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Edelweiss Park, a community-based tourist destination in Wonokitri Village, Pasuruan Regency, East Java Province, Indonesia. The Motivation, Opportunity, and Ability (MOA) model was used to study its thriving management and sustainability.

Source: Lestari AM, Khusaini M, Sholihah Q, Ciptadi G. The impact of community participation on tourism village management and sustainability: A case study in Wonokitri Village, Pasuruan. Page 366-378

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Editorial Office Address
Research and Academic Service, Research Management Unit,
Faculty of Environment and Resource Studies, Mahidol University
999, Phutthamonthon Sai 4 Road, Salaya, Phutthamonthon, Nakhon Pathom, Thailand, 73170
Phone +662 441 5000 ext. 2108
Website: https://ph02.tci-thaijo.org/index.php/ennrj/index
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CONTENT

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A Comprehensive Carbon Footprint Analysis and Emission Reduction in Wastewater Treatment Plants: A Case Study in Pattaya City

Woraphot Phongphalee[1], Apised Suwansaard[2], and Maneerat Khemkhao[1*]

[1]*Rattanakosin College for Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin, Thailand*
[2]*Faculty of Engineering, Rajamangala University of Technology Rattanakosin, Thailand*

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*** Corresponding author:**
E-mail:
maneerat.khe@rmutr.ac.th

ABSTRACT

This study analyzes the contributions of greenhouse gas (GHG) emissions in the wastewater treatment plants (WWTP) at Pattaya City to the areas of Naklua, Pattaya City, and Jomtien. This analysis was carried out 2021-2023 by visiting the sites, interviewing plant managers, filling out scientifically designed questionnaires and by processing the data obtained using computational methods developed by the Intergovernmental Panel on Climate Change. It was found that the total carbon footprint (CF) from both the Pattaya City and Jomtien WWTPs had the potential to contribute 5,610.61-6,020.18 tCO_2eq/year and that carbon intensity ranged between 0.45-0.47 kg CO_2eq/m^3 in treated wastewater. The study found that the main sources of emissions were the wastewater collection system (34.47-44.61%), activated sludge process (43.02-45.74%), and electricity consumption (30.02-39.48%). Therefore, the study suggests three options for GHG reduction. Installing solar cells on the office building roof could generate 156,780 kWh annually, resulting in a reduction of CO_2 emissions by 108.70 tCO_2eq/year, and a savings of 35,658.52 USD. This is equivalent to a 2.38% reduction in the WWTP's GHG emissions. Installing solar cells in the plant could also generate 823,680 kWh annually, leading to a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a savings of 187,304.58 USD. Installing a WWTP at station PS12 with a capacity of 60,874.65 m^3/day could also reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 36.41%, and result in a savings of 239,091.57 USD. To reach carbon neutrality and energy sustainability, the approaches for resource recovery, nutrient recycling, water reuse, and energy production on-site with combined heat and power (CHP) from biogas should be investigated in the future.

1. INTRODUCTION

As cities develop, the amount of municipal wastewater increases, necessitating the use of wastewater treatment plants to enhance water quality and reduce pollutants before discharging into water sources (Wang et al., 2022). The domestic wastewater system of Pattaya City has centralized wastewater treatment plants (WWTPs) that consist of the central combined sewer, pumping station, and central WWTP. There are two sites. The Pattaya City WWTP is located at Soi Nhong Yai and receives wastewater from the Pattaya and Naklua areas, and the Jomtien WWTP is located at Soi Wat Boon Kanjanaram and receives wastewater from the Jomtien area. The wastewater collection system consists of wastewater interceptors, wastewater delivery pipes, and pumping stations. There are 38 pumping stations located in the Pattaya and Naklua areas, 20 in the Jomtien area and also 15 water drainage pumping stations to prevent flooding. In addition, the system contains 1 water retardation reservoir, water diversion buildings (2 in the Pattaya and Naklua areas and 8 in the Jomtien area), and 4 storm water gates. The sewage pump is an automatic system.

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Most municipalities implement wastewater treatment plants to reduce harmful wastewater discharge into receiving water bodies (Enger et al., 2000). However, there are many potential sources of greenhouse gas (GHGs) emission from WWTPs during treatment. GHG can be released from WWTPs either directly or indirectly. The direct GHG emissions occur during wastewater and sludge treatment processes (IPCC, 2007), while the indirect GHG emissions occur from the consumption of energy, fuel, and chemicals required for wastewater treatment (Fitzsimons et al., 2016). WWTPs have been reported to be one of the largest minor GHG generators of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Corominas et al., 2012; Yerushalmi et al., 2013; Kyung et al., 2015). These GHGs all contribute to global warming. As stated by Myhre et al. (2013), the global warming potentials (GWP) of CO_2, CH_4, and N_2O account for 1, 34, and 298, respectively, over a 100-year period.

The carbon footprint (CF) is now seen as a way to measure sustainability in the wastewater sector and to measure how WWTPs affect climate change overall (Delre et al., 2019). As a result, reducing the CF has become one of the main topics of discussion in methods of improving WWTP performance (Ødegaard, 2016; Xu et al., 2017). All relevant forms of energy demand, i.e., electricity, heat, chemicals, fossil fuels, and transport, as well as GHG emissions of CO_2, CH_4, and N_2O, are now commonly accounted for in the CF assessment (Maktabifard et al., 2018).

It has been estimated recently that the GHG emissions of the waste sector in Thailand account for 3.74-4.73% of the total GHG emissions in Thailand (Ministry of Natural Resources and Environment, 2021). This sector is therefore one of the targets for reducing emissions in Thailand. In addition, GHG emissions from wastewater treatment and discharge accounted for 45.71% from the waste sector. Because of possible strict regulation by international climate change prevention protocols in the future, WWTPs could soon face the challenge of reducing their GHG emissions and maintaining the required quality of treated wastewater (Shahabadi et al., 2009). Therefore, it is necessary to accurately estimate the carbon footprint or GHG emissions from wastewater treatment plants in Thailand.

In a previous study by Phoolsap (2020), 4 WWTPs managed by the wastewater management authority in Chonburi province were assessed for GHG emissions. However, although Pattaya City is located in Chonburi province, there have been no studies done before on GHG emissions from Pattaya City. Therefore, the main aim of this study is to assess GHG emissions from WWTPs located in Pattaya City and to propose possible methods of reducing these emissions.

2. METHODOLOGY

2.1 Define study site, organizational boundaries, the scope of operations, and data collection

In this paper, the study site of the GHG emissions related to wastewater treatment were Pattaya City and Jomtien WWTPs. Pattaya City and Jomtien WWTPs span 0.128 and 0.021 km^2, respectively, with treatment capacities of 65,000 and 43,000 m^3/day, respectively.

There are three scopes for assessment of GHG emissions. The first scope is the direct GHG emissions, including stationary and mobile combustion, the wastewater treatment process including wastewater inflow rate (m^3/day), the influent and treated effluent concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total Kjeldahl nitrogen (TKN), and fugitive emission. The second scope are indirect GHG emissions from electricity usage. The third scope are other indirect GHG emissions including from chemicals, tap water, lubricants, etc. The boundaries and scopes for the Pattaya City and Jomtien WWTPs are shown in Figure 1.

The data included in this study was based on the daily operation reports of Pattaya City WWTPs and also on the annual operating data for the year 2021-2023 that was collected by visiting the plants, interviewing plant managers, filling out scientifically designed questionnaires using field data and by processing the data using computational methods developed by the Intergovernmental Panel on Climate Change.

2.2 Overall configuration of WTTPs

The studied WWTPs consisted of preliminary, primary, secondary, tertiary, sludge treatments, and wastewater treatment pools that were used to treat wastewater before discharging the treated water into the receiving water body (Figure 2). As shown in Figure 2, the wastewater entered into an inclined screw-type vortex grit chamber which removes sand from the incoming wastewater. After that, the wastewater is passed through a rotary drum screen. In the second step, an activated sludge (AS) system removes organic matter from the wastewater. This AS system consists of two main parts: the aeration tank and the sedimentation tank. The Pattaya City WWTP has a conventional AS, while the Jomtien WWTP has step feed biological nitrogen removal (BNR). In the fourth step, the Jomtien WWTP treated its wastewater with sodium hypochlorite in a chlorine contact tank and then collected it in an effluent pond before discharging it into the receiving water body. On the other hand, the Pattaya City WWTP-treated wastewater underwent filtration using a moving bed sand filter, followed by UV and chlorine disinfection. The treated water from both plants was also used for watering trees, lawns, and washing floors both inside and outside WWTP. The solids and extra sludge from the clarifier tank were then transferred into the storage tank and a cationic polymer was added for flocculation, and a gravity belt thickener was used to remove water from the sludge.

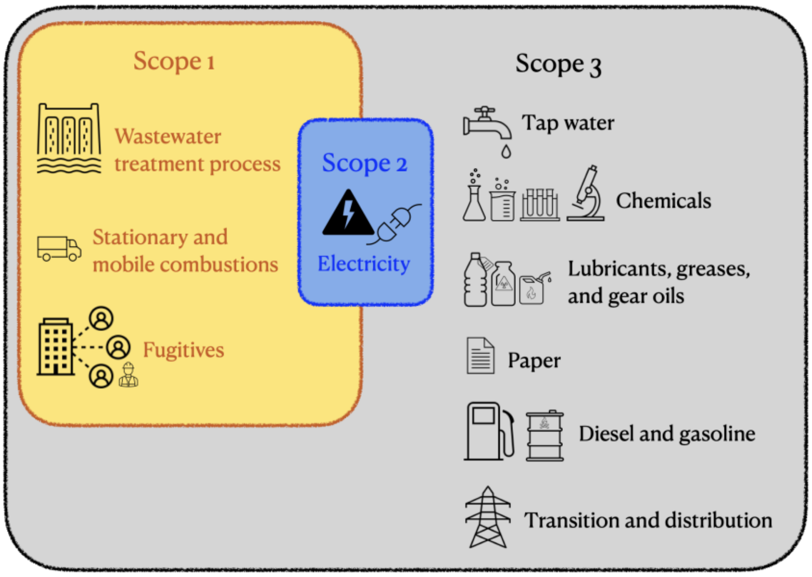

Figure 1. The boundaries and scopes for GHG emission from WWTP

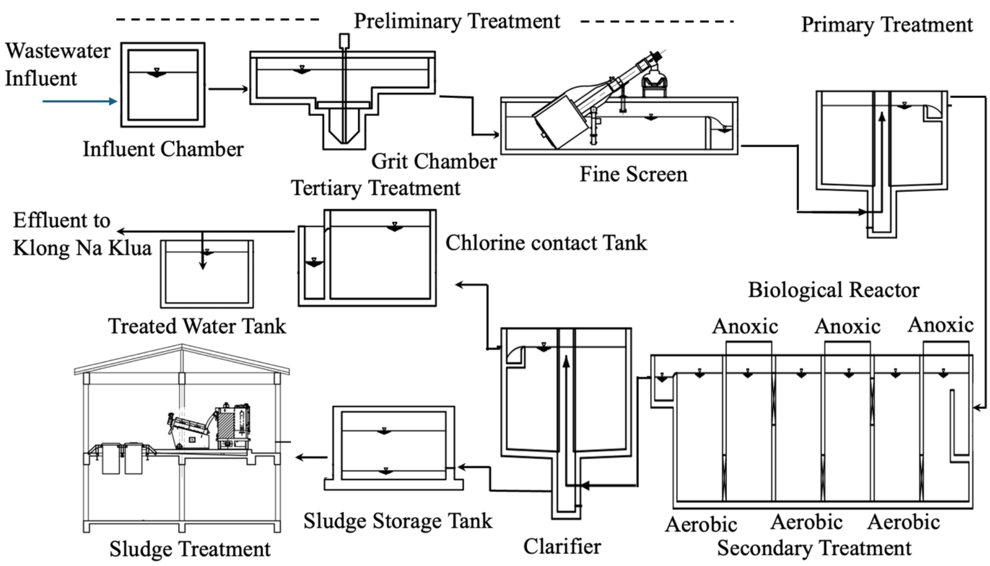

Figure 2. Overall wastewater treatment plant layout

2.3 GHG emission assessment from WWTPs

The GHG emissions of domestic Pattaya City WWTPs were analyzed according to the criteria "Guidelines for assessing an organization's carbon footprint" by the Thailand Greenhouse Gas Management Organization (TGO, 2015) with a level of limited assurance and a level of materiality of 5% (Threshold). The IPCC Vol. 2 for Scope 1 (April 1, 2022), the Thai National LCI Database for Scope 2 (July 2021), and the industry group for Scope 3

(January 1, 2023) were used to provide the emission factor (EF) for the evaluation of GHG emission (Table S1). In this study, the GHG footprint from the wastewater treatment plant was calculated in Equation (1).

$$GHG_i = AD_i \times EF_i \quad (1)$$

Where; GHG_i refers to the GHG emission from activity i ($kgCO_2eq$ or tCO_2eq), AD_i refers to activity data i (kg, m^3, kWh) and EF_i refers to emission factor of activity i ($kgCO_2eq$/unit).

The calculation of the corresponding CO_2eq uses the global warming potential (GWP) of 29.8 kg CO_2eq/kg CH_4 (fossil origin), 27.2 kg CO_2eq/kg CH_4 (non-fossil origin), and 273 kg CO_2eq/kg N_2O, based on a time period of 100 years (IPCC Sixth Assessment (AR6), 2024).

3. RESULTS AND DISCUSSION

3.1 Influent wastewater and properties of wastewater

Figure 3 shows the influent loading of incoming wastewater and its properties before and after treatment. The flow rate of wastewater from Pattaya City WWTP in 2021 increased from 47,083.43 m^3/day up to 57,171.44 m^3/day in 2022 but slightly increased to 58,757.04 m^3/day in 2023 (Figure 3(a)). The increase in population in Pattaya and Naklua was due to fast-growing tourism and hospitality after COVID-19. In contrast, the flow rate of Jomtien WWTP remained relatively constant between 2021 and 2023, ranging from 15,169.19 to 15,561.73 m^3/day. In both regions, these WWTPs were not overloaded since Pattaya City WWTP had a wastewater treatment capacity of 65,000 m^3/day, while Jomtien WWTP had a capacity of 45,000 m^3/day.

Treated wastewater from both sites has been tested and meets Thai national effluent quality criteria for discharge to the receiving water body (Figures 3(b)-3(c)). The removal efficiencies of COD and BOD from Pattaya City WWTP were 65.96±13.28% and 82.62±8.96%, respectively, whereas those from Jomtien WWTP were lower, at 54.78±17.58% and 60.23±16.61%, respectively. However, the TKN removal efficiency from Jomtien WWTP was 89.19±4.98%, slightly higher than that from Pattaya City WWTP, which was 81.92±9.56%. This is attributed to Jomtien WWTP's use of step feed BNR. In addition, the treated effluent was used as water reuse, which can produce 4,800 m^3/day, whereas the treated effluent from the Pattaya City WWTP after disinfection was discharged to Naklua Canal.

Nevertheless, these treated effluents are not proper for reuse in human or food contact applications (Kanchanapiya and Tantisattayakul, 2022). This is because new groups of emerging pollutants, such as per- and polyfluoroalkyl substances (PFAS), persistent organic pollutants (POPs), antibiotics, and pharmaceutical residues (Kunacheva et al., 2011; Schultz et al., 2006; Wang et al., 2022), were not included in the Thai national effluent quality. These pollutants may affect human health and the environment (Kanchanapiya and Tantisattayakul, 2022). In the future, freshwater sources could be in short supply in many areas and therefore these contaminants should be removed if the water is to be reused as a source of drinking water.

(a)

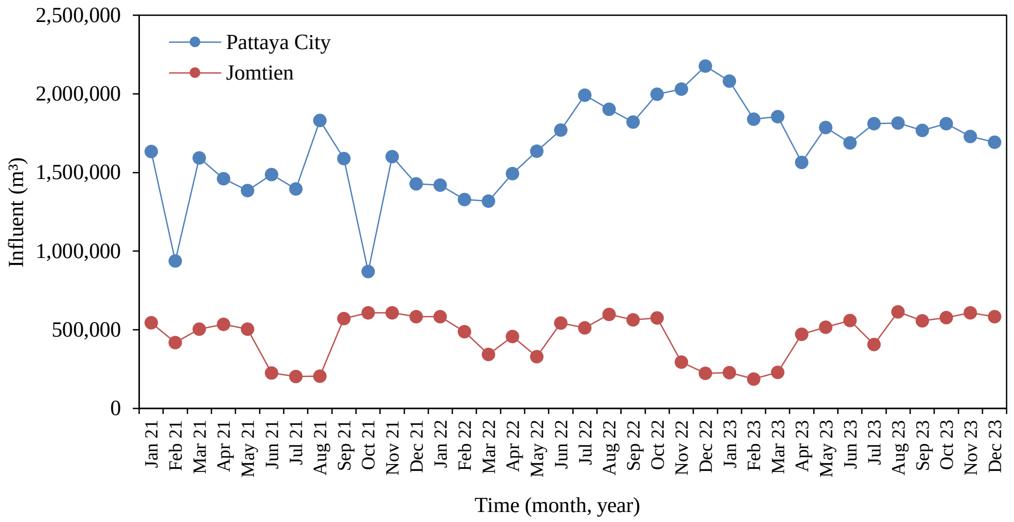

Figure 3. Wastewater loading and the properties of wastewater before and after treatment

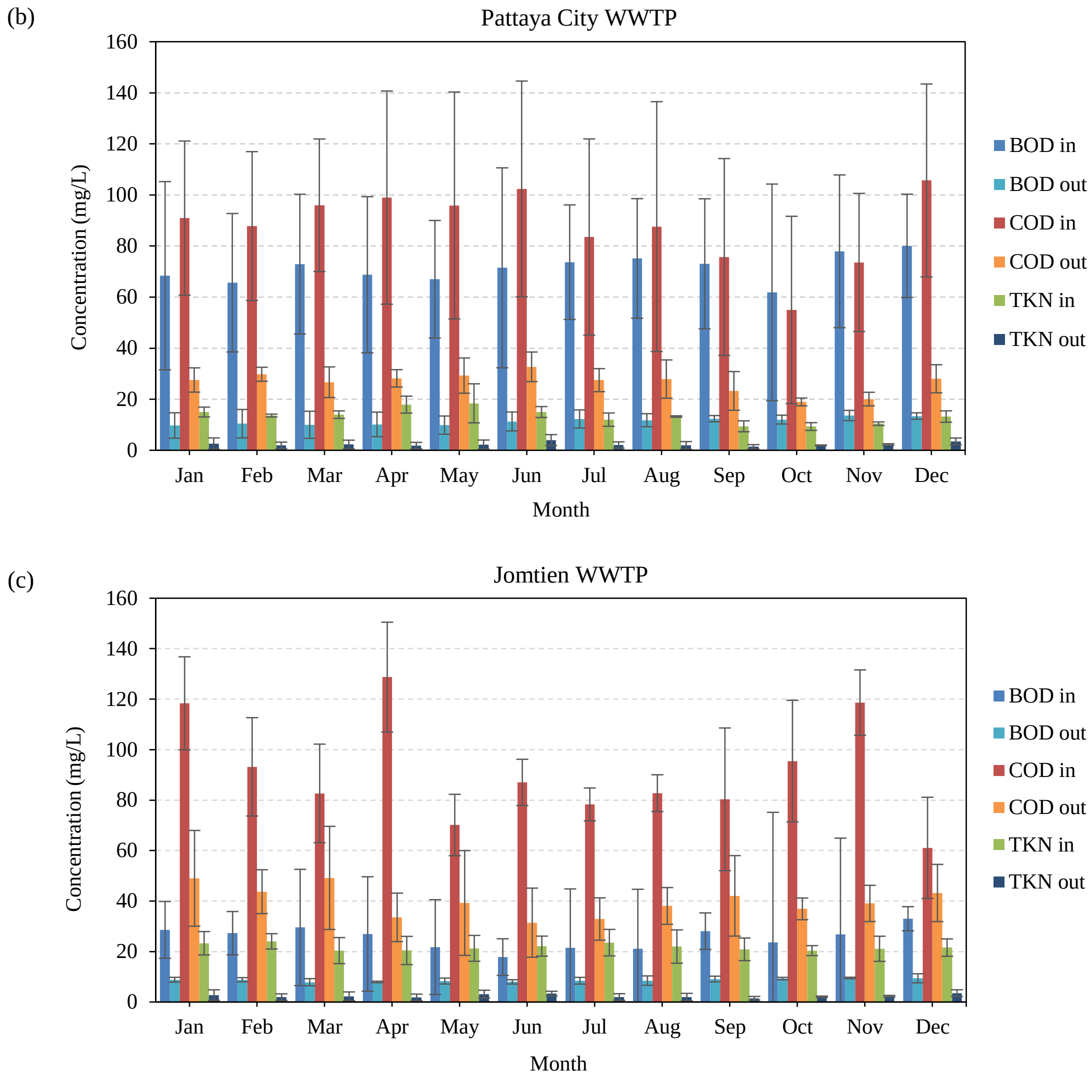

Figure 3. Wastewater loading and the properties of wastewater before and after treatment (cont.)

3.2 GHG footprint and carbon intensity from WWTP

3.2.1 GHG footprint from WWTP

Figure 4 shows the GHG emissions from the wastewater collection system and treatment plant. It was observed that the GHG footprint from Pattaya City WWTP was higher than that from Jomtien WWTP for all activities due to the higher volume of incoming wastewater.

The GHG emission from Pattaya City WWTP was 4,568.45±168.08 tCO_2eq/year, with scopes 1, 2, and 3 accounting for 55.44%, 44.18%, and 0.38%, respectively. The highest GHG emission of scope 1 was due to GHG release from the wastewater treatment process by microorganisms. A high volume of wastewater releases more GHG. The GHG footprint from Pattaya City WWTP was 4.22 times higher than that from Jomtien WWTP due to higher influent wastewater flow rate. This contributes to high energy consumption for the wastewater collection system and the aeration process, as well as for high GHG emissions from the activated sludge process. The Jomtien WWTP recorded GHG emissions of 1,204.92±65.78 tCO_2eq/year, calculated from scopes 1, 2, and 3, accounting for 60.59%, 36.52%, and 2.89%, respectively. The main carbon footprint comes from scopes 1 and 2, which are GHG emissions from wastewater treatment processes and electricity consumption.

The GHG footprints of Pattaya City and Jomtien WWTPs from the wastewater treatment plant were 1.4-2.2 and 3.9-4.5 times, respectively, higher than that of the wastewater collection system. Electricity consumption contributed the largest share of indirect GHG emissions (36.52-44.18%) and GHG emissions from the wastewater collection system (96.10-98.57%).

