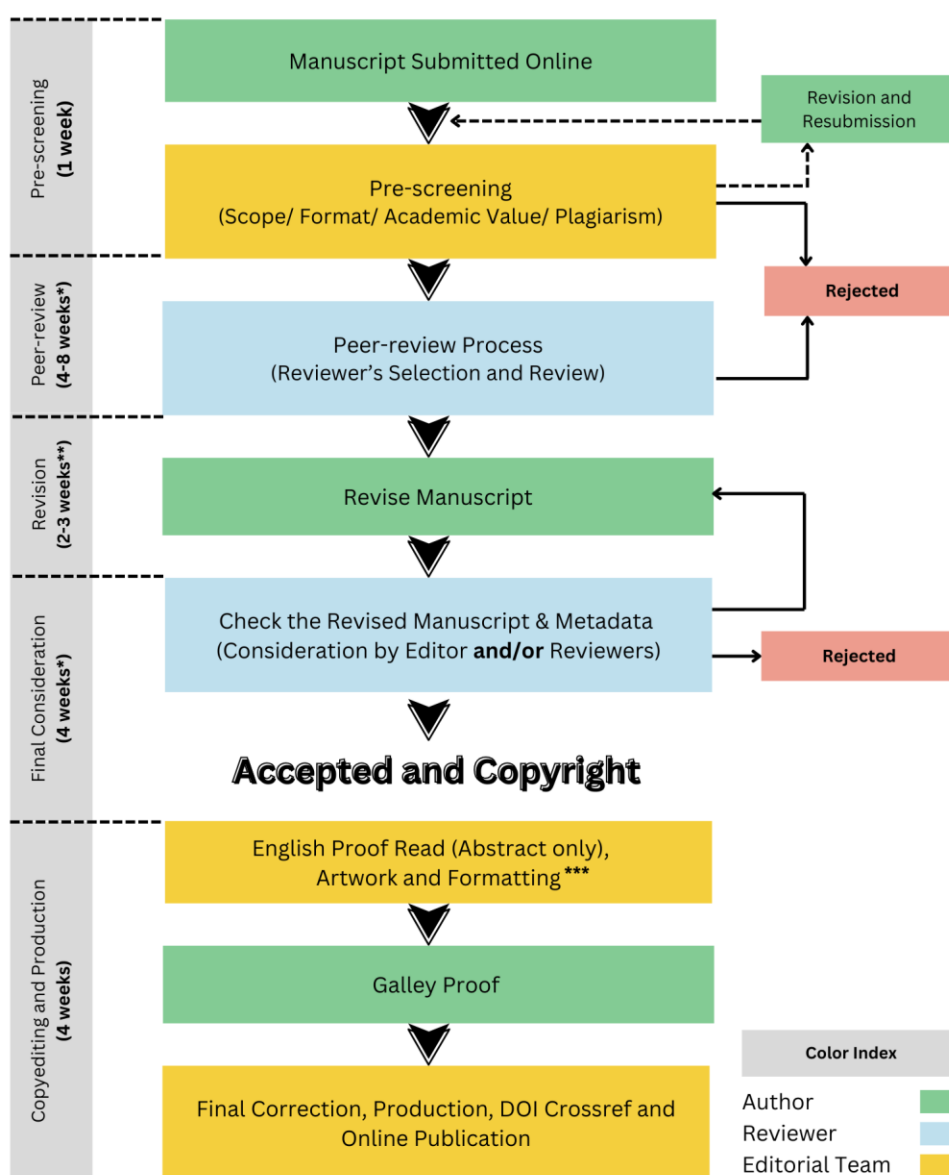
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2. Methodology

2.1 Sub-heading

2.1.1 Sub-sub-heading

Results presents the key findings in figures and tables with descriptive explanations in the text.

Tables

- Tables - look best if all the cells are not bordered; place horizontal borders only under the legend, the column headings, and the bottom.

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Discussion shows the interpretation of findings with supporting theory and comparisons to other studies. The Results and Discussion sections can be either separated, or combined. If combined, the section should be named Results and Discussion. **Conclusions** should include a summary of the key findings and take-home messages. This should not be too long, or repetitive but this section is absolutely necessary so that the argument of the manuscript is not uncertain or left unfinished.

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Sah D. Concentration, source apportionment and human health risk assessment of elements in PM_{2.5} at Agra, India. Urban Climate 2023;49:Article No. 101477.

Non-English articles

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Article in press

Dhiman V, Kumar A. Biomass and carbon stock estimation through remote sensing and field methods of subtropical Himalayan Forest under threat due to developmental activities. Environment and Natural Resources Journal 2024. DOI: 10.32526/enrj/22/20240018.

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Ph.D./Master thesis

Shrestha MK. Relative Ungulate Abundance in a Fragmented Landscape: Implications for Tiger Conservation [dissertation]. Saint Paul, University of Minnesota; 2004.

Website

Orzel C. Wind and temperature: why doesn't windy equal hot? [Internet]. 2010 [cited 2016 Jun 20]. Available from: <http://scienceblogs.com/principles/2010/08/17/wind-and-temperature-why-doesn/>.

Report organization

Intergovernmental Panel on Climate Change (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories: Volume 1-5. Hayama, Japan: Institute for Global Environmental Strategies; 2006.

Royal Gazette

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