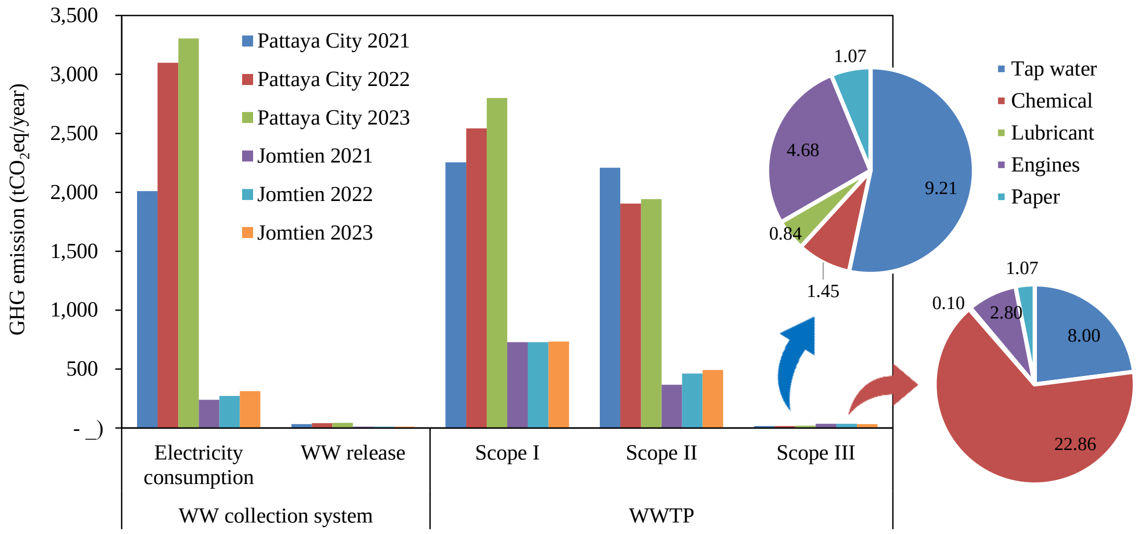

Figure 4. GHG footprint from wastewater collection system and WWTP during 2021-2023

3.2.2 Carbon intensity from WWTP

The GHG emission intensities of Pattaya City and Jomtien WWTPs were 0.237 and 0.218 kg CO_2eq/m^3, respectively (Table 1). In comparing with 4 WWTPs of Chonburi Province, these carbon intensities were 2.9-3.1, 1.2-1.4, and 1.2-1.3 times higher than those of Bangsaray Municipality, Sriracha Town Municipality, and Saen Suk Tai WWTPS, respectively, but were 1.3-1.4 times lower than that of Saen Suk Nuea WWTP (Phoolsap, 2020). The type of wastewater treatment system and the amount of wastewater loading contributed to the different carbon intensities of WWTPs in Chonburi province. That is, Bangsaray Municipality WWTP uses an aerated pond and has a flow rate of only 3,924.92 m^3/day. Meanwhile, Sriracha Town Municipality, Saensuk Tai, and Saensuk Nuea WWTPs use an oxidation ditch and have the flow rates of 9,779, 5,522.45, and 10,353 m^3/day, respectively.

In addition, Pattaya City and Jomtien WWTPs release 8-9 times less GHG than 7 WWTPs in Bangkok (Songpratheep and Jarusutthirak, 2018), 6.9-7.6 times less than a municipal WWTP in Iran (1.65 kg CO_2eq/m^3) (Aghabalaei et al., 2023), but 1.9-2.1 times more than 109 WWTPs in Spain (0.11 kg CO_2eq/m^3) (Maziotis and Molinos-Senante, 2023). It was due to the fact that each type of wastewater treatment system had different operating processes and operations, resulting in different GHG emissions.

Based on COD loading, the GHG emissions from the Pattaya City and Jomtien WWTPs were 2.99±1.39 kg CO_2eq/kg COD and 2.44±0.25 kg CO_2eq/kg COD, respectively. This was about the same as the Leachate WWTP, which had 2.61 kg CO_2eq/kg COD (Chanmit and Khemkhao, 2024).

Table 1. Carbon intensity of domestic WWTP from Thailand

Domestic WWTP	Carbon intensity (kg CO_2eq/m^3)	Reference
Chonburi Province		
Saen Suk Nuea	0.3127	Phoolsap (2020)
Saen Suk Tai	0.1869	
Sriracha Town Municipality	0.1747	
Bangsaray Municipality	0.0754	
Pattaya City, Chonburi	0.237±0.020	This study
Jomtien, Chonburi	0.218±0.011	
Bangkok Metropolitan Administration		
Rattanakosin, Si Phraya, Chong Nonsi, Chatuchak, Din Daeng, Nongkhaem, Thungkru	1.50-2.69	Songpratheep and Jarusutthirak (2018)

The average GHG emissions associated with the electricity consumption of Pattaya City and Jomtien WWTPs were 1.36±0.13 and 1.66±0.17 kg CO_2eq/kWh, respectively, close to China's 1.17 kg CO_2eq/kWh. In contrast, WWTPs in the USA, South Africa, and Germany released less GHG emission per kWh (0.72, 0.99, and 0.68 kg CO_2eq/kWh, respectively) (Wang et al., 2016).

According to data updated on October 31, 2024, the registered population in Pattaya City counts 116,654, and the non-registered population is 4 times higher. In addition, there are 1,000,000 tourists per month. Therefore, for all activities associated with wastewater generation during 2021-2023, the GHG footprint based on people ranged from 0.628-0.770 kg CO_2eq/person equivalent.

3.2.3 Key emission hotspots from WWTP

In Pattaya City, Thailand, there are three key emission hotspots associated with domestic wastewater treatment (Figure 4). The first hotspot is the wastewater collection system, where the pumps consume 30.80-40.75% of Pattaya City's total energy consumption, while Jomtien's WWTPs consume 17.33-19.74%. The second hotspot involves treating wastewater under aerobic conditions, which releases GHG when microorganisms remove BOD (27.58 kg CO_2eq/kg BOD) and TKN (178.27 kg CO_2eq/kg TN) from wastewater.

The aeration system, mixing, pumping, separation, and sludge treatment primarily cause the plant's electricity consumption, which accounts for 44.18% of the GHG footprint in Pattaya City and 60.59% in Jomtien WWTP. Gu et al. (2017) reported that aeration and additional sludge treatment are energy-intensive processes in WWTPs.

However, specific electrical consumption for units of the wastewater process in Pattaya City and Jomtien WWTPs were 0.18±0.03 and 0.13±0.02 kWh/m^3, respectively, lower than that from some other countries. For example, the energy input in a conventional AS system was 0.33-0.60 kWh/m^3 in USA (Wang et al., 2016; Bodik and Kubaska, 2013), 0.46 kWh/m^3 in Australia (Bodik and Kubaska, 2013), 0.40-0.43 kWh/m^3 in Germany (Wang et al., 2016), 0.42 kWh/m^3 in Sweden (Olsson, 2012), 0.52 kWh/m^3 in Switzerland (Hernández-Sancho et al., 2011), 0.53 kWh/m^3 in Spain (Hernández-Sancho et al., 2011), 0.269-0.31 kWh/m^3 in China (Wang et al., 2016; Bodik and Kubaska, 2013), 0.243 kWh/m^3 in Korea (Chae and Kang, 2013), and 0.304-1.89 kWh/m^3 in Japan (Yang et al., 2010; Bodik and Kubaska, 2013). Specific energy demand in WWTPs decreases with increasing inflow. However, the specific energy demand increases as the concentrations of pollutants in the influent, such as COD, BOD5, and nitrogen increase (Gu et al., 2017).

3.2.4 Operational cost

The cost of electricity and tap water usage gradually increased the operational cost of both wastewater treatment plants (Table 2). The operational cost of Pattaya City accounted for 1,386,212-1,864,155 USD/year and was 3.93-4.71 times higher than that of Jomtien WWTP. The operational cost per wastewater volume was 0.007 USD/m^3 for Pattaya City WWTP and 0.006 USD/m^3 for Jomtien WWTP.

Table 2. Operational costs of WWTP during 2021-2023

Details	Pattaya City			Jomtien		
	2021	2022	2023	2021	2022	2023
Operational fees						
- Chemical cost	104,400	104,400	104,400	14,500	14,500	14,500
- Other expenses	457,309	457,309	457,309	202,887	202,887	202,887
Electricity cost						
- Wastewater treatment plant	396,190	377,202	451,249	76,120	98,964	108,865
- Wastewater pumping station	400,897	584,828	833,782	49,483	57,107	62,494
Tap water cost						
- Wastewater treatment plant	13,707	14,374	15,923	9,220	9,206	7,095
- Wastewater pumping station	548	551	1,493	110	90	159
Total (USD/year)	1,386,212	1,538,665	1,864,155	352,320	382,754	395,998

Note: 1 Baht=0.029 USD (November 9th, 2024)

3.3 Options for reducing GHG footprint from WWTP

Implementing energy efficiencies will help reduce energy consumption and lead to a reduction in GHG emissions from energy usage. These include improving process operations and installing energy-saving equipment (Maktabifard et al., 2018). The Pattaya WWTPs have replaced the large aerator with a small aerator and replaced it with a blower instead of a mechanical surface aerator. Automatic aeration control equipment has also been installed for the optimal operation of aeration systems and water pumps.

Based on the GHG footprint in Figure 4, the reduction of the carbon footprint should focus on Pattaya City WWTP. Installing 268 modules of 600-watt solar cells on the office building roof of Pattaya City WWTP could generate approximately 238,582.98 kWh annually. The performance of the solar cells was calculated and analyzed using the performance ratio (PR). The WWTP achieved a PR of 81.3%, resulting in a reduction of CO_2 emissions by 108.70 tCO_2eq/year and a reduction of electricity fees by 2,840 USD/month with a payback period 4.73 years, which is equivalent to a 2.38% reduction in the WWTP's GHG emissions. Installing solar cells on 1,408 modules in the WWTP would generate 1,253,450.15 kWh annually. This led to a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a monthly reduction in electricity fees of 14,920.5 USD with a payback period 4.80 years.

Pattaya City WWTP is situated in elevated areas and necessitates pumps for the transportation of wastewater, leading to significantly elevated electricity expenses (Figure 5). This WWTP comprises 34 pumping stations for combined sewer collection from Pattaya and Naklua areas. In 2023, electricity based on pumping stations consumed 5,523,331 kWh, or 1,493 USD per year. Installing a WWTP at station PS12, which receives a flow rate of 59,679 m^3/day, or 716,148 m^3 of wastewater annually, would reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 35.13%, and can save 239,091.57 USD.

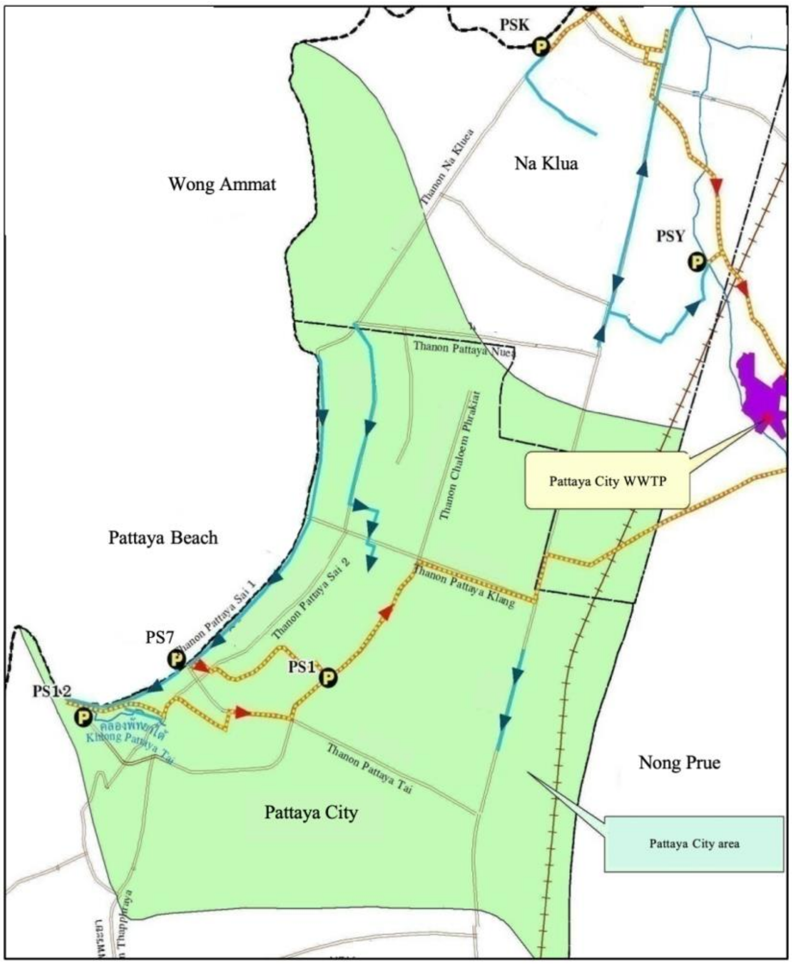

Figure 5. Wastewater collection system for Pattaya City WWTP

4. CONCLUSION

The total CF footprint from both Pattaya City and Jomtien WWTPs was estimated to be 5,610.61-6,020.18 tCO_2eq/year and the carbon intensity ranged between 0.628-0.770 kg CO_2eq/PE, 0.45-0.47 kg CO_2eq/m^3, 4.43-6.99 kg CO_2eq/kg COD, and 2.99-3.06 kg CO_2eq/kWh. The operational cost per wastewater volume was 0.013 USD/m^3. The results revealed the main sources of emissions: the wastewater collection system accounting for 34.47-44.61%, the activated sludge process counting for 43.02-45.74%, and electricity consumption counting for 30.02-39.48%. Optimal costs and GHG emissions from operating WWTPs depend on the quantity of BOD, TKN, and SS removed from wastewater. Therefore, different methods for reducing operational costs and GHG emissions should be defined by the regulator for WWTPs.

This study suggested three options for GHG reduction.

1. Installing solar cells on the office building roof produced electricity of 238,582.25 kWh/year, which could reduce GHG emissions by 108.70 tCO_2eq/year (a 2.38% reduction from total GHG emissions in WWTP) and save 32,825.73 USD.

2. Installing solar cells in the plant would generate 1,253,450.15 kWh annually, resulting in a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a saving of 170,095.12 USD.

3. Installing a WWTP at station PS12 with a capacity of 59,679 m^3/day would reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 36.41%, and result in a savings of 239,091.57 USD.

The WWTP should maintain a balance of effluent quality, energy efficiency, and GHG emissions. Therefore, if the municipal wastewater treatment plants have a goal for carbon neutrality and energy sustainability, the approaches for resource recovery, nutrient recycling, water reuse, and energy production on site with combined heat and power (CHP) from biogas should be investigated in the future.

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AUTHOR CONTRIBUTION

Conceptualization, W.P., A.P. and M.K.; Methodology, W.P.; Software, W.P. and M.K.; Validation, W.P., A.P. and M.K.; Formal Analysis, W.P. and M.K.; Investigation, W.P. and M.K.; Resources, W.P.; Data Curation, W.P. and M.K.; Writing - Original Draft Preparation, W.P. and M.K.; Writing - Review and Editing, A.P. and M.K; Visualization, W.P. and M.K.; Supervision, A.P. and M.K.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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Comparative Fiber Morphology of Four Underutilized Native Tree Species in Maguindanao, Philippines

Jayric F. Villareal[1*], Rafael U. Untong[1], Anisa U. Mispil[1], Cindy E. Poclis[1], Charry Mae S. Numeron[2], and Oliver S. Marasigan[3]

[1]*College of Forestry and Environmental Studies, Mindanao State University-Maguindanao, Bangsamoro Autonomous Region in Muslim Mindanao (BARMM), Philippines*
[2]*Northeastern Mindanao State University - Bislig Campus, Surigao del Sur, Philippines*
[3]*Forest Products Research and Development Institute (FPRDI), Department of Science and Technology (DOST), Laguna, Philippines*

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*** Corresponding author:**
E-mail: jfvillareal@msumaguindanao.edu.ph

ABSTRACT

The focus of this study was to characterize and compare the fiber morphology (fiber length, fiber diameter, lumen diameter, cell wall thickness, and cell wall fraction) and derived values (Runkel ratio, slenderness ratio, flexibility ratio, Mulhsteph ratio, rigidity coefficient, and Luce's shape factor) of four underutilized native tree species grown in the Maguindanao region, namely; Dita (*Alstonia scholaris* (L.) R. Br.), Himbabao (*Broussonetia luzonica* Blanco), Tangisang Bayawak (*Ficus variegata* Blume), and Kalukoi (*Ficus callosa* Willd.). Wood samples from the selected trees (between 10-20 years old) were collected at dbh level (1.30 m) and then macerated for three hours. The macerated wood fibers were observed under a Euromex compound microscope and then measured using ImageJ Software. Results revealed that *F. variegata* had the longest recorded fiber (2.73 mm) with the thickest cell wall (9.57 µm) and highest values for cell wall fraction (36.72%), Runkel ratio (0.74), slenderness ratio (60.48), Mulhsteph ratio (53.63%), rigidity coefficient (0.17), and Luce's shape factor (0.43). As for fiber diameter, *F. callosa* (52.83 µm) was largest. Moreover, *A. scholaris* fibers recorded the largest lumen diameter (38.73 µm) with the highest flexibility ratio (77.74%). Analysis of variance showed significant differences relative to fiber morphology and their derived values, except for slenderness ratio. Results suggested that the four underutilized species are good not only for pulp and paper production, but also have potential for light construction, wooden toys and shoes, pencil slats, matchsticks, toothpicks, ice cream spoons, popsicle sticks, boxes, shelves, molding, veneer and plywood, buoys, and floats. In further validation of the suitability of materials towards intended uses, characterization of other wood properties (e.g., physical and mechanical) and consideration of factors like genetic control, locations/habitats, stand density, elevation, age and diameter classes, height level and wood types are recommended.

1. INTRODUCTION

Escalating demands for wood products, driven by expanding domestic and international markets, have significantly reduced the availability of many commercially valuable wood species. This decline not only jeopardizes critical ecosystem services but also disproportionately impacts various communities (Díaz et al., 2019). In response to these challenges, the Philippine government enacted Executive Order No. 23, series of 2011, to combat deforestation, forest degradation, habitat loss, and illegal logging (Government of the Philippines, 2011). However, despite these efforts, the increasing needs of residential, commercial, and construction projects

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have outstripped the declining supply of timber and other wood products (USDA FAS, 2021).

In light of this, the exploration of sustainable alternatives to traditional wood species has become increasingly urgent, not just to alleviate the material shortage but also as a crucial component of broader climate mitigation and adaptation strategies (Numeron et al., 2023). The Philippines, an archipelago of varied regions, provides the finest environments for the cultivation and growth of some of the most unusual plant species on Earth (Javargas, 2021). With approximately 3,600 native tree species in the Philippines, of which 67% are endemic (De Jesus, 2021), some of these are underutilized (lesser known) species which offer significant potential. Unfortunately, infrastructure development, urbanization, and a lack of public awareness are accelerating the decline of these native and endemic species (IUCN Urban Alliance, 2021).

In South-Central Mindanao, particularly in Maguindanao Province, Ligawasan Marsh Wetland Biodiversity Reserve (LMBWR) is one of the most significant ecosystems in the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM) (Tanalgo et al., 2024). Considering the existence of different native tree species thriving abundantly in areas such as Dita, Himbabao, Tangisang Bayawak, and Kalukoi, it is vital to have comprehensive data on these species as well as inclusively accounting their values towards sustainable ecosystems. These underutilized naturally growing trees in the BARMM, are essential for maintaining local biodiversity and contributing to the timber industry. However, security concerns in the region have limited the characterization of the potential native tree species, with a forest cover of approximately 299,195 ha, (45%) of the region's total land area of 1,293,552 ha (Saiden, 2020). Hence, further study of these available native trees in the region is vital.

Dita (*Alstonia scholaris* (L.) R. Br.) is a fast-growing, typhoon-resistant tree that can reach heights between 30 to 40 m. It is highly effective in controlling soil erosion and is naturally distributed across South Asia, Southeast Asia, and Southern China. This species thrives in lowland environments, flourishing in both primary and secondary forests. The bark of the *A. scholaris* tree, widely harvested in the Philippines and nearby islands, is a significant component of traditional medicinal practices (Florentino et al., 2010). Although classified as a species of least concern by the IUCN (2024), further study is needed to improve its conservation and utilization strategies and fully understand its ecological benefits and role in maintaining forest health (Sutcliffe and Malabrigo, 2020).

Himbabao (*Broussonetia luzonica* Blanco) is a drought-tolerant, fast-growing tree native to the Philippines, capable of reaching heights of up to 25 m, with trunk diameters around 30 cm. It is commonly found in second-growth forests at low to medium elevations throughout the country. While *B. luzonica* is traditionally used as a vegetable in certain parts of Luzon, its widespread presence indicates potential for research aimed at improving its nutritional value and cultivation practices, which could enhance its market potential (Florido, 2010). Additionally, *B. luzonica* is recognized for its medicinal uses, including anti-inflammatory properties and digestive benefits, though its anatomical and morphological features remain underexplored (Quintos et al., 2022).

Tangisang Bayawak (*Ficus variegata* Blume) is native to the Philippines and many other countries such as the Andaman Islands, Australia, China, India, Indonesia, Japan to name a few. This tropical fig tree, part of the Moraceae family, typically grows in warm, humid lowland forests. Generally reaching a height of about 15 m, older specimens can grow up to 30 m. It boasts an erect trunk up to more than 1 m in diameter, adorned with tabular roots, which are flattened roots similar to buttresses, at the base. Its smooth bark, a grey-brown color, is associated with abundant milky sap when it sustains damage (Stuart, 2016; Malabrigo and Umali, 2022).

Kalukoi (*Ficus callosa* Willd.) is another fast-growing fig tree species within the Moraceae family. Native to the Philippines, Southern China, Indochina, and Malesia, *F. callosa* can grow up to 29 m in height, with trunk diameters of approximately 55 cm (Florido, 2010). It usually has a straight bole buttressed in older trees and harvested from the wild for local use as a food and source of wood and fiber. Despite this, its lightweight and durable wood makes it suitable for small-scale livelihood applications, such as boat construction (Osmeña et al., 2000).

Characterizing the properties of underutilized wood species is crucial for determining suitable processing techniques and ensuring optimal use (Marbun et al., 2019). The characterization of these species will not only provide information regarding their potential as alternative resources to meet the increasing demands of the wood industry but also support conservation and sustainable development efforts. This study underscores the importance of further research into the *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* tree species found in Maguindanao, particularly on fiber morphology and their derived values, as they are strongly correlated with the other properties of the wood, for their potential contributions to wood-based industries, conservation, and sustainable practices.

2. METHODOLOGY

2.1 Plant materials and sample collection

The wood samples of Dita (*A. scholaris*), Himbabao (*B. luzonica*), Tangisang Bayawak (*F. variegata*), and Kalukoi (*F. callosa*) were collected at Datu Odin Sinsuat, Maguindanao del Norte (07°08' N 124°16′ E), Bangsamoro Autonomous Region in Muslim Mindanao (BARMM), Philippines with an elevation ranging from 85-110 m.a.s.l. (Figure 1), displaying a tropical monsoon climate (Classification: Am). Three mature trees (between 10-20 years old) with a straight bole were selected per species with an average diameter of 20 cm at breast height (DBH) level (1.3 m). Wood samples were extracted at three distinct locations (Due North, East, and West) within the tree's DBH level which were free from defects, knots or injuries, using a 5.15 mm diameter by 100 mm long alloy steel increment borer, with a fine-threaded tip. After extraction, wood samples were placed in the zip lock for safekeeping. The extracted wood samples located between the pith and bark portions were used for fiber maceration and measurement.

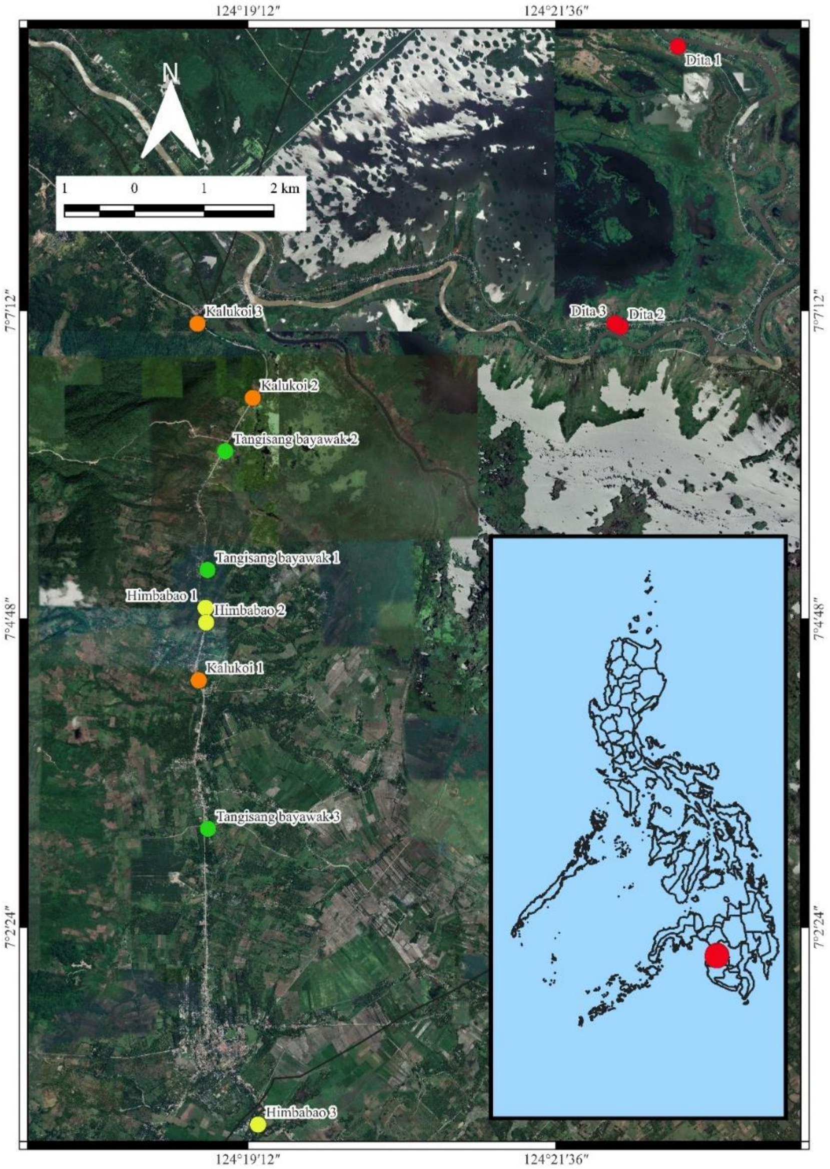


Figure 1. Location map of the four native tree species in Maguindanao del Norte, Philippines

2.2 Wood fiber morphology

2.2.1 Fiber maceration

Matchstick-sized samples were prepared from the collected wood samples and then macerated in equal volumes (1:1) of acetic acid and hydrogen peroxide (50% concentration), following the procedure of Espiloy et al. (1999). The maceration was done in a water bath and heated for three hours at 100°C until the samples turned white and became soft to separate individual fibers. Afterward, the samples were then washed with distilled water until acid-free and subjected to microscopic observation and measurement.

2.2.2 Fiber measurement

Before fiber measurement, the macerated samples inside the test tubes were shaken to ensure the separation of different structural elements. Twenty-five undamaged fibers were observed per replicate under the Euromex compound microscope and measured using ImageJ Software (ImageJ 1.45). The length, diameter, and lumen diameter of each fiber were measured according to the International Association of Wood Anatomists (IAWA) standard (Wheeler et al., 1989), while the cell wall thickness was determined based on the difference between the fiber diameter and lumen diameter. Also, cell wall fraction (1) was calculated using the equation used by Eloy et al. (2024).

$$\text{Cell wall fraction} = \frac{2 \text{ x Cell wall thickness}}{\text{Fiber diameter}} \text{ x } 100 \quad (1)$$

2.2.3 Derived values

Based on the fiber morphology data, the derived values such as Runkel ratio (2), slenderness ratio (3), flexibility ratio (4), Mulhsteph ratio (5), and rigidity coefficient (6) were computed using the equation used by Hartono et al. (2022). While the luce's shape factor (7) was determined using the equation followed by Takeuchi et al. 2016. The assessment for the potential of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* as raw materials for pulp and paper production was conducted using the Indonesian Timber Assessment Criteria as Raw Materials for Pulp and Paper (Hartono et al., 2022).

$$\text{Runkel ratio} = \frac{2 \text{ x Cell wall thickness}}{\text{Lumen diameter}} \quad (2)$$

$$\text{Slenderness ratio} = \frac{\text{Fiber length}}{\text{Fiber diameter}} \quad (3)$$

$$\text{Flexibility ratio} = \frac{\text{Lumen diameter}}{\text{Fiber diameter}} \times 100 \quad (4)$$

$$\text{Mulhsteph ratio (\%)} = \frac{\text{Fiber diameter}^2 - \text{Lumen diameter}^2}{\text{Fiber diameter}^2} \times 100 \quad (5)$$

$$\text{Rigidity coefficient} = \frac{\text{Cell wall thickness}}{\text{Fiber diameter}} \quad (6)$$

$$\text{Luce's shape factor} = \frac{\text{Fiber diameter}^2 - \text{Lumen diameter}^2}{\text{Fiber diameter}^2 + \text{Lumen diameter}^2} \quad (7)$$

2.3 Statistical analysis

One-way analysis of variance (ANOVA) was used to compare the wood fiber morphology and derived values of the species. Also, Tukey's honest significant difference was used to determine the significant differences among the mean values of the data. The statistical analyses were carried out using Jamovi version 2.3 (Jamovi Project, 2022).

3. RESULTS AND DISCUSSION

3.1 Fiber morphology

The fiber morphology of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species such as fiber length, fiber diameter, lumen diameter, and cell wall thickness, were presented in Table 1. Likewise, the Tukey's honest significant difference result on the fiber morphology of these four species was shown in Figure 2.

Table 1. Fiber morphology of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species

Property	Wood species				Significant level of difference (p-value)
	A. scholaris	*B. luzonica*	*F. variegata*	*F. callosa*	
Fiber length (mm)	1.79	1.44	2.73	1.82	0.010*
Fiber diameter (µm)	49.50	35.83	52.13	52.83	0.005*
Lumen diameter (µm)	38.73	26.33	33.07	37.40	0.034*
Cell wall thickness (µm)	5.40	4.73	9.57	7.70	<0.001*
Cell wall fraction (%)	21.82	26.40	36.72	29.15	0.088^{ns}

*significant at 0.05 significant level; ns=not significant

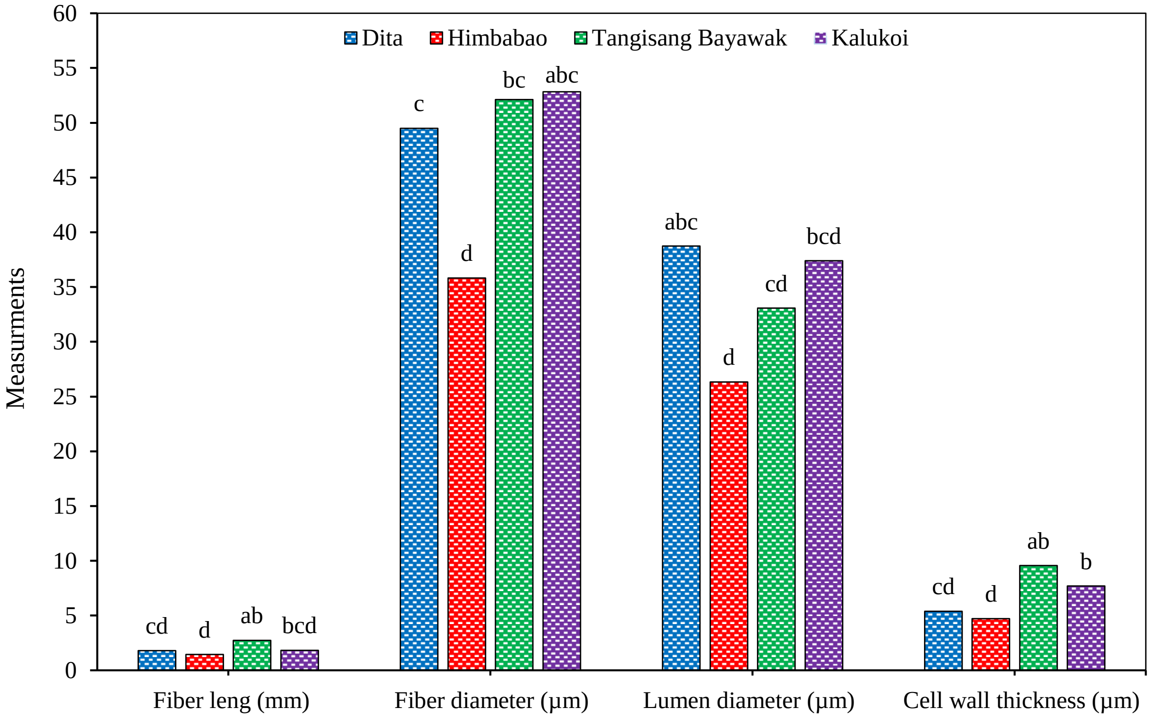


Figure 2. Tukey's honest significant difference result on the fiber morphology of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species (In each property, means with common letters (a, b, c, d) are not significant)

3.1.1 Fiber length (mm)

The result of the study showed that *F. variegata* records the longest fiber (2.73 mm), followed by *F. callosa* (1.82 mm), *A. scholaris* (1.79 mm) and *B. luzonica* (1.44 mm). Analysis showed that the fiber length of these four wood species was significantly different with a p-value of 0.010. Moreover, *F. variegata* exhibited 41.79% and 61.75% significantly higher than *A. scholaris* and *B. luzonica* species, respectively. While compared to *F. callosa*, *F. variegata* showed a 40.09% difference, but not significant. On the other hand, the average fiber length results were relatively shorter than the fiber of softwoods (3.50 mm) (Sharma et al., 2011), but longer compared to *Eucalyptus tereticornis* (0.72 mm), *E. grandis* (0.92 mm) (Sharma et al., 2011), *Ficus carica* subsp. *Carica* (0.95 mm) (Yaman, 2014), Plumwood (0.98 mm) (Kiaei et al., 2014), hardwoods (1.00 mm) (Anupam et al., 2016), 3-, 5-, and 7-year-old Falcata trees (1.16, 1.14, and 1.17 mm, respectively) (Alipon et al., 2021), *Ganophyllum falcatum* (1.20 mm) (Villareal et al., 2022b), *Aquilaria cumingiana* (0.98 mm) (Villareal et al., 2022a), and *Melia azedarach* (0.57 mm) (Megra et al., 2022).

Based on Salehi's (2001) characterization, fiber of *F. variegata* falls under 3rd group with > 1.90 mm fibers, while fibers of *F. callosa*, *A. scholaris*, and *B. luzonica* fall under the 2nd group, characterized to have an average fiber length ranging from 0.90 to 1.90 mm. Moreover, Madsen et al. (2013) reported that fibers ranging from 1 to 5 mm are commonly used for making composite materials with in-plane isotropic properties, i.e., composite materials with a non-specific orientation. According to Suansa and Al-Mefarrej (2020), fibers with an average length greater than 0.4 mm are deemed suitable as raw materials for papermaking. Generally, long fibers with thin cell walls were much preferable for pulp and paper manufacturing since the longer the fiber, the higher the tearing tensile, and bursting strength, and folding endurance of the paper (Sharma et al., 2011). Thus, the four underutilized wood species examined in this present study may be used for pulp and paper production and other composite materials. Among the four species, *F. variegata* might exhibit higher bursting strength, tensile strength, tearing strength, and folding endurance given the longer fiber length it showed.

3.1.2 Fiber and lumen diameter (µm)

The result of the study showed that *F. callosa* fibers having a diameter of 52.83 µm had recorded the largest value, followed by *F. variegata*, *A. scholaris*, and *B. luzonica* with 52.13, 49.50, 35.83 (µm), respectively. Significant difference was shown on the fiber diameter of these four species with a p-value of

0.005. It was also observed that *F. callosa* fibers differ significantly to *B. luzonica* fibers with 38.35% difference. As compared to other wood species like *E. tereticornis* (15.00 µm), *E. grandis* (19.00 µm) (Sharma et al., 2011), *F. carica* (21.40 µm) (Yaman, 2014), hardwoods (25.00 µm), Plumwood (13.77 µm) (Kiaei et al., 2014), *Gmelina arborea* (27.00 µm) (Prabawa, 2017), *G. falcatum* (23.00 µm) (Villareal et al., 2022b), *A. cumingiana* (32.00 µm) (Villareal et al., 2022a), and *M. azedarach* (13.45 µm) (Megra et al., 2022), the fibers of four wood species in this present study were relatively larger. While *B. luzonica* fiber seem to be comparable to softwood (35.00 µm) (Kiaei et al., 2014) and 3-, 5-, and 7-year-old Falcata trees (35.40, 37.40, and 38.00 µm, respectively) (Alipon et al., 2021), but relatively lower than the rest of the wood species of this present study.

In terms of lumen diameter, the present study showed that *A. scholaris* fiber (38.73 µm) was relatively larger than *F. callosa* (37.40 µm), *F. variegata* (33.07 µm), and *B. luzonica* (26.33 µm) fibers. Significant differences in lumen diameter across species were observed with a p-value of 0.034. A significant difference was only seen between *A. scholaris* and *B. luzonica* fibers with 38.12% difference. In view of wood drying, *A. scholaris* wood may dry faster as it has larger lumen diameter where the removal of water from wood is facilitated (Eloy et al., 2024). Eloy et al. (2024) also reported that lumen diameter together with fiber diameter showed a direct effect in the drying of wood, a directly proportional relationship with moisture content, and an inversely proportional relationship with basic density as well as the values of mechanical properties. Moreover, the average lumen diameter results of these four wood species were relatively larger than those of *E. tereticornis* (5.12 µm), *E. grandis* (6.67 µm) (Sharma et al., 2011), *F. carica* (12.50 µm) (Yaman, 2014), Plumwood (5.60 µm) (Kiaei et al., 2014), *G. arborea* (21.00 µm) (Prabawa, 2017), *G. falcatum* (9.36 µm) (Villareal et al., 2022b), *A. cumingiana* (23.40 µm) (Villareal et al., 2022a), and *M. azedarach* (13.03 µm) (Megra et al., 2022). As compared to 3- , 5-, and 7-year-old Falcata trees (28.90, 30.90, and 31.70 µm, respectively) (Alipon et al., 2021), *B. luzonica* fibers was relatively thinner while the rest of the wood species of this present study were moderately larger. Technically, lumen diameter influences the beating process in pulp and paper production because liquid penetrates the fibers' empty spaces (Kiaei et al., 2014). According to Moya Roque and Tomazello-Filho (2007), lumen diameter can be affected by the physiological growth of wood as the tree ages and expands in girth. It was also pointed out by Anupam et al. (2016) that fiber lumen varies for different species. The results of the present study suggest that the four tree species exhibited favorable beating processes that would greatly affect the quality of pulp and paper products.

3.1.3 Cell wall thickness (µm)

The result of the study showed that *F. variegata* fibers exhibited thicker cell wall with 9.57 µm, followed by *F. callosa* (7.70 µm), *A. scholaris* (5.40 µm), and *B. luzonica* (4.73 µm). Significant difference was observed across species with a p-value of <0.001. Among these four species, *F. variegata* cell wall differs significantly with *A. scholaris* and *B. luzonica* cell walls with 55.71% and 67.69% differences, respectively.

The average cell wall thickness results of these four underutilized wood species were relatively thicker than *G. arborea* (3.00 µm) (Prabawa, 2017), 3-, 5-, and 7-year-old Falcata trees (3.30, 3.20, and 3.10 µm, respectively) (Alipon et al., 2021), and *M. azedarach* (2.52 µm) (Megra et al., 2022). As compared to *E. tereticornis* (4.74 µm) (Sharma et al., 2011), Plumwood (4.08 µm) (Kiaei et al., 2014), *F. carica* (4.50 µm) (Yaman, 2014), and *A. cumingiana* (4.36 µm) (Villareal et al., 2022a), the cell wall thickness of *A. scholaris* and *B. luzonica* were relatively comparable. While *F. variegata* and *F. callosa* appears thicker than the others like *E. grandis* (6.27 µm) (Sharma et al., 2011), and *G. falcatum* (6.26 µm) (Villareal et al., 2022b). Basically, cell wall thickness increases towards maturity and usually governs fiber flexibility. With a thicker cell wall, it is expected to produce a bulky and course surfaced with large amount of void volume paper (Sharma et al., 2011). Based on the present result, paper made from *F. variegata* and *F. callosa* fibers will be more rigid but less dense compared to *A. scholaris* and *B. luzonica* fibers, which likely produce denser and well-formed paper.

3.1.4 Cell wall fraction (%)

The result of the study showed that *F. variegata* obtained the highest cell wall fraction with 36.72%, followed by *F. callosa* (29.15%), *B. luzonica* (26.40%), and *A. scholaris* (21.82%). Moreover, *F. variegata* has 22.98% difference to *F. callosa*, 32.70% to *B. luzonica*, and 50.90% difference to

A. scholaris. However, analysis showed no significant difference. The results of the present study showed relatively lower than the findings of Eloy et al. (2024) on *Peltophorum dubium* (64.00%), *Parapiptadenia rigida* (57.80%), and *Eucalyptus grandis*×*Eucalyptus urophylla* (55.20%), while relatively higher than *Schizolobium parahyba* (21.60%). Basically, materials with higher cell wall fraction values would exhibit slower flow of water resulting to a reduced drying speed associated with a smaller proportion of cell lumens that retain less moisture when saturated (Eloy et al., 2024). A cell wall fraction less than 40% indicates to be a good pulpwood material. It also considered as an index for bending resistance which is related to flexibility of fiber (Takeuchi et al., 2016). The cell wall fraction exhibits a direct correlation with the basic density of wood, while inversely correlated with wood moisture (Lima et al., 2014; Eloy et al., 2024). Moreover, a higher CWF increases the basic density of the wood, and improves its mechanical properties, making the wood more resistant (Sette Junior et al., 2012; Tanabe et al., 2016). Based on the present result, *F. variegata* wood may display a slower drying rate, while *A. scholaris* may have the shortest rate of drying. The results also suggest the suitability of the wood species for pulpwood material.

3.2 Derived values

The derived values of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species, such as the Runkel ratio, slenderness ratio, flexibility ratio, Mulhsteph ratio, rigidity coefficient, and luce's shape factor were presented in Table 2. While Figure 3 showed the Tukey's honest significant difference result on the derived values of these four species.

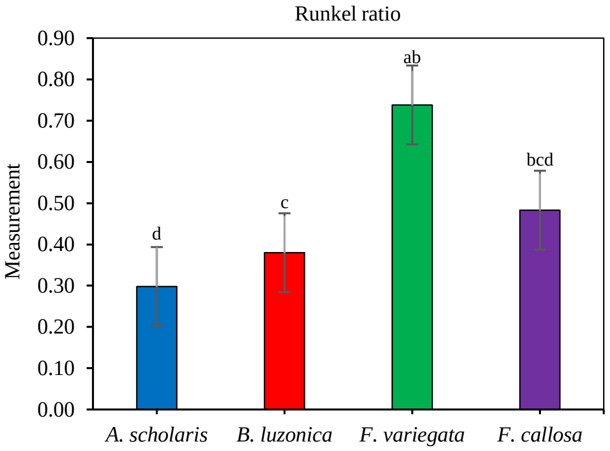
3.2.1 Runkel ratio

The results of the study showed that the highest Runkel ratio was recorded by *F. variegata* with 0.74, while *A. scholaris* recorded the lowest value with 0.30. Analysis of variance revealed that there is a significant difference in the Runkel ratio among the four underutilized wood species. Particularly, *F. variegata* fibers were significantly higher than *A. scholaris* and *B. luzonica* fibers having 84.94% and 64.04% differences. While *F. callosa* fibers were 41.77% lower than *F. variegata*, but not significant.

Table 2. Derived values of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species

Property	Wood species				Significant level of difference (p-value)
	A. scholaris	*B. luzonica*	*F. variegata*	*F. callosa*	
Runkel ratio	0.30	0.38	0.74	0.48	0.014*
Slenderness ratio	37.13	42.04	60.48	35.87	0.129^{ns}
Flexibility ratio (%)	77.74	73.02	65.35	71.09	0.018*
Mulhsteph ratio (%)	39.08	46.28	53.63	47.15	0.027*
Rigidity coefficient	0.11	0.14	0.17	0.14	0.018*
Luce's shape factor	0.24	0.30	0.43	0.33	0.008*

*significant at 0.05 significant level; ns=not significant



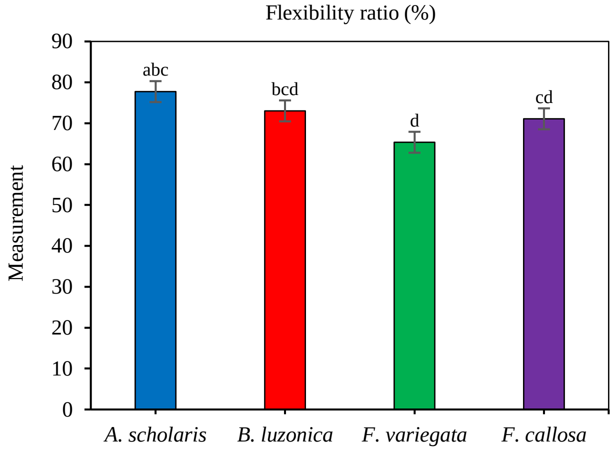


Figure 3. Tukey's honest significant difference result on the derived values of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species (In each property, means with common letters (a, b, c, d) are not significant)

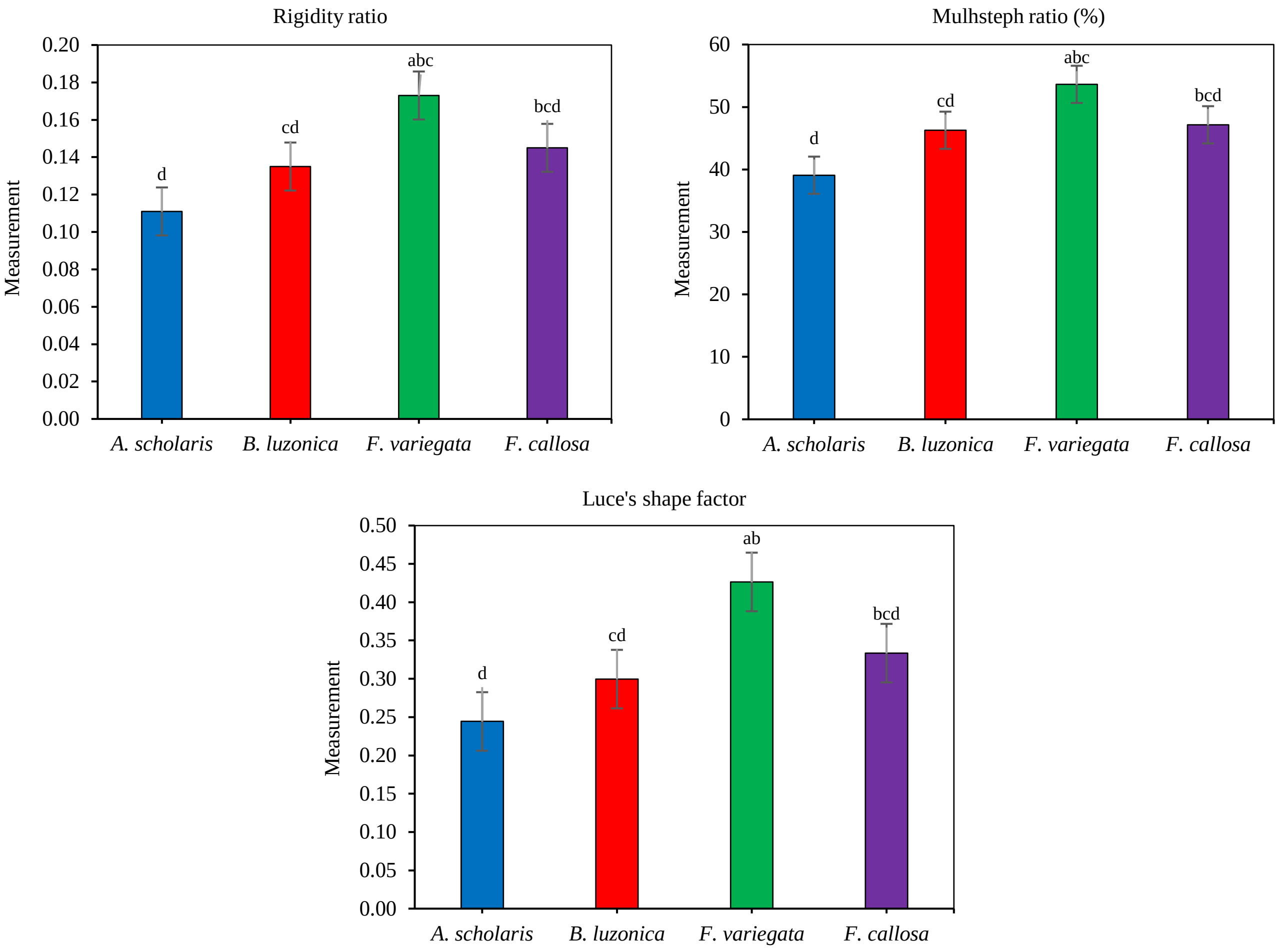


Figure 3. Tukey's honest significant difference result on the derived values of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* wood species (In each property, means with common letters (a, b, c, d) are not significant) (cont.)

The present result was relatively lower than the Runkel ratio of *G. falcatum* (1.62) (Villareal et al., 2022b), but higher to 3-, 5- and 7-year-old *Falcata* trees (0.24, 0.22, and 0.26, respectively) (Alipon et al., 2021). Compared to *A. cumingiana* (0.39) (Villareal et al., 2022a), and *M. azedarach* (0.39) (Megra et al., 2022), the Runkel ratio result of *B. luzonica* was relatively comparable, while lower than *F. variegata* and *F. callosa* results. Accordingly, a Runkel ratio below 1.0 tends to indicate thin-walled fibers with good mechanical strength properties and are considered as the standard values that are relatively favorable in the viewpoint of papermaking (Sharma et al., 2011; Kiaei et al., 2014). Thus, the Runkel ratio results suggested that the four wood species are likely suitable for pulp and paper making and other materials were strength and durability are not critical requirements.

3.2.2 Slenderness ratio

F. variegata recorded the highest slenderness value with 60.48, while *F. callosa* got the lowest value of 35.87. Moreover, *F. variegata* fibers showed 35.96%, 47.86%, and 51.08% differences of slenderness results for *B. luzonica*, *A. scholaris*, and *F. callosa* fibers. However, no significant difference was observed signifying a comparable value of the slenderness ratio of the four wood species.

The slenderness ratio results of the study were relatively higher than those of 3-, 5-, and 7-year-old *falcata* trees (34.33, 31.98, and 31.90, respectively) (Alipon et al., 2021), and *A. cumingiana* (30.95) (Villareal et al., 2022a), while lower compared to Plumwood (73.28) (Kiaei et al., 2014). Except for *F. variegata*, the previous slenderness results of *M. azedarach* (42.47) (Megra et al., 2022) and *G. falcatum* (56.71) (Villareal et al., 2022b) exhibited higher values. The present slenderness results were within the permissible range value of 33 or above (Kiaei et al., 2014). This further suggests the suitability of materials to pulp and paper making.

3.2.3 Flexibility ratio (%)

The results of the study showed that *A. scholaris* fibers have the highest flexibility ratio having 77.74%, while *F. variegata* fibers got the lowest value with 65.35%. A significant difference was observed across species. *A. scholaris*, with the highest flexibility ratio varied significantly with *F. variegata* showing 17.32% difference. The present results of the study were relatively higher than those of Plumwood (41.38%) (Kiaei et al., 2014) and *G. falcatum* (42.09%) (Villareal et al., 2022b), while lower compared to 3-, 5-, and 7-year-old Falcata trees (81.99, 82.78, and 82.84%, respectively) (Alipon et al., 2021), and *M. azedarach* (96.90%) (Megra et al., 2022). In comparison with *A. cumingiana* (72.31%) (Villareal et al., 2022a), the flexibility results of *A. scholaris* and *B. luzonica* found higher, while *F. variegata* and *F. callosa* results found lower.

In relation to flexibility classifications devised by Bektas et al. (1999), *A. scholaris* fibers were considered highly elastic fiber (greater than 75%) while the other three wood species were characterized as elastic fibers (ranging from 50-70%). This indicates efficiency and appropriateness for paper manufacture since the flexibility expresses the fibers' ability to collapse during beating or drying of the paper web providing more bonding area (Zobel and Van Buijtenen, 1989). Thus, the flexibility ratio results, especially fibers of *A. scholaris* will likely display higher tensile strength and further suggest the suitability of materials for pulp and paper making. Hartono et al. (2022) stated that with a higher flexibility ratio, it is expected to display higher tensile strength.

3.2.4 Mulhsteph ratio (%)

The result of the study revealed that the highest Mulhsteph ratio was obtained by *F. variegata* (53.63%) while the lowest was recorded by *A. scholaris* (39.08%). A significant difference was observed across species. *F. variegata* was 31.38% significantly higher than *A. scholaris*, while 12.85% and 14.71% differences were observed towards *F. callosa* and *B. luzonica*, respectively. Regardless of wood species, the Mulhsteph ratios result fall in class II with values ranging from 30-60% based on the classification used by Hartono et al. (2022). The Mulhsteph ratio value affects the pulp's density, as well as the smoothness of paper and the plasticity between the fibers (Hartono et al., 2022). Based on the observed results, fibers of these four species could produce a paper that is relatively conducive in terms of smoothness and pliability which difficult to tear when folded.

3.2.5 Rigidity coefficient

F. variegata showed relatively higher rigidity coefficient with 0.17 compared to *F. callosa* (0.14), *B. luzonica* (0.14), and *A. scholaris* (0.11). Moreover, *F. variegata* showed 43.66% difference for *A. scholaris*, 24.68% for *B. luzonica*, and 17.61% for *F. callosa*, but only *F. variegata* and *A. scholaris* differed significantly. Except for *F. variegata* that falls under class III (>0.15 values), the present rigidity coefficient results fall under class II ranges from 0.10-0.15 based on the classification used by Hartono et al. (2022). Fibers with a low value of rigidity coefficient signify a substantial value wherein the fiber will be more flexible, and the paper produced will not easily be torn when given a tensile load (Hartono et al., 2022). With the present results, papers from the fibers of four wood species have considerable rigidity and stiffness, especially papers made from *A. scholaris* which recorded the lowest value; hence, it will not be easily torn-apart when given a tensile load.

3.2.6 Luce's shape factor

The result showed that the luce's shape factor of *F. variegata* (0.43) was relatively higher than *F. callosa* (0.33), *B. luzonica* (0.30), and *A. scholaris* (0.24). Analysis of variance revealed a significant difference in the luce's shape factor across species. Specifically, *F. variegata* was significantly higher than *B. luzonica* and *A. scholaris* with 35.62% and 56.72% difference, respectively. The present results were comparable with the two *Eucalyptus* species examined by Ona et al. (2001): *E. camaldulensis* (0.34) and *E. globulus* (0.32). Luce's shape factor was considered as an index for the beating resistance of the pulp, where a lower value indicates a less resistance to beating (Takeuchi et al., 2016). It is also a significant fiber index which related to paper sheet density and a value of less than 0.5 luce's shape factor would signifies favorable value associated with good strength for pulp and paper making (NagarajaGanesh et al., 2023). Thus, the result of luce's shape factor further confirms the potential of *A. scholaris*, *B. luzonica*, *F. variegata*, and *F. callosa* fibers for paper production.

Results suggested that the four underutilized native wood species are good not only for pulp and paper production, but also potential for light construction wherein strength and durability are not critically important including wooden toys and shoes, pencil slats, matchsticks, toothpicks, ice cream spoons, popsicle sticks, boxes, shelves, molding, sash, door, veneer and plywood, buoys, and floats, etc. Further, the diverse factors like genetic control, locations/habitats, stand density, elevation, age and diameter classes, height level and wood types, etc. (Alipon et al., 2021; Adimahavira et al., 2023), would likely be the contributors to the significant differences observed in the results.

4. CONCLUSION

The present study underscored the fiber morphology (fiber length, fiber diameter, lumen diameter, cell wall thickness, and cell wall fraction) and derived values (Runkel ratio, slenderness ratio, flexibility ratio, Mulhsteph ratio, rigidity ratio, and luce's shape factor) of the four underutilized native tree species thriving in the Maguindanao province, Philippines. The result revealed that *F. variegata* records the longest and thickest fibers having 2.73 mm length and 9.57 µm cell wall. Likewise, *F. variegata* records the highest values in terms of cell wall fraction, Runkel ratio, slenderness ratio, Mulhsteph ratio, rigidity coefficient, and luce's shape factor having 36.72%, 0.74, 60.48, 53.63%, 0.17, and 0.43, respectively. As to fiber diameter, *F. callosa* (52.83 µm) was the largest, while *A. scholaris* recorded the largest lumen diameter (38.73 µm) and the highest flexibility ratio (77.74%). Moreover, except for the slenderness ratio, the result showed significant differences on the fiber morphology and their derived values. Results suggested that the four underutilized native wood species are good not only for pulp and paper production, but also potential for light construction wherein strength and durability are not critically important including, wooden toys and shoes, pencil slats, matchsticks, toothpicks, ice cream spoons, popsicle sticks, boxes, shelves, molding, veneer and plywood, buoys, and floats, etc.

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AUTHOR CONTRIBUTIONS

Conception and design of study; Jayric F. Villareal, Rafael U. Untong, Anisa U. Mispil, Cindy E. Poclis, Charry Mae S. Numeron, Oliver S. Marasigan. Acquisition of data; Jayric F. Villareal, Rafael U. Untong, Anisa U. Mispil, Cindy E. Poclis. Analysis and/or interpretation of data; Jayric F. Villareal, Rafael U. Untong, Anisa U. Mispil, Cindy E. Poclis, Oliver S. Marasigan. Drafting the manuscript; Jayric F. Villareal, Rafael U. Untong, Anisa U. Mispil, Cindy E. Poclis, Charry Mae S. Numeron, Oliver S. Marasigan. Revising the manuscript for significant intellectual content; Jayric F. Villareal, Cindy E. Poclis, Oliver S. Marasigan. Approval of the version of the manuscript to be published; Jayric F. Villareal, Cindy E. Poclis, Oliver S. Marasigan.

DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

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Greenhouse Gas Mitigation Strategies for Lowland Rice Cultivation under Common Farm Practices, and Accompanying Influencing Factors for Acceptability among Local Farmers in Myanmar

Myo Thet Tin[1], Amnat Chidthaisong[2], Nathsuda Pumijumnong[1], Noppol Arunrat[1], and Monthira Yuttitham[1*]

[1]*Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom, Thailand*
[2]*The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, 126 Prachauthit Rd, Bangmod, Tungkru, Bangkok, Thailand*

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*** Corresponding author:**
E-mail:
monthira.yut@mahidol.ac.th

ABSTRACT

The main purpose of the study was to determine agricultural rice establishment options with specific fertilizer application methods which produce less methane, and lower nitrous oxide emissions (Lower Global Warming Potential. Greenhouse Gases Index and Abatement cost) while still maintaining an acceptable rice yield. To do so, methane (CH_4) and nitrous oxide (N_2O) emissions, and grain yields from rice fields were explored, under different farmer fertilizer application methods and two different crop establishment options currently practiced by local farmers, namely transplanted rice (TPR) and wet bed direct seeded rice (WDSR). Both were measured in field experiments. In this study, it was found that rice cultivation emitted CH_4 and N_2O at the rate of 3.23±0.94 mg/m^2/h (ranging from 1.83-4.68) and 0.089±0.024 mg/m^2/h (ranging from 0.073-0.135), respectively. In addition, TPR produced more CH_4 and N_2O than WDSR did across the different fertilizer methods at almost each growth stage throughout the growing period. Finally, the result was a pair of rice cultivation practices-including WDSR with urea nitrogen fertilizer application (WF1)-which show great potential for mitigating GHG emissions in the Myanmar agricultural sector. Lower GWP, GHGI, and AAC with acceptable productivity were all seen. Moreover, this study was designed to investigate influencing factors on acceptability of local farmers upon WF1. Some 36% of respondents among local farmers were willing to accept WF1 with conditions, while 30% acceptability was found in neutral respondents, not yet decided on practices of rice cultivation for coming seasons. According to multiple regression analysis, the influencing factors of farmers' acceptability towards WF1 were their rice cultivation experience, the number of available agriculture information sources, and the total quantity of cultivated land for rice growing.

1. INTRODUCTION

Agriculture contributes around 10-12% of the world's total human-caused greenhouse gas (GHG) emissions, and is responsible for 60% of global nitrous oxide (N_2O) and 50% of methane (CH_4) emissions (Smith et al., 2008). Carbon dioxide is also a greenhouse gas, and globally, CO_2 emissions from soil are largely balanced by the net primary productivity and CO_2 absorption by crops, resulting in a total contribution of less than 1% to agriculture's global warming potential (GWP) (Smith et al., 2007). Nitrous oxide is a significantly more potent greenhouse gas, with a radiative forcing potential about 12 times greater than that of methane (Shukla et al., 2019).

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Upland agricultural systems are predominantly responsible for the emission of N_2O, whereas flooded rice (Oryza sativa) systems emit a combination of CH_4 and N_2O (Song et al., 2021a). An earlier study has documented that the GWP of GHG gas emissions originating from rice cultivation is approximately four times greater than either wheat or maize (Linquist et al., 2012). Therefore, the majority of strategies aimed at mitigating overall GWP from rice cultivation primarily concentrate on the reduction of CH_4 emissions. Nonetheless, it is imperative to acknowledge that these mitigation approaches should encompass not only CH_4 but also N_2O emissions, given that certain strategies designed to decrease CH_4 emissions may inadvertently lead to an increase in N_2O emissions (Klüber and Conrad, 1998).

The primary cause of methane (CH_4) emissions from agricultural land stems from biologically mediated processes involving methanogenic bacteria and resulting from organic matter decomposition, particularly under anaerobic soil conditions (Conrad, 2002; Sass et al., 2002). Simultaneously, emissions of nitrous oxide (N_2O) are influenced by nitrification and denitrification processes in the soil (Smith, 2010). Various studies indicate that lowland flooded fields play a crucial role in CH_4 emissions, while making a minor contribution to N_2O emissions (Ly et al., 2013). Furthermore, the release of N_2O is linked to the application of nitrogen fertilizers and dry soil conditions (Linquist et al., 2012; Linquist et al., 2015). The results of these studies highlight the significant association between farming practices, such as water management and fertilizer application methods, and the emissions of CH_4 and N_2O.

An effective approach for mitigating CH_4 emissions involves mid-season drainage, which in turn entails the temporary removal of irrigation water, as demonstrated in various field experiments (Arunrat et al., 2018; Nayak et al., 2015). The outcomes of these field experiments indicated that mid-season drainage substantially reduces CH_4 fluxes while enhancing rice yields (Islam et al., 2020; Liu et al., 2014; Song et al., 2021c; Tang et al., 2016). However, this practice may lead to increased N_2O emissions due to the creation of relatively saturated soil conditions, which are positively correlated with N_2O production, revealing a trade-off effect between CH_4 and N_2O (Arunrat et al., 2018; Islam et al., 2020; Liu et al., 2014; Song et al., 2021c; Tang et al., 2016).

The interaction of CH_4 with the atmosphere in croplands is subject to the influence of nitrogen fertilizer application (Cai et al., 1997). Various impacts from CH_4 emissions have been observed as a result of nitrogen fertilizer applications (Kong et al., 2021; Linquist et al., 2012; Liu et al., 2012b). The stimulation of CH_4 emissions has been documented in certain instances following nitrogen fertilizer applications (Liu and Greaver, 2009; Shang et al., 2011), whereas in other experimental settings, they have been found to hinder CH_4 production (Venterea et al., 2005). Additionally, there are scenarios where no significant correlation is established between nitrogen fertilizer application and methane emission rates (Mosier et al., 2006). Nitrogen fertilizer has the capacity to undergo either nitrification or denitrification in soil, and then subsequently be released as N_2O (Smith, 2010). Moreover, the application of nitrogen fertilizer stands out as a critical practice with direct or indirect implications on N_2O emissions (Nayak et al., 2015; Venterea et al., 2011). Numerous field studies focusing on N_2O emissions and the effects of nitrogen fertilizer application have been conducted, further identifying correlated influencing factors-such as crop type, application rate, and timing-all of which have been extensively documented (Linquist et al., 2012; Venterea et al., 2005). The timing and method of nitrogen fertilizer application, whether split or not, has been advocated for both upland and lowland crops in terms of greenhouse gas fluxes. Split application of N fertilizer has proven to be an effective approach in reducing N_2O emissions from potatoes, especially under conditions of adequate rainfall and reduced aeration (Kong et al., 2021). Furthermore, the timing of early and late spring fertilization in maize has shown a significant impact on greenhouse gas fluxes (Venterea et al., 2005). Additionally, managing fertilizer application through the split method can influence methane and nitrous oxide emissions in both upland and lowland rice cultivation, as detailed by Kong et al. (2021) and Linquist et al. (2012). The impact of compound fertilizers, typically containing nitrogen (N), phosphorus (P), and potassium (K), on enhancing fertilizer efficiency has been noted, albeit with potential environmental repercussions due to mismanagement in application practices (Gupta et al., 2016; Haque and Biswas, 2021).

Myanmar is traditionally an agricultural country and this sector contributes approximately 20.1% of national Gross Domestic Product (GDP). Rice is a major crop of the country within this sector (MoALI, 2019). The majority of rice farming systems employ transplanted rice (TPR) and wet bed direct seeded rice (WDSR) for local farmers. Generally, the TPR method utilizes intensive inputs, namely water and labor, with a high cost of production (Chauhan et al., 2017; MoALI, 2019) while the WDSR method, seeded directly on non-puddle soil, has become very common especially among local farmers since it can help solve water shortage and labor scarcity problems, while also producing a high cost-benefit ratio (Janz et al., 2016; Pathak et al., 2013). Several pieces of research have indicated that crop establishment with WDSR and appropriate water management is potentially a better CH_4 mitigation strategy than the TPR method (Liu et al., 2014). It has also been highlighted that the average CH_4 emissions from TPR were more than 80% of the emissions produced by WDSR in two-year experiments (Gupta et al., 2016). Additionally, WDSR with midseason drainage likely diminishes the CH_4 emission rate by up to 50%. Thus, WDSR may be easily accepted by different levels of rice farmers because of its reduced requirements for water, and its lower cost of production. The capacity of adaptation to climate change may also be better for WDSR, which has a relative tolerance to both drought and water stress (Pathak et al., 2013).

The understanding of climate change and GHG emissions related to rice cultivation in Myanmar is currently in its early stages among policymakers, farmers, and researchers. Additionally, there is a lack of existing research on GHG emissions from rice fields (Oo et al., 2015).

Both the private and public sectors have failed to recognize the potential negative impact of the agricultural sector on the environment. The Ministry of Natural Resources and Environmental Conservation (MONREC) enacted the Environmental Conservation Law in 2012. However, this legislation neglected to address GHG emissions from the agricultural sector, focusing instead on the industrial sector, urban development, tourism, and mining. Additionally, the System of Rice Intensification (SRI) policy was introduced in 2018 as part of the national plan by the Ministry of Agriculture, Livestock, and Irrigation (MOALI) and the Department of Planning (DoP). This policy aimed to enhance national food security and boost rice exports by advancing agricultural economics, without taking environmental concerns into account. Consequently, it is imperative for Myanmar to conduct primary field experiments that specifically address GHG emissions from the agricultural sector.

The escalating demand for rice production has raised significant environmental concerns regarding the rise in GHG emissions (Lubbers et al., 2013). Consequently, there is a crucial need to comprehend the trade-offs between enhancing rice yield and minimizing GHG emissions, and to further facilitate the formulation of effective mitigation and adaptation strategies. Significant reductions in CH_4 and N_2O emissions from rice fields can be achieved by implementing various mitigation measures. Nonetheless, numerous substantial challenges exist, hindering the integration of these mitigation options into local rice cultivation practices. Hence, it is essential to identify opportunities for emissions reduction in rice production that align with the existing practices of farmers, thus ensuring their prompt acceptance in case of positive outcomes. Furthermore, a comprehensive understanding of farmers' decision-making processes regarding the adoption of mitigation strategies within their established practices is essential to pinpoint the barriers that impede adoption as determining factors.

The objectives of this study encompass quantifying the emissions of CH_4 and N_2O from rice utilizing two distinct fertilizer application methods within two differing farming systems. Furthermore, the study assesses global warming potential (GWP), greenhouse gas intensity (GHGI), and abatement costs associated with various combinations of fertilizers and farming systems. Lastly, the study identifies factors that influence the acceptability of farmers towards adopting mitigation techniques.

2. METHODOLOGY

2.1 Measuring GHG emissions

2.1.1 Study area

The field experiment was conducted at Kyaukse research station in Kyaukse Township, Mandalay region, located at 21º36′47″ N 96º7′49″ E and an elevation of 77 m.a.s.l. in Myanmar. This region has a history of diverse agricultural traditions practiced by local farmers. The soil characteristic of the area is classified as carbonated alluvial (gleysol) in the FAO/UNESCO system, featuring a fine texture and shallow soil profile. The soil exhibits good water drainage and high-water percolation rates, although it has a low capacity for retaining moisture. These soil conditions make it suitable for cultivating field crops using a paddy-upland cropping system, including green gram, chickpea, sesame, and sunflower as upland crops, and rice as a lowland crop (Tin et al., 2022).

2.1.2 Field experiment design, treatments and layout

Two factors were identified in accordance with the current practices of local farmers: crop establishment (Transplanted rice-TPR and Wet direct seeded rice-WDSR) and fertilizer (F0, F1, and F2). The experimental setup consisted of two factors with three replications, following a split plot design. The methods of crop establishment and fertilizer application utilized in this study were based on the traditional practices of rice cultivation by local farmers (Tin et al., 2022).

In terms of crop establishment factors, the TPR was grown in a wet environment and created by puddling. Twenty-day-old SinThuKha (IRYn1068-7-1 (Manawthukha/IRBB21)) seedlings were transplanted, and until one week before they matured, they were kept submerged in water up to 10 cm deep. However, they were irrigated once more as soon as the water level rose to 1 cm above the soil. The WDSR produced puddling and leveling when it was grown in damp conditions. Following thorough leveling of the land and water drainage, sprouted seeds from the same variety of rice, weighing 70 kg/ha, were manually sown in a line. When seedlings were thriving and the water level was between 3 and 5 cm, irrigation was started. Flooded water was maintained at a depth of roughly 10 cm, and irrigation was restarted as soon as the water rose 1 cm above the soil. There were three treatments for the fertilizer factor: urea, muriate of potash (MOP), triple super phosphate (TSP), and compound fertilizer (15:15:15) (Tin et al., 2022).

2.1.3 Gas sample and analysis

In this study, a closed chamber was utilized to gather the gas emitted from the rice field (Yuesi and Yinghong, 2003; Zhou et al., 2018). The chamber consisted of two parts: an aluminum base measuring 30 cm in width, 40 cm in length, and 15 cm in height, and an acrylic cover measuring 30 cm in width, 40 cm in length, and either 60 cm or 120 cm in height. The chamber base was embedded 7.5 cm into the soil throughout the cultivation period, with the joints sealed by water. The cover has two holes on its top surface-one for gas collection and the other for inserting a plug to measure the internal air temperature. Two cover heights were used depending on the growth stage of the rice plants: the 60 cm height for the early stage and the 120 cm height for the later stage (Tin et al., 2022).

Throughout the growing period, 54 gas samples were collected weekly from six treatments, each replicated three times. Sampling occurred at 0, 10, and 20-minute intervals between 9:00 am and 12:00 pm, based on methods adapted from multiple references. (Huang et al., 2017; Liu et al., 2012a; Venterea et al., 2011). Gas samples were drawn into aluminum foil multi-layer bags equipped with ABS valves (0.5 L capacity) using a portable battery-powered air pump (SB-980). The chamber's internal air temperature was measured with a thermometer featuring a sensor tip and documented at the time of sampling. The gas samples were then analyzed for CH_4 and N_2O using a gas chromatograph (GC) (SHIMADZU Model 2010 Plus). The analysis employed an SH-Rt-Q-BOND column (serial no. 1357883) with a flame ionization detector (FID) for CH_4 and an electron capture detector (ECD) for N_2O (Tin et al., 2022).

As per the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5), equivalence values are applied where 1 kg of N_2O is equivalent to 265 kg of CO_2, and 1 kg of CH_4 is equivalent to 28 kg of CO_2 in terms of their impact on climate change (Myhre et al., 2013). The greenhouse gas intensity (GHGI) in kilograms of CO_2 equivalent per hectare was calculated by dividing the global warming potential (GWP) of CH_4 and N_2O emissions by the rice grain yield, as described by Haque and Biswas (2021). Total GWP (kg CO_2 eq/ha) = (CH_4 emission × 28) + (N_2O emission × 265).

$$\text{GHGI} = \text{Total GWP}/\text{Grain yield}$$

2.2 Factors influencing local farmers' acceptability of GHG mitigation strategies

Personal interviews were conducted within a specific radius of 10 km around the field experiment location, targeting farmers selected purposively for a community-based survey. Two villages, Kula and Pyiban, situated within this radius, were included. Kula village, located southeast of the field experiment site, is approximately eight miles away, while Pyiban village, located south of the research farm, is approximately three miles away. Kula has 164 rice farmers, whereas Pyiban has 105 rice farmers (MoALI, 2019).

2.2.1 Sample size

The personal interviews were conducted at specific locations within a 15 km radius of the field experiment, with farmers purposively selected for a community-based survey. The two villages within this radius, Kula and Pyiban, have populations of 164 and 105 rice farmers, respectively. The total sample size was calculated using the formula of Yamane (1967).

$$n = \frac{N}{1} + N * e^2$$

Where; n=sample size, N=total number of rice farmer households, e=level of precision (10%)=0.1, N=269.

$$n = \frac{269}{1} + 269 * 0.1^2 = 72.9$$

n ≈ 73 (N=269, was taken from rice farmer households from two villages).

$$\text{Sample fraction } \frac{n}{N} = \frac{73}{269} = 0.27$$

According to the sample size calculation formula, a total of 73 sample farmers were randomly selected for the survey. This study included 73 farmers from a larger group of 269 farming households, representing 27% of the households in the two villages. Details of the sample size are provided in the following Table 1.

Table 1. Sample size calculation

Name of village	Total rice growing area (acres)	Total farming households	Sample size	% of total rice farming households
Ku La	421	164	45	27%
Pyiban	512	105	28	27%
Total	933	269	73	27%

2.2.2 Data collection method

Standardized questionnaires served as the primary tool for collecting both quantitative and qualitative data at the household level. The survey gathered background information on local farmers' experiences and knowledge related to agriculture and environmental impacts. Additionally, personal interviews were conducted to assess local farmers' perceptions and acceptance of selected methods for establishing crops with lower greenhouse gas emissions and alternative practices for applying nitrogen fertilizer.

All 73 respondents for the personal interviews were paddy farmers with a minimum of three years of experience in rice cultivation. The interviews were conducted within a 15 km radius around the field experiment (or research plots), specifically targeting farmers selected for a community-based survey. The two villages within this radius are Kula and Pyiban, in Kyaukse Township.

2.2.3 Data analysis

This study utilized factor analysis to identify factors influencing farmers' acceptability. Multiple regression analysis (using the least squares method) was employed to apply a model that determines the correlation coefficients (β values) of independent factors affecting farmers' acceptability. Additionally, t-values of individual independent factors, along with R-squared (R^2) and F-values, were computed to assess significance and interpret the relationships between independent variables (such as X1, X2, X3, etc., representing farmers' situations) and the dependent factor of farmers' acceptability.

A regression model was specified in explicit form as follows:

$$\text{Model: } Y = \alpha + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \beta 6X6 + U$$

Where: Y=acceptability scores of rice farmers, α=Constant term, β1-β7=regression coefficients, X1=Age, X2=education level, X3=experience in rice cultivation, X4=agricultural information sources, X5= profit from rice cultivation, X6=land cultivated for rice.

3. RESULTS

3.1 Rice grain yield and GHG emissions

In this research, rice cultivation emitted CH_4 and N_2O at rates of 3.23±0.94 mg/m^2/h (ranging from 1.83 to 4.68) and 0.089±0.024 mg/m^2/h (ranging from 0.073 to 0.135), respectively, as the average fluxes across the entire field experiment. Additionally, the Transplanting of Puddled Rice (TPR) method resulted in higher CH_4 and N_2O emissions compared to the Water-saving Direct Seeded Rice (WDSR) method across various fertilizer applications and growth stages throughout the growing season. Previous studies, (e.g. Sandhu et al., 2021), have demonstrated that Direct Seeded Rice (DSR) methods can significantly reduce

CH_4 emissions compared to conventional transplanting methods, potentially lowering GHG emissions by at least 8%.

Table 2 presents rice grain yields and fluxes of CH_4 and N_2O as influenced by crop establishment methods and fertilizer applications (Tin et al., 2022).

Table 2. Rice grain yield (kg/ha) and fluxes of CH_4 and N_2O as affected by crop establishment and fertilizer

No	Treatment		Grain yield (kg/ha)	Average flux (mg/m^2/h)	
	Crop estb. method	Fertilizer		CH_4	N_2O
1	TPR	F_0	5,370.39	3.27198	0.1348830
2	TPR	F_1	6,846.36	3.58669	0.0976081
3	TPR	F_2	6,868.53	4.68619	0.0683357
4	WDSR	F_0	5,283.60	1.83577	0.0738248
5	WDSR	F_1	6,527.40	2.71568	0.0844403
6	WDSR	F_2	6,100.08	3.29895	0.0778937
	5% LSD		891.276	1.65580	0.1003500
1	TPR		6,361.76	3.84828	0.1002760
2	WDSR		5,970.36	2.61680	0.0787196
	5% LSD		783.367 NS	0.95597*	0.0579372 NS
1		F_0	5,327.00	2.55378	0.1043540
2		F_1	6,686.88	3.15119	0.0910242
3		F_2	6,484.30	3.99257	0.0731147
	5% LSD		640.357*	1.17083 NS	0.0709582 NS
	C, V%		12.90	28.20	61.60

TPR=transplanted rice, WDSR=wet direct seeded rice, F_0=no nitrogen, F_1=urea, F_2=compound fertilizer, LSD=the least significant difference, NS=Not significant, *=significant at 5% probability level

The results indicated that across all combinations of crop establishment methods (TPR and WDSR) and fertilizer treatments (F0, F1, and F2) tested in this experiment, there were no statistically significant differences in rice grain yields (Table 3). Specifically, grain yields between TPR and WDSR did not differ significantly regardless of the fertilizer applied at the 5% significance level. Among the fertilizer treatments (F0, F1, and F2), grain yields were significantly different only when comparing F0 (without nitrogen) to the others. However, there were no significant differences in grain yields between F1 and F2 treatments (Tin et al., 2022).

3.2 Global warming potential (GWP) and greenhouse gas intensity (GHGI)

Table 3 shows that all fertilizer treatments applied with TPR resulted in higher greenhouse gas emissions compared to those applied with WDSR. This highlights that TPR consistently produces more GHG emissions than WDSR in the Myanmar agricultural fields of our study. In terms of GHGI, the values associated with TPR across all fertilizer treatments were generally higher than those for WDSR. According to Song et al. (2021c), WDSR practice can lead to a 75% reduction in GHGI compared to flooded TPR. This underscores that the WDSR planting method is likely more acceptable when considering lower GHGI across different fertilizer treatments, especially when compared to TPR. When focusing on WF1 (WDSR with urea) and WF2 (WDSR with compound fertilizer), GHGI values were similar, though WF1 yields were 7% higher compared to WF2. Therefore, based on the analysis of GWP and GHGI-WF1 (WDSR with urea) appears to be the most cost-effective strategy for mitigating GHG emissions (Tin et al., 2022).

3.3 Average abatement cost (AAC)

In Table 4, the calculated production cost of six treatments (two crop establishments paired with three fertilizer combinations) and average abatement cost (AAC) of four fertilizer treated treatments are mentioned. For production cost among the four-F1 (urea) paired with TPR, and WDSR, F2 paired with TPR and WDSR- the lowest calculated AAC were found to be F1 and WDSR. The major limitations of TPR are labor availability, a time-consuming pace, and high production costs. Total abatement costs (TAC) are calculated as the production cost of fertilizer, minus the production cost of control- whereas total abatement potential (TAP) is obtained by subtracting $GWP_{control}$ from $GWP_{treatment}$. Thus, average abatement cost (AAC) is determined through TAC divided by TAP. In that regard, TF1 (transplanted rice with urea fertilizer) is realized to be more acceptable than TF2 (transplanted rice with compound fertilizer) especially in term of mitigation, as TPRF1 gave (-4,004.219) AAC. When compared between WF1 and WF2, WF1 contributes lower AAC than WF2. This indicates a more suitable pairing for GHG mitigation. Also in the AAC assessment of this study, TF1 and WF1 were found to be relatively acceptable for GHG mitigation techniques to date.

Table 3. Average GWP (kg CO_2eq/ha) and GHGI of six treatments

No	Treatment		Rice grain yield	CH_4	N_2O	GWP	GHGI
	Crop estb. method	Fertilizer	(kg/ha)	(kg/ha)	(kg/ha)	(kgCO_2eq/ha)	(kgCO_2eq/ka)
1	TPR	F_0	5,370.39	109.93	4.53	4,238.48	0.79
2	TPR	F_1	6,846.36	120.51	3.27	4,213.94	0.62
3	TPR	F_2	6,868.53	157.45	2.29	4,996.56	0.73
4	WDSR	F_0	5,283.60	61.68	2.48	2,362.09	0.45
5	WDSR	F_1	6,527.40	91.24	2.83	3,281.23	0.50
6	WDSR	F_2	6,100.08	110.84	2.61	3,773.66	0.62

TPR=transplanted rice, WDSR=wet direct seeded rice, F_0=no nitrogen, F_1=urea, F_2=compound fertilizer

Table 4. Average Abatement Cost (MMK kgCO_2/eq)

No	Treatment		Production cost (MMK/ha)	Total abatement cost (MMK/ha)	Total abatement potential (kgCO_2eq/ha)	Average abatement cost (MMKkgCO_2/eq)
	Crop estb. method	Fertilizer				
1	TPR	F_0	1,047,220	-	-	-
2	TPR	F_1	1,145,500	98,280	-24.54	- 4,004.22
3	TPR	F_2	1,185,800	138,580	758.08	182.80
4	WDSR	F_0	1,010,170	-	-	-
5	WDSR	F_1	1,108,450	98,280	919.14	106.93
6	WDSR	F_2	1,148,750	138,580	492.43	281.42

TPR=transplanted rice, WDSR=wet direct seeded rice, F_0=no nitrogen/control, F_1=urea, F_2=compound fertilizer, MMK=Myanmar Kyat (1 USD=1,650 in 2019) *Fertilizer costs are calculated based on current relevant market price as of July 2019. Urea 50kg=MMK 26,000, TSP 50kg=MMK 25,000, MOP 50kg=MMK 22,000, 15:15:15 compound fertilizer 50kg=MMK 40,000

3.4 Mitigation technique selection

As indicated, the results of this study analyzed GHG emissions from different farming systems, crop establishment and nitrogen fertilizer practices, global warming potential (GWP), and greenhouse gas intensity (GHGI). Moreover, the production cost of rice cultivation and average abatement cost (AAC) were calculated to figure out the pairs of proper rice crop establishment methods and nitrogen fertilizer application practices which create less GHGs, while also still producing acceptable rice yields throughout the field experiments.

The overall findings of this study indicated the pairing of wet bed direct seeded rice (WDSR) and urea fertilizer application (WF1) was the most appropriate agricultural practice for GHG mitigation with a sustainable rice production profile. This pairing gives off relatively less methane and nitrous oxide than other techniques, while still providing acceptable rice yield, as well as lower GWP, GHGI and AAC.

According to the statistical analysis, the grain yields of TF1, WF1, TF2, and WF2 (WDSR with compound fertilizer) were not statistically different to each other at 5% probability level in this study. This finding made sense, as these crop establishment methods and fertilizer application practices are currently adopted by local farmers at the ground level, and the farmers frequently select agricultural practices which ensure both productivity and profit.

Regarding GHG emissions, 47% of methane flux was higher in TPR (as compared to WDSR) while there were no significant differences among F0, F1, and F2 in average flux of CH_4. With regard to average nitrous oxide fluxes, neither crop establishment (TPR, WDSR) nor fertilizer type (F0, F1, and F2) were found to be significantly different.

In the case of GWP (Table 4), both TF1 and TF2 were higher than WF1 and WF2, and the result of TPR produced more GHG emissions than WDSR. Furthermore, the GHGI of WDSR with all fertilizer treatments was found to be generally lower than that of TPR. It is noticeable that the WDSR planting method is likely to be more acceptable than TPR across the fertilizer treatments (owing to lower GHGI). Thus, within our GWP and GHGI analysis, WF1 (WDSR with urea) is noted to be most suitable for GHG mitigation.

Although the AAC analysis gave two options for transplanted rice cultivation-urea (TF1) and WF1, both relatively acceptable for environmental friendly agricultural practices-other aspects of GWP and GHGI were rendered with production rates. It then became clear that WF1 appeared to be the particular rice establishment option, or fertilizer application method, with the least CH_4 or N_2O emissions possible, without reducing rice yield.

3.5 Factors influencing acceptability among local farmers

3.5.1 Profile of respondents

The profile of respondents describes demographic and socio-economic characteristics of the respondents from the two villages of Pyiban and Kula. The demographic characteristics include age, education level, and experience in rice cultivation while the agricultural characteristics include current practices of fertilizer application, and crop establishment methods for rice cultivation systems (Table 5).

(1) Age

In the study area, the age of rice farmers was dispersed; ranging from 20 to 64. In Kula village, respondents' age groups were evenly dispersed between young (age 18 to 30) and middle (31 to 60) with 47% of each. Only 6% of respondents were in the group older than 60. In Pyiban village, the highest amount existed in the middle age group (57%) followed by older than 60 (25%), then the lowest amount of respondents was 18 to 30 (18%).

(2) Education level

Primary education was the most common level completed in Kula village (more than half of respondents; 53%), followed by secondary and high school education, which were 29% and 13%, respectively. Only 5% of respondents reached the college/university level of education in Kula village. However, respondents in Pyiban village noted 39% for secondary education, the highest group level for this village. In the case of university education level however, there was not a single graduate in Pyiban village.

(3) Experience in rice cultivation

Three groups were outlined for rice cultivation experience: low (3-9 years), medium (10-16) and high (above 16). Comparisons for the two villages are presented in Table 4. Most of the respondents for both villages had medium experience 62% of farmers in Kula village and 57% in Pyiban village. Low experience farmers were second most prevalent for both those villages.

(4) Agricultural information sources

The distribution of agricultural information is sorted by numbers of sources, with three groups outlined: low (1-3 sources), medium (4-6) and high (7-9) for the two villages (shown in Table 4). In Kula village, 51% of respondents access one to three sources of agricultural information, making it the largest group in this village. Whereas in Pyiban village, most of the farmers who responded access four to six sources of agricultural information (54%). However, few respondents in both Kula (18%) and Pyiban (7%) accessed high sources of information.

In the studied villages, there were nine main information sources. The most popular (and readily available) agricultural sources for this study area were other farmers/friends (71 respondents), social media (70 responds) and private fertilizer companies' sales-men (68 respondents). Moreover, government extension workers were also an important source of agricultural knowledge and information, as 52 respondents in the survey listed them as major sources of information. They are followed by television and newspapers, which some farmers still accessed as primary agricultural information sources. The least favorite information sources were radio and magazines, not more than four respondents accessed them regularly (Figure 1).

(5) Available land for rice cultivation

Farmers were categorized into three groups: small cultivated areas (lower than 5 acres), medium cultivated areas (6 to 10 acres) and highly cultivate areas (above 10 acres) based on rice cultivation of their own land (Table 5). Greater percentages of small, cultivated areas and medium cultivated areas were found in Kula village, and most farmers from Kula village (56%) cultivated rice plots smaller than 5 acres. However, the highest percentage was found in Pyiban village, where half of the respondents cultivated rice plots sized between six to 10 acres.

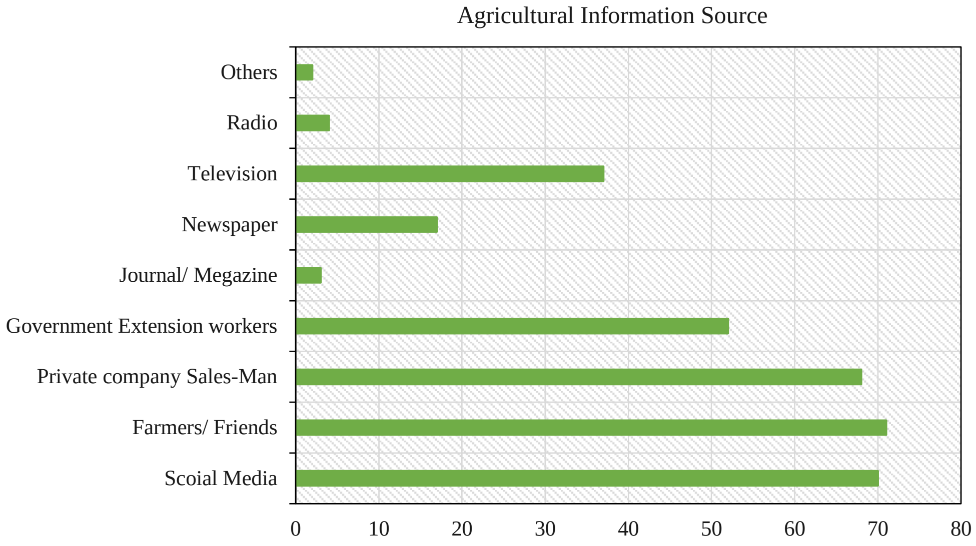

Figure 1. Sources of agricultural information used by farmers

Table 5. Characteristic profiles of farmers

Characteristic	Categorization	Kula village (n=45)		Pyiban village (n=28)	
		F	%	F	%
Age	Young (18-30)	21	47	5	18
	Middle (31-60)	21	47	16	57
	Old (61 and above)	3	6	7	25
Education level	Primary	24	53	9	32
	Secondary	13	29	11	39
	High School	6	13	8	29
	College/University	2	5	0	0
Rice cultivation experience (in years)	Low (3-9)	14	31	8	29
	Medium (10-16)	28	62	16	57
	High (16 and above)	3	7	4	14
Agri-information sources	Low (1-3)	23	51	11	39
	Medium (4-6)	14	31	15	54
	High (7-9)	8	18	2	7
Cultivated land (in acres)	Small (<5)	25	56	11	39
	Medium (6-10)	18	40	14	50
	High (>10)	2	4	3	11
N-fertilizer and crop establishment	TF1	10	22	9	32
	TF2	12	27	8	29
	WF1	11	24	9	32
	WF2	12	27	2	7

TF1-TPR with urea, TF2-TPR with compound fertilizer, WF1-WDSR with urea, WF2-WDSR with compound fertilizer

(6) Current rice cultivation practices

The distribution of respondents was based on the four major types of practice in the study area: transplanted rice with urea (TF1); transplanted rice with compound fertilizer (TF2); wet bed direct seeded rice with urea (WF1) and wet bed direct-seeded rice with compound fertilizer (WF2). All four were practiced by the two villages. This study highlighted that all four types were more or less equally distributed among respondents in the two villages (Figure 2).

In Figure 2, TF1=TPR with urea; TF2=TPR with compound fertilizer; WF1=WDSR with urea; WF2=WDSR with compound fertilizer Both TF2 and WF2 practices had 27% usage and these results were relatively higher than the other two practices in Kula village. In contract, TF1 (32%) and WF1 (32%) were practiced by most of the farmers in Pyiban village. The lowest amount was WF2, with 7% of Pyiban village's respondents. In this study of the two villages, the most commonly applied practice was TF2 (28% of all respondents), followed by WF1 with 27% (Figure 2).

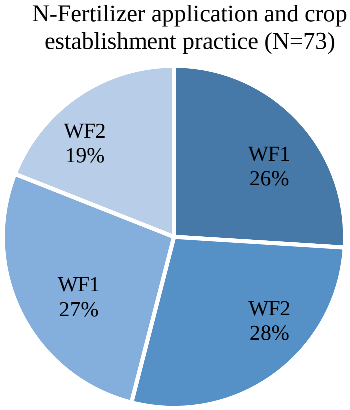

Figure 2. N-fertilizer application and crop establishment in rice cultivation

(7) Profit from rice cultivation

The grain yields and cost of rice cultivation (Supplementary data) data of this analysis were collected from a 2021 field survey, with a basis of 8,500 MMK per bucket of rice (Sin Thuka rice cultivar -IRYn1068-7-1, Manawthukha/IRBB21). The market price was derived from the yearly report of the Department of Agriculture Research, Kyaukse Township as secondary data. Concerning the net income (or profit) of rice production, farmers who practiced WF1 were higher than WF2. It also showed the least profit of any practice in Kula village, since the cost of production for WF2 was the second highest among the rice cultivation practices (Table 6). However, WF2 in Pyiban village showed moderate profit, more or less on par with TF1.The average grain yield of Kula village was also higher than Pyiban village, and Kula village's average profit (282,211 MMK) was less than the profit of the Pyiban village (306,129 MMK).

3.6 Acceptability of local farmers on GHG mitigation techniques

The acceptability of local farmers is shown in Table 7. There are five degrees of acceptability: willing to accept; willing to accept with conditions; neutral; not willing but not strongly rejecting; and not willing to accept. The greatest number of local farmers (drawn from overall respondents) were willing to accept WF1 with conditions (36%). The second highest percentage of acceptability was found to be neutral, with 30% of respondents still not yet decided on their practices for rice cultivation for the coming season.

Table 6. Grain yield and profit by different types of rice cultivation practice

Rice cultivation practice	Kula village (n=45)			Pyiban village (n=28)		
	Cost (Kyats)	Grain yield (basket/ac)	Profit (Kyats)	Cost (Kyats)	Grain yield (basket/ac)	Profit (Kyats)
TF1	489,000	90.36	279,060	473,300	91.48	304,280
TF2	547,800	96.53	272,705	521,300	93.27	271,495
WF1	486,000	93.40	307,900	462,900	95.34	347,490
WF2	522,000	93.08	269,180	498,600	94.10	301,250
Average	511,200	93.00	282,211**	489,025*	94.00	306,129**

*=Significant at 5% level, **=Significant at 1% level

Table 7. Acceptability of local farmers by villages on WF1

Acceptability of local farmers	Kula (n=45)		Pyiban (n=28)		Total (n=73)	
	f	%	f	%	f	%
Willing to accept (5)	3	7	5	18	8	11
Willing to accept with conditions (4)	12	27	14	50	26	36
Neutral (3)	17	38	5	18	22	30
Not willing, but not strongly rejecting (2)	9	20	4	14	13	18
Not willing to accept (1)	4	8	0	0	4	5

3.7 Factors influencing farmers' acceptability of WF1

In this study, age, educational level, experience in rice cultivation, agricultural information sources, profit from rice cultivation and land cultivated for rice were estimated to be the critical influencing factors, according to step-wise statistical analysis (Table 8). The standardized coefficient of all factors was statistically positive, which shows the influences and factors were positively related with farmers' acceptability. Meanwhile, the rice cultivation experience of farmers was 95% significant in determining farmers' acceptability. Here farmers with rice-growing experience were more willing to accept the WF1. Farmers with knowledge of multiple rice cultivation practices were also rarely hesitant to change their current practices. According to the multiple regression analysis, available information sources for agriculture was also significantly correlated with the acceptability of the local farmers, and its coefficient was positive as well. This finding can perhaps be interpreted as farmers who accessed more information sources related to agriculture then displayed greater acceptability of the WF1 practice in the study area. Moreover, available land for rice cultivation was also significant (90%) and positively correlated with farmers' acceptability since the agriculture practice-especially irrigation management and land preparation-cannot promptly be changed by individuals working in fields that are homogenously bonded to each other, and in environments where the farmers need to follow the practices of the majority.

Table 8. Influencing factors on farmers' acceptability (min=1, max=5)

Variables	Standard error	Coefficient (Standardized)	T-Value	Probability value
Age	0.131	0.163	0.778	0.446
Education level	0.026	0.170	0.852	0.405
Rice-growing experience	0.023	0.400	2.157	0.046**
Information sources	0.025	0.351	2.454	0.024**
Profit	0.130	0.142	0.178	0.482
Cultivated land	0.015	0.449	1.947	0.066*

*=Significant at 10% level, **=Significant at 5% level,

4. DISCUSSION

4.1 Emissions patterns of CH_4 and N_2O

Although measuring GHG emissions from rice cultivation has been systemically researched in a number of regional countries in Southeast Asia, there is little reliable information available in Myanmar. This is especially true of field experiments regarding CH_4 and N_2O emissions from existing farms, where farmers have adopted different fertilizer applications under different rice establishment methods (Win et al., 2021).

Thus, insights were gained from this study regarding the consequences of local farmers adopting agricultural practices related to CH_4 and N_2O emissions from rice cultivation. In this study, the trade-off effect between CH_4 and N_2O occurred, which in turn agreed with other previous research findings (Janz et al., 2016; Kong et al., 2021; Song et al., 2021b; Tin et al., 2022).

Alongside rice growth throughout the season, CH_4 fluxes in this study were found to increase continuously until 90 DAS; Day after seeding (EPI stage) and after that descend rapidly. This was in line with similar results in previous studies (Gaihre et al., 2013).

In all likelihood, this is due to crop residue accumulation which favors CH_4 emission (Janz et al., 2019). Moreover, the period between 83 DAS and 90 DAS (EPI stage) had the highest water depth (Table 3). The effect of continuous flooded rice fields on CH_4 emission has been well documented, and it has been found to assist CH_4 production by creating anaerobic situations (Gupta et al., 2016; Song et al., 2021a; Vo et al., 2018; Zhou et al., 2018). Anaerobic situations in soil aid methanogenesis bacteria, which are the major source of CH_4 concentrations in the atmosphere (Haque and Biswas, 2021; Islam et al., 2020; Kong et al., 2021).

On the other hand, trends in N_2O emission were not found to be similar with CH_4 trends. Namely, fluxes were higher at the 30 DAS mark, and were regularly reduced to the minimum rate at 69 DAS, or the tiller stage. Furthermore, the curve of N_2O emissions increased again till the EPI stage, this was the highest stage of N_2O, while CH_4 fluxes decreased again from the highest point.

According to N_2O emission data, the rate of N_2O positively responded to both low water depth situations and N fertilizer applications. Drier situations and N fertilizer are perfect boosters to generate the nitrification and denitrification process in the soil, and that knowledge clearly explains why N_2O emission become higher during low water depths and when applying N fertilizer (Granli, 1994; Janz et al., 2016; Kong et al., 2021).

4.2 Influencing factors on farmers' acceptability

The proper combination of rice crop establishment methods and nitrogen fertilizer application practices produces less greenhouse gas emissions accompanied by an acceptable rice yield. This appeared through the field experiments, as WF1 based on its grain yield GWP, GHGI and AAC results, and is currently also being practiced by some local farmers. Moreover, the WF1 group had the highest rate of net income according to the social survey. As per local farmers' perceptions, the highest rate (36% of respondents; from two villages, Kula and Pyiban) were willing to accept the pairing of WDSR and WF1 for their coming season of rice cultivation. In fact, some farmers well realized the value of WF1 and were willing to change to it. But many remained reluctant to promptly alter their strategies, due to obstacles on the ground level.

According to multiple regression analysis, the factors influencing farmers' acceptability of WF1 were: the rice cultivation experiences of farmers; the number of available information sources for agriculture; and land available for rice cultivation. The results of the analysis showed that even when farmer experiences varied, especially in rice cultivation, they were not hesitant to change their current practices, since they were confident they could handle varieties of cultivation methods, given enough knowledge and information. This also agreed with other previous research, as past rice cultivation experiences have shown to significantly influence acceptability regarding low-carbon agricultural practice (Hou and Hou, 2019). Besides, a case study in Thailand revealed that agricultural experience is the most significant determinant in farmers' adaptive capacity (Arunrat et al., 2017). Also, Hou and Ying (2014) observed that farmers' decisions regarding plantation methods largely depend on personal observation and experience in farm management, especially when they had no way to obtain comprehensive market information by themselves (Wang and Zhang, 2013).

This fact also linked with the second determining factor. The more farmers accessed information related to agriculture, the greater their acceptability of WF1 practices in the study area. Numbers in previous findings support this result, with Arunrat et al. (2017) defining institutional accessibility as attending training about agricultural practices, climate change, and adaptation strategies. Most were in turn found to affect farmers' adaption of practices positively.

The article of Ng et al. (2011) indicated that farmers who had sound communication and networking with other farmers showed a greater desire to practice new agricultural methods. Moreover, the availability of land for rice cultivation was positively correlated with farmers' acceptability-though cultivation systems were not easy to change individually when agriculture lands were adjacent each other. This was due to several factors, namely irrigation management and land preparation could not promptly be changed by individuals, when the fields were homogenously bonded to each other. Farmers still needed to follow the practices of the given majority. However, this result disagreed with the findings of J. Hou and Hou (2019) which mentioned that small production scale was more strongly correlated with farmers' acceptability and adoption decisions regarding environmental friendly agriculture practices than it was for farmers who had large production scale.

5. CONCLUSION

Today, several pieces of research have highlighted that changing the cultivation practice from TPR to WDSR has become a way to make sense of, and even resolve the high cost of farming inputs-namely water and labor scarcity and these changes have been adapted by farmers themselves based on their experiences and indigenous knowledge.

Fortunately, the findings of this study indicated that the pair of practices (WDSR+F1) has great potential in mitigating GHG emissions from the agricultural sector, since lower GWP and GHGI lead to acceptable productivity. Further, insights upon the consequences of local farmers adopted agricultural practices and its effects on CH_4 and N_2O emissions from rice cultivation were a large gain from this study. Here, the trade-off effect between CH_4 and N_2O occurred, and this result agreed with other research findings. Furthermore, the main results showed that the sociodemographic information of local farmers-such as the rice cultivation experience, numbers of available information sources, and the overall size of rice-cultivated land-were significantly and positively correlated with their intention to accept the WF1 practice as a GHG mitigation strategy in rice cultivation.

Much of the information from this study is useful scientific knowledge, which may be used for future research and further studies, especially in figuring out GHG mitigation strategies under the sustainable development umbrella. However, the findings of this study may not be used to generalize the features of all small farmers in the central dry zone of Myanmar, since it was a pioneer field experience in the region, with several limitations-including limited equipment and facilities, and restrictions on budget and time. Therefore, there may be wiggle room to fulfill cost efficient GHG mitigation strategies for Myanmar.

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Landslide Disaster Risk for Small and Medium Agricultural Enterprises (SMAEs)

Ngadisih[12*], Bambang Purwantana[1], Devi Yuni Susanti[1], Ismi N. Puspitaningrum[2], Guruh Samodra[2,3], Peter Strauss[4], Sigit Supadmo Arif[1], Murtiningrum[1], Sri Rahayoe[1], Joko Nugroho W.K.[1], Lilik Sutiarso[1], Nursigit Bintoro[1], Radi[1], Andri Prima Nugroho[1], Rizki Maftukhah[1], Rudiati Evi M.[1], Chandra Setyawan[1], Bayu D.A. Nugroho[1], and Prieskarinda Lestari[1]

[1]Universitas Gadjah Mada, Faculty of Agricultural Technology, Department of Agricultural and Biosystems Engineering, Yogyakarta, Indonesia
[2]Universitas Gadjah Mada, Disaster Research Center, Yogyakarta, Indonesia
[3]Universitas Gadjah Mada, Faculty of Geography, Department of Environmental Geography, Yogyakarta, Indonesia
[4]Institute for Land and Water Management Research, Pollnbergstrasse 1, A-3252 Petzenkirchen, Austria

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*** Corresponding author:**
E-mail: ngadisih@ugm.ac.id

ABSTRACT

Small and Medium Agricultural Enterprises (SMAEs) are crucial for economic development in many developing countries, particularly in rural areas. Following a disaster, SMAEs experience the most profound impacts on their capital, logistics, workforce, and marketing operations. This study examines the impact of landslides on SMAEs in Selopamioro village, Bantul Regency of Special Region Yogyakarta. The study focused on the economic sensitivity of SMAEs and assessed their spatial distribution and classifications using drone aerial imagery and a village landslide database from 2010 to 2024. A total of 120 SMAEs were identified and classified by type in accordance with Indonesian laws. A representative sample of 60 SMAEs was validated using the Slovin formula. The study employed a hybrid survey methodology, combining interviews with village and hamlet leaders and on-site surveys using standardized questionnaires. The results showed that SMAEs in all hamlets of Selopamioro village have relatively low sensitivity, indicating that recent landslides have had limited effects on their sustainability. The village's disaster response capacity was moderate, but the study identified deficiencies in planning for potential future landslides. This study provides valuable insights for SMAEs and local governments regarding proactive risk mitigation strategies.

HIGHLIGHTS

The study provides valuable insights into the economic impacts of landslides on SMAEs and highlights the need for proactive measures to build resilience and reduce vulnerability in landslide-prone areas.

1. INTRODUCTION

Small and medium agricultural enterprises (SMAEs) play a crucial rolerural employment and economic development in developing countries such as Indonesia (FAO, 2012). They contribute significantly to employment generation and Gross Domestic Product (GDP) growth (Eskesen et al., 2014), and their success in meeting the demand for

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rice (Anggreini and Asyikin, 2023) is closely linked to social security, economic stability (Nurhaedah, 2022), political stability, and national security. SMAEs are essential for economic sustainability in both developed and developing nations (Radović-Marković et al., 2017) and they continuously strive to mitigate disaster impacts while working toward autonomous recovery (Satpathy et al., 2025). However, SMAEs are highly vulnerable to disasters, which can severely affect their capital, logistics, labor, and marketing sectors (Morrish and Jones, 2020). To enhance the income of SMAEs', governments should support small business development (Nasution et al., 2022; Ebrahim et al., 2023).The impact of landslides on agriculture differs between SMAEs and larger agricultural enterprises, as SMAEs often lack financial resilience and alternative resources. Landslides can result in long-term soil degradation, reduced crop yields, and disruptions in supply chains, disproportionately affecting smallholder farmers. I particular, road blockages caused by landslides hinder transportation and market access, further exacerbating economic losses. Alstadt et al. (2012) argues that investments in transportation infrastructure are essential for improving labor market ensuring efficient goods distribution, which, fosters economic growth.

Accessibility is crucial for business development, especially in rural areas where slope stability is at risk (Raza et al., 2022). Agricultural land use, such as monocropping and terraced farming, significantly influences slope stability, surface flow regulation, and vegetation loss due to erosion (Garcia-Chevesich et al., 2021). Landslides cause damage to land and agricultural infrastructure, including irrigation systems, dams, farm roads, and production facilities (Kainthola et al., 2021; Manurung et al., 2016). Climate change has been increasing the likelihood of landslides, indirectly affecting SMAEs. Slope stability depends on various factors, with precipitation being the most significant (Gallage et al., 2021; Jemec et al., 2023). Climate change can alter the frequency and severity of extreme precipitation globally, escalating risks associated with rainfall-induced landslides (Gariano and Guzzetti, 2022; Jakob, 2022). Landslides result in significant human and economic losses in China (Lin et al., 2020) and Indonesia (Sharif, 2021; Utami et al., 2021). Hilly areas often experience landslides, particularly in low-lying areas between hills, which can adversely impact on humans and the environment (Intarat et al., 2024; Lau and Zawawi, 2021). Landslides in remote areas have the potential to cause unexpected ecological and social damage (Putra et al., 2021). Various landslide studies have been conducted globally, categorized into landslide inventories (Hong et al., 2020; Ngadisih et al., 2017), hazard assessment (Mersha and Meten, 2020), and risk assessment (Wubalem, 2020).

The study utilizes landslide inventory to assess the age, activity, depth, and velocity of landslides in a village. However, this method faces challenges such as spectral differences, object-based classification, difficulty in obtaining bi-temporal imagery, and less accuracy when applied to other areas (Gariano and Guzzetti, 2022; Lin et al., 2020; Sukristiyanti et al., 2021). It also suffers from frequent classification errors. The study aims to assess the risks of SMAEs in a village and evaluate the risks of disasters affecting their sustainability. This study aims to assess the risks faced by SMAEs in a village and evaluate the risks of disasters affecting their sustainability. It seeks to develop a landslide disaster risk assessment method that integrates physical and socio-economic aspects at the village level, filling a gap in previous research that has primarily focused on larger administrative units. By incorporating SMAEs, which play a vital yet often overlooked role in rural economies, this study provides a more comprehensive risk evaluation. The modified approach supports a bottom-up disaster risk reduction strategy, contributing to the Sustainable Development Goals (SDGs), particularly in the areas of poverty alleviation and rural resilience. The novelty of this study lies in the risk assessment concept that integrates both physical and socio-economic aspects at the smallest administrative level (i.e., village). Previous studies have primarily focused on risk assessment at the district or sub-district level. To support the achievement of the SDGs through a bottom-up approach that begins at the village level, we have modified existing risk assessment methods. Accordingly, this study adopts several parameters commonly used for risk assessment at the district/provincial level and adapts them to the village level.

2. METHODOLOGY

2.1 Study site

Selopamioro Village, located in Imogiri District, Bantul Regency, is the research area with a history of landslides and a large number of SMAEs. The village spans 2,275 hectares (ha), including lowlands at an altitude of 100 meters above sea level. The topography consists of 30% flat to wavy areas and

70% wavy to hilly, which limits the land available for cultivation by farmers. The topography consists of 30% flat to wavy areas and 70% wavy to hilly, making land cultivation by farmers relatively small. The village is divided into several hamlets, including Lenteng I, Lenteng II, Lemahrubuh, Jetis, Kedungjati, Nogosari, Nawungan I, Nawungan II, Kajor Wetan, Kajor Kulon, Siluk I, Siluk II, Pelemantung, Putat, Kalidadap I, Kalidadap II, and Srunggo I. Selopamioro Village was chosen because it is identified as the poorest and most disaster-prone village in the district. Strengthening SMAEs is expected to drive economic growth and help the village escape poverty through disaster risk reduction-based development.

2.2 Data collection

2.2.1 Landslides inventory

Landslide distribution and classifications were determined manually from aerial images obtained by a drone flight in 2022. The aerial photographs provided a comprehensive view of the affected areas and facilitated the mapping of the landslides. Additionally, historical landslide data was obtained from the village office, which has maintained a database of landslide occurrences since 2010. The landslide inventory technique was also used by Thongley and Vansarochana (2021) in Bhutan. It uses a workflow consisting of landslide inventory, preparation factors, NGO (Non-Government Organization) development, and then validating the data. To classify landslides, visual identification is used without orthomapping. The image capture technique used is oblique aerial photography. This technique provides a distinctive landslide viewpoint compared to using vertical (orthogonal) aerial photography. Another advantage of aerial photography is the 20 MP image resolution, which can help landslide observations. Thus, aerial photography can be used to determine the characteristics of landslides based on visual appearance (Figure 1).

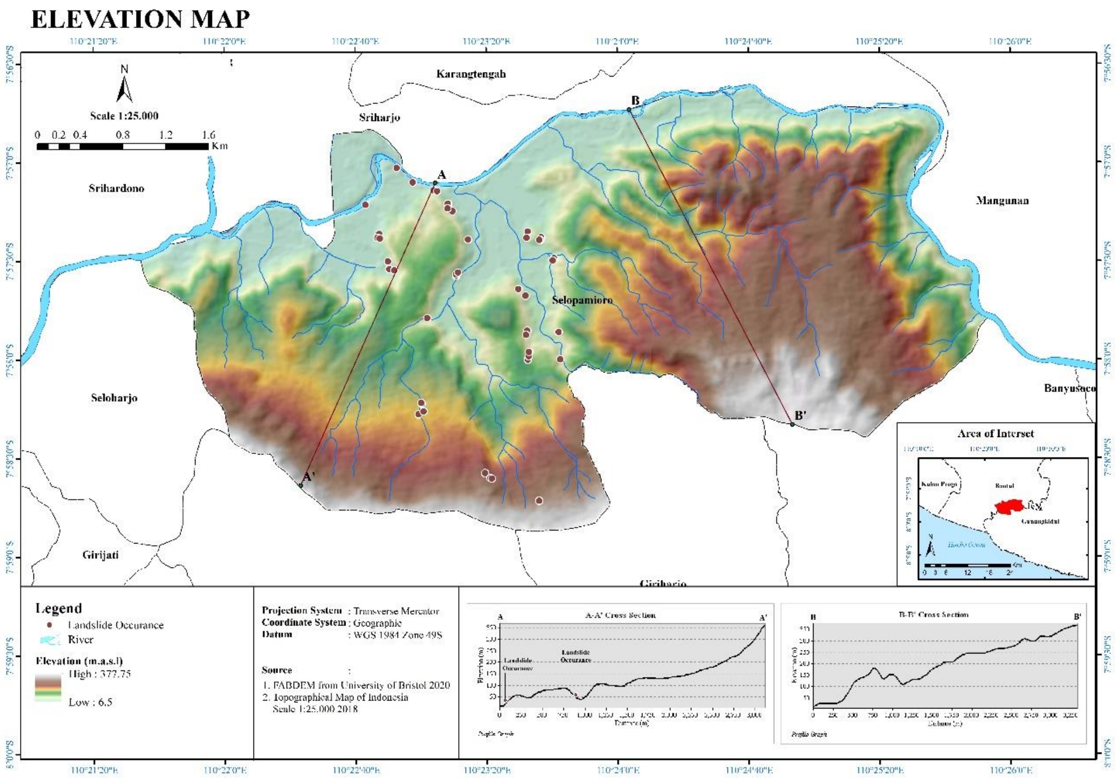

Figure 1. Elevation map of the village Selopamioro, including spots of observed landslide occurrence

2.2.2 SMAEs data acquisition

Information regarding the number and categories of SMAEs was obtained from the village administration, including a detailed listing of SMAEs operating in the region, categorized according to the stipulations outlined in Law No. 20 of 2008 concerning Micro, Small, and Medium Enterprises, which define the classification of such businesses in Indonesia. During the initial mapping phase, 120 SMAEs were identified.

2.2.3 Selection of samples

The Slovin formula was used to determine the sample size from 120 identified SMAEs, resulting in 60 SMAEs. The capacity assessment included 19 respondents, including village officials and their staff.

The equation (1) was used to determine the sample size from a known population (Sugiyono, 2017). The sample was validated through consultations with village and hamlet leaders to confirm the current status of the SMAEs, leading to adjustments in the data. This study aimed to assess the vulnerability of SMAEs actors in Selopamioro to landslides.

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

Where; n=sample size; N=population size; e=Allowance for inaccuracy due to tolerable sampling error, then squared.

The value of e=0.1 (10%) is used for large populations. The value of e=0.2 (20%) is used for small populations. In this study, we used the value of e=0.2 because the sample population was small.

(1) Capacity and Hazard Assessment

A survey was conducted to assess disaster capacity in SMAEs, involving interviews with village and hamlet leaders. The index technique (Table 1) was used to evaluate the resilience of SMAEs to landslides, incorporating input from local leadership. The study focuses on regional capacity, represented by the village government administration unit. Village-level policy makers are needed for SMAE resilience. The hazard evaluation used the frequency ratio method to examine historical and geographic elements contributing to landslide hazards.

Table 1. Disaster capability index

Component	Value (%)	Class		
		Low	Medium	High
		(0-0.333)	(0.334-0.666)	(0.667-1)
Regional resilience	40	Value transformation 0-0.40	Value transformation 0.41-0.80	Value transformation 0.81-1
Community preparedness	60	<0.33	0.34-0.66	0.67-1

(2) SMAEs actor survey

A survey was conducted on the proprietors and managers of 60 selected SMAEs, based on field updates. Many reductions were due to profession changes, address changes, and deceased business actors. Data was collected using a structured survey tool to assess understanding of landslide hazards, readiness, and vulnerability. An interview instrument with a Likert scale was used to quantify responses (Table 2).

Table 2. Likert scale

Class	Description
1	Very unsuitable
2	Unsuitable
3	Quite suitable
4	Suitable
5	Very suitable

2.3 Data analysis

2.3.1 Hazard assessment

In this study, 60% of the data inventory was collected and used for model training, while the remaining 40% was reserved to test the accuracy level. The data distribution was plotted into the parameters of the landslide hazard model. The parameters used in this study include water related factors such as Stream Power Index (SPI) and Topographic Wetness Index (TWI), along with topographic factors like slope, aspect, plan curvature, profile curvature, and elevation (Al'Afif et al., 2024; Samodra et al., 2017). All water-related and topographic factors are compiled using FABDEM with a spatial resolution of 30×30 meter. Additional factors used include geological formation, distance to faults, distance to roads, distance to rivers, and land use sourced from the 2018 Indonesia Topographic Map at a scale of 1:25,000. Twelve factors influencing landslides were analyzed in raster format with a 30×30 resolution, adjusted to the spatial resolution of FABDEM (Figure 2).

The frequency ratio method (equation 2) was used to assess landslide threat in a site study. This method identifies future landslide events using the same conditions as past ones. The ratio between landslide area and total area, along with the probability of a landslide event occurring compared to its absence for a given attribute factors, are crucial elements. The greater the ratio, the stronger the relationship between landslide events and related factors. This method helps identify regions of elevated risk (Pratiwi, 2018).

$$FR = \frac{LAi/LDi}{\sum LAi/\sum LDi} \quad (2)$$

Where; FR=frequency ratio; LAi=number of pixels of containing landslide in the i-th variable class; LDi=number of pixels of each class in the whole area in the i-th variable class; ∑LAi=total number of pixels of containing landslide in the i-th variable class; ∑LDi=total number of pixels of whole area in the i-th variable class.

The FR values were standardized to a probability value range of [0, 1] as relative frequency (RF) in the subsequent stage. The RF values are obtained by dividing the FR value by the total sum of FR values within a single parameter.

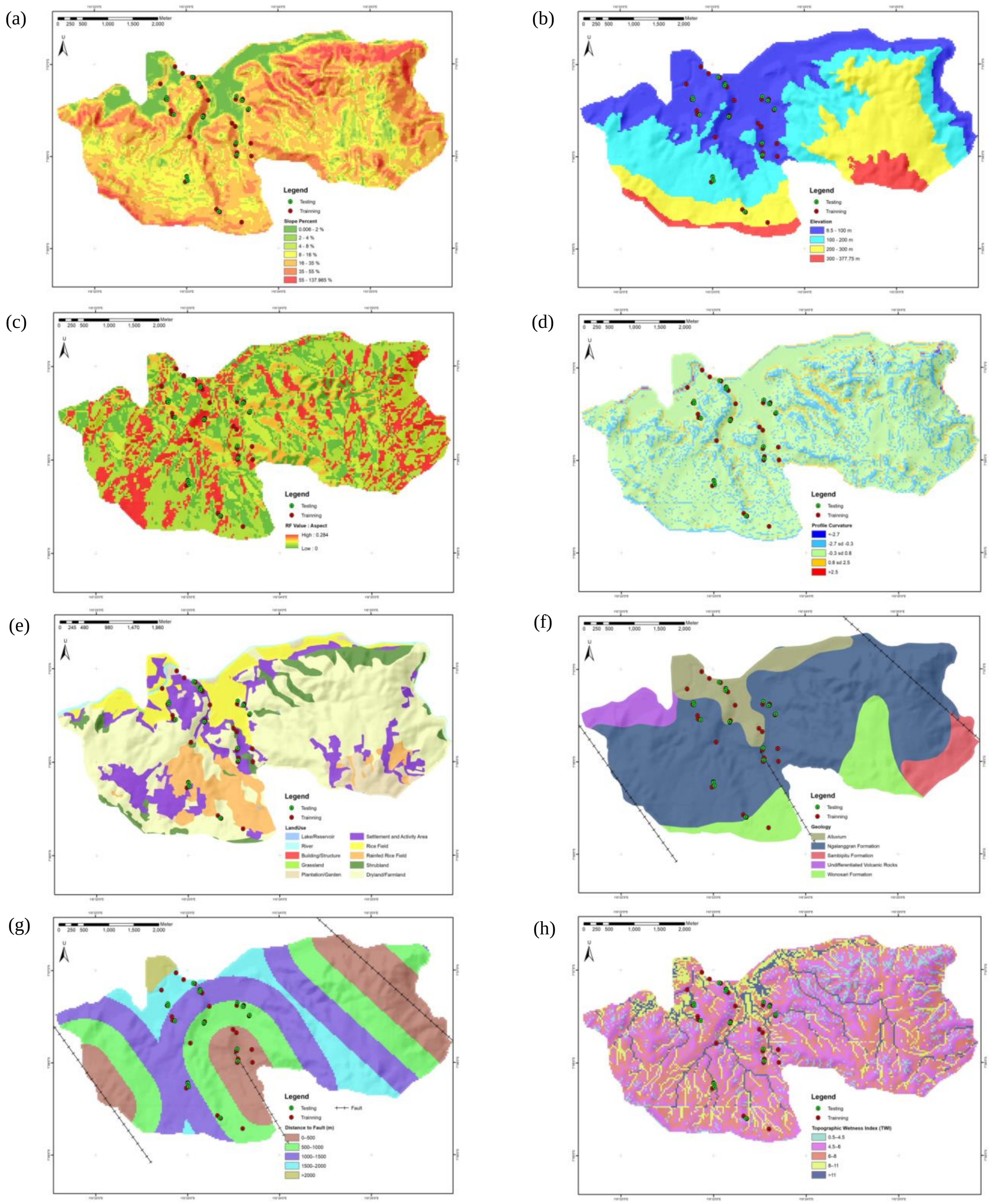

Figure 2. Maps of landslide controlling factors: (a) slope, (b) elevation, (c) aspect, (d) profile curvature, (e) land use, (f) geology, (g) distance to fault, (h) TWI, (i) distance to river, (j) distance to road, (k) SPI, and (l) plan curvature

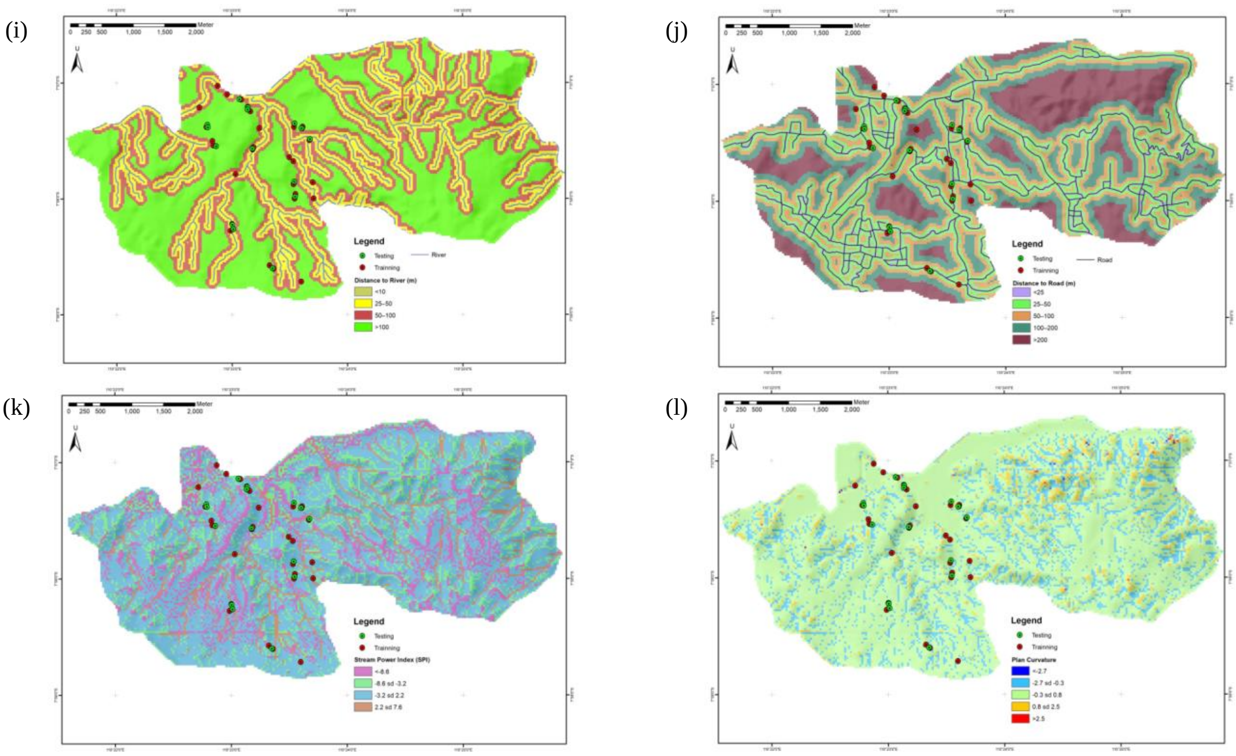

Figure 2. Maps of landslide controlling factors: (a) slope, (b) elevation, (c) aspect, (d) profile curvature, (e) land use, (f) geology, (g) distance to fault, (h) TWI, (i) distance to river, (j) distance to road, (k) SPI, and (l) plan curvature (cont.)

The RF still has the limitation of treating all conditioning elements equally after equalization. To overcome this limitation and consider the interdependencies among the independent variables, the prediction rate (PR) was generated for the evaluation of each conditioning component using the training data set (Youssef et al., 2023). Equation (3) was used to get the PR for each class:

$$PR = \frac{(RF\ max - RF\ min)}{(RF\ max - RF\ min)min} \quad (3)$$

The PR of each component and the RF of each class were then combined to form the landslide susceptibility index (LSI), as illustrated below:

$$LSI = \sum(RF \times PR) \quad (4)$$

The vulnerability map for landslides is generated using the LSI value, ensuring accuracy and reliability. The model's success rate is evaluated using the Receiver Operating Characteristic (ROC) from 60% of training data and 40% of testing data, with the AUC value above 0.5 or 50% indicating a successful model.

(3) Vulnerability and capacity index

Vulnerability indices are crucial in assessing the susceptibility of communities to hazards. These indices include social, economic, physical, and environmental factors. Environmental vulnerability is not considered due to the absence of protected area land use, and regional geography, infrastructure, and historical exposure are not considered. The disaster vulnerability index is strengthened by considering these factors. The susceptibility and capability of SMAEs are assessed using an index approach that consolidates data from surveys. Vulnerability indices include social vulnerability, economic vulnerability, and physical vulnerability. Social vulnerability includes factors like gender, age, age group, disability group, and income level. Economic vulnerability includes business capital size, while physical vulnerability refers to the value of business buildings. In this study, environmental vulnerability is not considered due to the absence of protected area land use.

(4) Risk evaluation

The overall risk to SMAEs from landslides was determined by integrating the hazard, vulnerability, and capacity assessments into a unified risk index. The risk was spatially mapped, providing a clear visual representation of the most vulnerable areas. Disaster risk studies can be carried out using the equation (3) and the flow diagram of this research is presented in Figure 3.

$$Risk = Hazard \times \frac{Vulnerability}{Capacity} \quad (5)$$

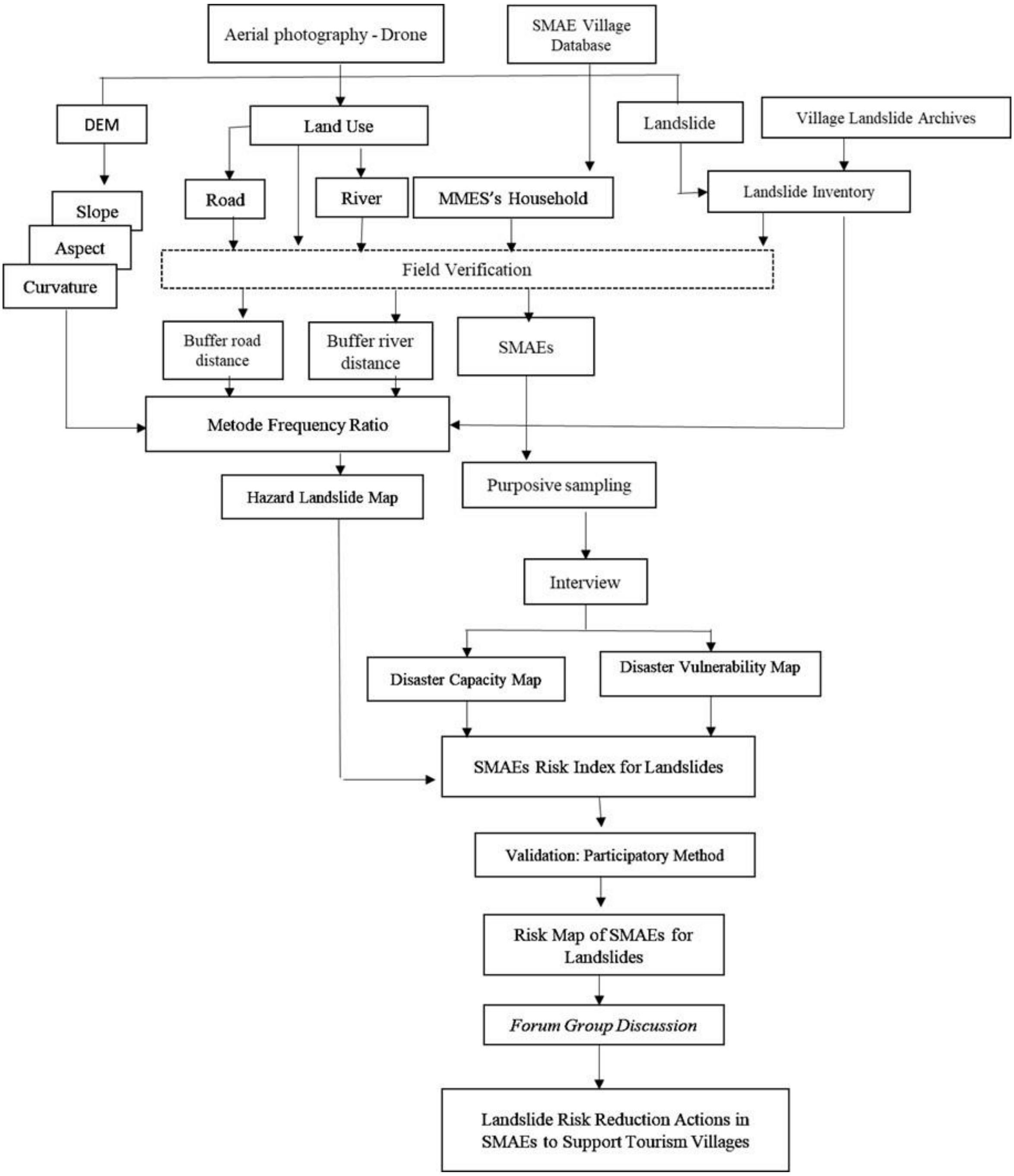

Figure 3. Method's flow chart

3. RESULTS AND DISCUSSION

3.1 Landslide inventory

The preliminary inventory in Selopamioro village identifies multiple landslide sites and scars caused by natural and anthropogenic factors, such as deforestation and poor agricultural practices (Fadilah et al., 2019). The inventory was compiled through field surveys and image analysis using remote sensing imagery from 2010 to 2020. Selopamioro Village has a slope gradient ranging from flat to moderate, with some hamlets having a gentle slope. Landslide points are dispersed throughout the village area, aligning with research by Damayanti et al. (2023) indicating Selopamioro Village has the highest level of landslide vulnerability in Imogiri Sub-district, after Wukirsari Village, with a vulnerability area of 364.4 hectares. Landslide inventory is presented on the map in Figure 4.

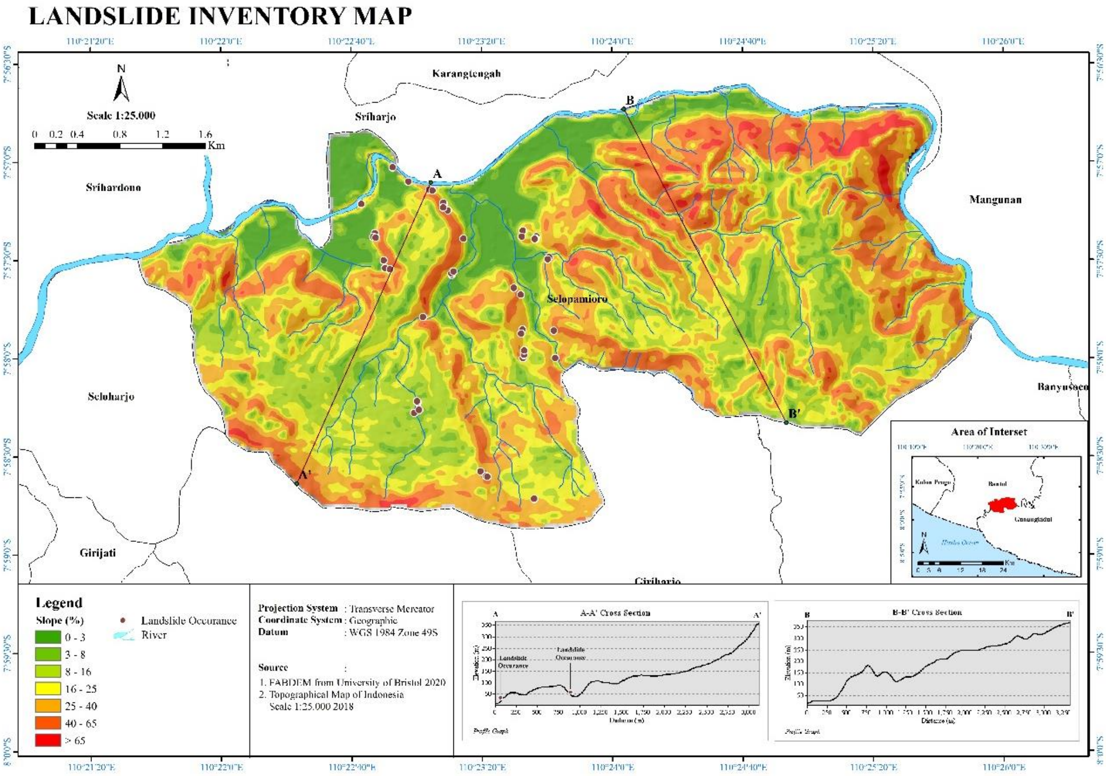

Figure 4. Landslide inventory map

3.2 Distribution SMAEs

SMAEs in this study is categorized into three sectors: Upstream Agroindustry, Downstream Agroindustry, and Primary Sector. Upstream industry produces agricultural tools and machinery and the production facility industry used in the agricultural cultivation process. The Downstream industry processes agricultural products into raw materials or goods that are ready to be consumed or is a post-harvest industry and agricultural product processing (Pratiwi et al., 2017). The SMAEs sector in Selopamioro Village is predominantly composed of Downstream Agroindustry in each hamlet. As shown in Figure 5, the hamlet with the most downstream SMAEs is Siluk I, followed by Pelemantung, Jetis, Lemahrubuh, and Nawungan I. Siluk I Hamlet is located in a relatively flat area, such as soil type, water drainage, and human activities, can also play a role in mitigating or exacerbating the risk in flat areas with no landslide points, as are Pelemantung, Lemahrubuh, and Nawungan I. In contrast, Jetis Hamlet, despite being located on a steep slope, has no recorded landslide points, according to the inventory data, which has allowed for the construction of many SMAEs in the area. Srunggo II Hamlet, located on a moderate slope, has a considerable number of landslide points, which has limited the number of SMAEs built there. Similarly, Kajor Wetan Hamlet is located in an area with a high level of landslide hazard, affecting the number of same in that location. Research by Nagara and Wibowo (2024) indicates that steeper land has greater potential for landslides, leading to higher difficulties and costs associated with land acquisition, including in the construction of SMAEs.

3.3 Vulnerability assessment

The study used a disaster vulnerability index for SMAEs in Selopamioro village, focusing on physical, social, and economic components. The analysis revealed that all SMAEs had low overall vulnerability to landslides, suggesting a low risk of landslide impacts on these enterprises (Table 3). Disaster vulnerability is linked to property damage and human casualties, and higher vulnerability can result in increased damage or prolonged recovery periods (Heryawan et al., 2016). The vulnerability indices analyzed were social vulnerability, economic vulnerability, and physical vulnerability. Social vulnerability, which includes factors like gender, age, disability group, and income level, emerged as the most significant contributor to overall SMAE vulnerability in Selopamioro. However, the study by Febriani (2020) found that economic vulnerability was higher in certain regions of Selopamioro Village, while social vulnerability was more moderate. This discrepancy may be due to the focus on SMAEs actors as the unit of analysis, rather than village administration.

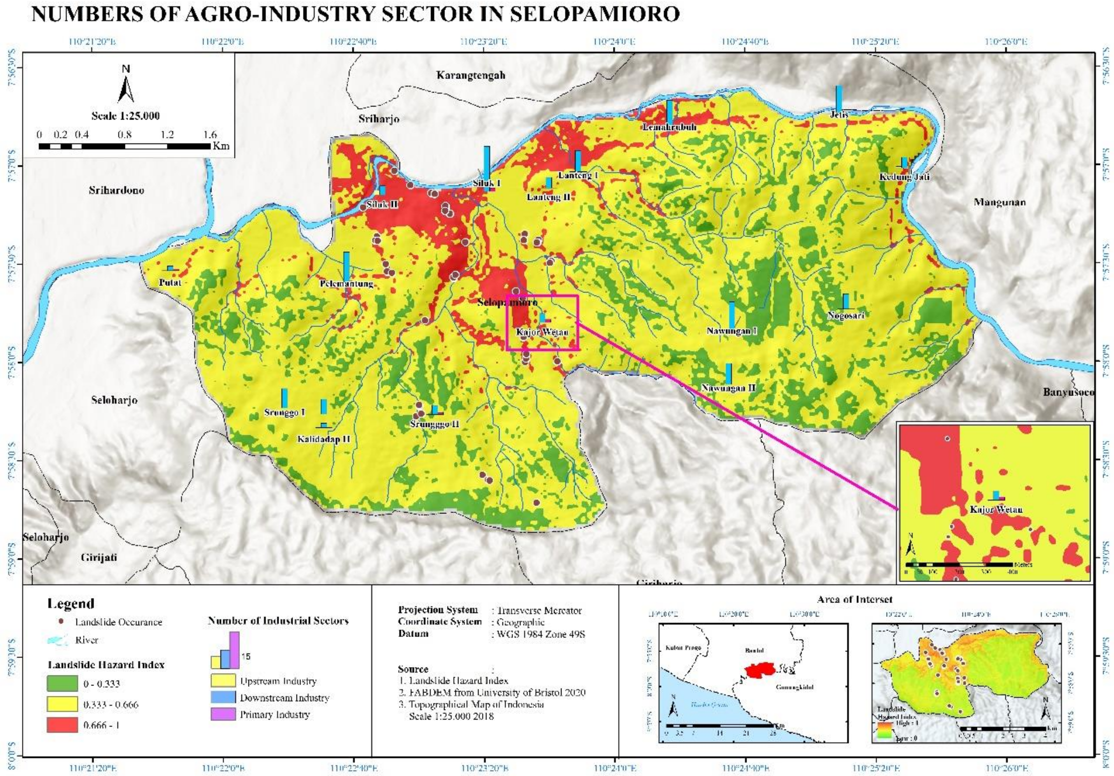

Figure 5. SMAEs distribution in Selopamioro

Table 3. Total vulnerability table of Selopamioro Village

No	Hamlet	Social vulnerability		Economy vulnerability		Physics vulnerability		Total vulnerability	
		Volume	Class	Volume	Class	Volume	Class	Volume	Class
1	Jetis	1.4	Low	0.6	Low	0.4	Low	0.81	Low
2	Kajor Kulon	1.5	Low	0.6	Low	0.4	Low	0.85	Low
3	Kajor Wetan	1.5	Low	0.6	Low	0.4	Low	0.85	Low
4	Kalidadap I	1.5	Low	0.6	Low	0.4	Low	0.85	Low
5	Kalidadap II	1.6	Low	0.6	Low	0.4	Low	0.89	Low
6	Kedung Jati	1.5	Low	0.6	Low	0.4	Low	0.85	Low
7	Lanteng I	1.4	Low	0.6	Low	0.4	Low	0.81	Low
8	Lanteng II	1.5	Low	0.6	Low	0.4	Low	0.85	Low
9	Lemahrubuh	1.4	Low	0.6	Low	0.4	Low	0.81	Low
10	Nawungan I	1.4	Low	0.6	Low	0.4	Low	0.81	Low
11	Nawungan II	1.4	Low	0.6	Low	0.4	Low	0.81	Low
12	Nogosari	1.5	Low	0.6	Low	0.4	Low	0.85	Low
13	Pelemantung	1.4	Low	0.6	Low	0.4	Low	0.81	Low
14	Putat	1.4	Low	0.6	Low	0.4	Low	0.81	Low
15	Siluk I	1.4	Low	0.6	Low	0.4	Low	0.81	Low
16	Siluk II	1.5	Low	0.6	Low	0.4	Low	0.85	Low
17	Srunggo I	1.5	Low	0.6	Low	0.4	Low	0.85	Low
18	Srungggo II	1.4	Low	0.6	Low	0.4	Low	0.81	Low
Class index		Low	1-1.6						
		Medium	1.7-2.3						
		High	2.4-3.0						

3.4 Capacity index analysis

The Capacity Index Analysis was used to evaluate the preparedness of 18 hamlets in Selopamioro Village for mitigating landslide risk. The results showed a "Medium" capacity level, indicating a lack of resilience to disasters (Table 4). The index ranged from 0.4 to 0.8, indicating significant gaps in preparedness measures. One example was the absence of an early warning system for disasters, indicating that while some measures are in place, there are still significant gaps that need to be addressed.

Selopamioro Village has a "Medium" capacity level for landslide preparedness, but its priority index for all hamlets is low (Figure 6). Factors contributing to this include insufficient policies and regulations related to landslide prevention and mitigation, inadequate coordination and resource allocation in the disaster response framework, and the absence of comprehensive landslide risk evaluations for specific regions. Currently, comprehensive landslide risk evaluations for particular regions within the village are missing under Integrated Risk Assessment and Planning, regarding the main barriers to conducting comprehensive landslide evaluations, including insufficient data, lack of expertise, and limited resources. These evaluations are not fully incorporated into the village's development plans. In the Information System Development, Training, and Logistics domain, early warning systems, communication protocols, and public awareness campaigns regarding landslides are inadequate. Training programs for homeowners and emergency workers on landslide preparedness and response are also limited. The absence of equipment or vital resources for disaster mitigation can hinder response operations. Specific methods for mitigating landslide hazards in highly sensitive village regions are lacking. Current mitigation strategies, including slope stabilization and drainage improvement, are inadequate and require further development. Purnamasari et al. (2024) with their research in Central Java added that the material layer is very important for sustainable land management strategies aimed at controlling landslides. In addition, the potential depth of the sliding plane is managed through effective environmental management practices, including proper disposal of household waste and minimizing steep slope cutting.

Table 4. Total capacity table of Selopamioro Village

No	Hamlet	Priority index					Hamlet capacity index	Capacity level
		Strengthening policies and institutions	Risk assessment and integrated planning	Information system development, training and logistic	Thematic handling of disaster-prone areas	Increasing the effectiveness of disaster prevention and mitigation		
1	Jetis	1.6	0.6	0.2	0.5	0.5	0.74	Medium
2	Kajor Kulon	1.4	0.6	0.2	0.5	0.2	0.65	Medium
3	Kajor Wetan	1.7	0.6	0.2	0.5	0.5	0.76	Medium
4	Kalidadap I	1.5	0.6	0.2	0.5	0.4	0.64	Medium
5	Kalidadap II	1.5	0.3	0.2	0.25	0.25	0.53	Medium
6	Kedung Jati	1.7	0.5	0.2	0.5	0.5	0.74	Medium
7	Lanteng I	1.4	0.6	0.2	0.5	0.3	0.67	Medium
8	Lanteng II	1.6	0.6	0.2	0.5	0.5	0.74	Medium
9	Lemahrubuh	1.5	0.6	0.2	0.5	0.4	0.69	Medium
10	Nawungan I	1.7	0.6	0.2	0.5	0.5	0.76	Medium
11	Nawungan II	1.4	0.6	0.1	0.3	0.5	0.6	Medium
12	Nogosari	1.2	0.6	0.1	0.2	0.5	0.53	Medium
13	Pelemantung	1.4	0.3	0.1	0.5	0.4	0.6	Medium
14	Putat	1.7	0.3	0.2	0.5	0.5	0.7	Medium
15	Siluk I	1.5	0.5	0.2	0.2	0.5	0.59	Medium
16	Siluk II	1.7	0.6	0.2	0.25	0.4	0.66	Medium
17	Srunggo I	1.4	0.6	0.2	0.5	0.3	0.67	Medium
18	Srungggo II	1.7	0.4	0.2	0.5	0.2	0.67	Medium

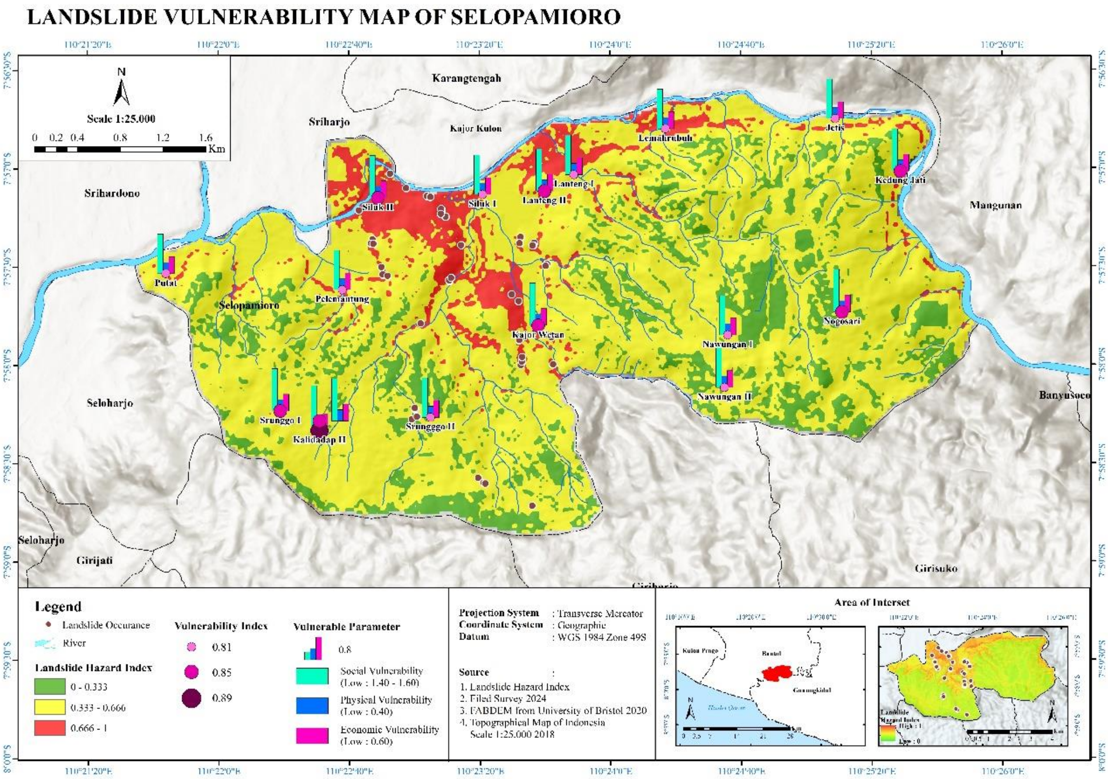

Figure 6. Landslide Vulnerability in Selopamioro

3.5 Hazard analysis

A key step in landslide susceptibility modeling is identifying the connection between previous landslides and their contributing factors. Based on calculations in Table 5, the factors of elevation, geological formation, profile curvature, and plane curvature had the highest values compared to other landslide determining factors. Meanwhile, land use, SPI, distance to roads, slope, TWI, distance to faults, aspect, and distance to rivers had the lowest values.

Table 5. Frequency ratio (FR), Relative frequency (RF) for each class, and the prediction rate (PR) for each conditioning factor

Factor	Class code	Class	Class pixels	Percent class pixels	Hotspot pixels	Percent hotspot pixels	FR	RF	PR
Land use	1	Water body	340	1.5	0	0.0	0.00	0.00	1.6
	2	Building/structure	2	0.0	0	0,0	0.00	0.00	
	3	Grassland	13	0.1	0	0.0	0.00	0.00	
	4	Plantation/garden	1,148	5.0	3	0.1	0.02	0.28	
	5	Settlement and activity Areas	3,664	16.0	15	0.6	0.03	0.44	
	6	Paddy field	2,290	10.0	1	0.0	0.00	0.05	
	7	Rainfed paddy field	2,256	9.8	1	0.0	0.00	0.05	
	8	Shrubland	1,571	6.9	2	0.1	0.01	0.14	
	9	Cultivated land	11,637	50.8	5	0.2	0.00	0.05	
		Total	22,921		27		0.08	1.00	
Elevation (m)	1	6.5-100	7,962	34.7	22	0.8	0.02	0.79	2.8
	2	100-200	7,219	31.5	2	0.1	0.00	0.08	
	3	200-300	6,273	27.4	3	0.1	0.00	0.14	
	4	300-377.75	1,467	6.4	0	0.0	0.00	0.00	
		Total	22,921		27		0.03	1.00	

Table 5. Frequency ratio (FR), Relative frequency (RF) for each class, and the prediction rate (PR) for each conditioning factor (cont.)

Factor	Class code	Class	Class pixels	Percent class pixels	Hotspot pixels	Percent hotspot pixels	FR	RF	PR
Slope (%)	1	0-2	1,640	7.2	0	0.0	0.00	0.00	1.3
	2	2-4	685	3.0	0	0.0	0.00	0.00	
	3	4-8	1,657	7.2	1	0.0	0.01	0.13	
	4	8-16	4,771	20.8	4	0.1	0.01	0.18	
	5	16-35	8,692	37.9	15	0.6	0.01	0.36	
	6	35-55	4,418	19.3	7	0.3	0.01	0.33	
	7	>55	1,058	4.6	0	0.0	0.00	0.00	
		Total	22,921		27		0.04	1.00	
Aspect	1	North	5,916	25.8	6	0.2	0.01	0.10	1.0
	2	Northeast	4,241	18.5	7	0.3	0.01	0.17	
	3	East	2,770	12.1	3	0.1	0.01	0.11	
	4	Southeast	1,087	4.7	3	0.1	0.02	0.28	
	5	South	769	3.4	0	0.0	0.00	0.00	
	6	Southwest	1,486	6.5	2	0.1	0.01	0.14	
	7	West	2,731	11.9	3	0.1	0.01	0.11	
	8	Northwest	3,921	17.1	3	0.1	0.01	0.08	
		Total	22,921		27		0.08	1.00	
Plan curvature	1	<-2.7	16	0.1	0	0.0	0.00	0.00	1.8
	2	-2.7 to -0.3	4,213	18.4	8	0.3	0.02	0.51	
	3	-0.3 to 0.8	17,463	76.2	18	0.7	0.01	0.27	
	4	0.8 to 2.5	1,211	5.3	1	0.0	0.01	0.22	
	5	>2.5	18	0.1	0	0.0	0.00	0.00	
		Total	22,921		27		0.03	1.00	
Profile curvature	1	<-2.7	15	0.1	0	0.0	0.00	0.00	2.4
	2	-2.7 to -0.3	4,993	21.8	3	0.1	0.01	0.11	
	3	-0.3 to 0.8	16,300	71.1	18	0.7	0.01	0.20	
	4	0.8 to 2.5	1,563	6.8	6	0.2	0.03	0.69	
	5	>2.5	50	0.2	0	0.0	0.00	0.00	
		Total	22,921		27		0.05	1.00	
Stream power index (SPI)	1	<-8.6	3,900	17.0	1	0.0	0.00	0.05	1.5
	2	-8.6 to -3.2	4,053	17.7	7	0.3	0.01	0.32	
	3	-3.2 to 2.2	13,276	57.9	15	0.6	0.01	0.21	
	4	2.2 to 7.6	1,692	7.4	4	0.1	0.02	0.43	
		Total	22,921		27		0.05	1.00	
Topographic wetness index (TWI)	1	0.5-4.5	1,525	6.7	3	0.1	0.02	0.28	1.2
	2	4.5-6	9,889	43.1	11	0.4	0.01	0.16	
	3	6-8	7,158	31.2	9	0.3	0.01	0.18	
	4	8-11	3,133	13.7	1	0.0	0.00	0.04	
	5	>11	1,216	5.3	3	0.1	0.02	0.35	
		Total	22,921		27		0.06	1.00	
Geology	1	Alluvium	2,288	10.0	10	0.4	0.04	0.76	2.4
	2	Undifferentiated Volcanic Rocks	1,050	4.6	0	0.0	0.00	0.00	
	3	Formasi Ngalanggran	15,475	67.5	16	0.6	0.01	0.18	
	4	Sambipitu Formation	1,150	5.0	0	0.0	0.00	0.00	
	5	Wonosari Formation	2,958	12.9	1	0.0	0.00	0.06	
		Total	22,921		27		0.05	1.00	

Table 5. Frequency ratio (FR), Relative frequency (RF) for each class, and the prediction rate (PR) for each conditioning factor (cont.)

Factor	Class code	Class	Class pixels	Percent class pixels	Hotspot pixels	Percent hotspot pixels	FR	RF	PR
Distance to fault (m)	1	0-500	5,467	23.9	7	0.3	0.01	0.25	1.1
	2	500-1,000	6,886	30.0	8	0.3	0.01	0.22	
	3	1,000-1,500	7,511	32.8	7	0.3	0.01	0.18	
	4	1,500-2,000	2,727	11.9	5	0.2	0.02	0.35	
	5	>2,000	330	1.4	0	0.0	0.00	0.00	
		Total	22,921		27		0.04	1.00	
Distance to road (m)	1	<25	2,604	11.4	8	0.3	0.03	0.46	1.5
	2	25-50	5,464	23.8	12	0.4	0.02	0.33	
	3	50-100	5,307	23.2	4	0.1	0.01	0.11	
	4	100-200	5,123	22.4	1	0.0	0.00	0.03	
	5	>200	4,423	19.3	2	0.1	0.00	0.07	
		Total	22,921		27		0.06	1.00	
Distance to river (m)	1	<10	1,849	8.1	3	0.1	0.01	0.31	1.0
	3	25-50	4,526	19.7	6	0.2	0.01	0.25	
	4	50-100	5,523	24.1	7	0.3	0.01	0.24	
	5	>100	11,023	48.1	11	0.4	0.01	0.19	
		Total	22,921		27		0.04	1.00	

Based on the results of the analysis using the frequency ratio, the landslide hazard index value in the study area ranges from 0-1 (Figure 7). The closer the value is to 1, the higher the level of danger. Landslides in the study area strongly influenced by topographic conditions where landslides occur in areas with an altitude of 0-100 m with a slope of 16-55%. Although the soil moisture level is at 4.5-6, the dominant surface material of the landslide is in the Nglanggaran geological formation, which is old volcanic material that has weathered so that landslides are easy to occur. This is not much different from the research of Radjah et al. (2020) in Karangkobar. Their research shows that the highest FR value is found in the distance of the area from the highway in the range of 0-25 m, the distance from the river in the range of 100-125 m, flat curvature and use of garden land.

An accuracy test was conducted to determine the level of accuracy between landslide maps and landslide distribution (Figure 8). From the AUC calculation, the success rate value obtained from the training data was a value of 0.887 (Figure 9). While the prediction rate value from the testing data was 0.849. From both values, it can be concluded that the level of accuracy is good.

Hazard is one of the variables used to calculate the risk level. The determination of the index class is based on the Landslide Hazard Map obtained from the official website of the Center for Volcanology and Geological Disaster Mitigation (PVMBG). The landslide map classifies the hazard index class into three classes, namely low, medium, and high. Tian et al. (2017) identified three factors contributing to landslides: (1) terrain data (elevation, slope angle, slope aspect, curvature, slope position, distance to drainage); (2) geological data (lithology); and (3) seismic data (seismic intensity, peak ground acceleration, and distance to the causative source). Fadilah et al. (2019) asserted that landslides mostly result from gravitational pressures on steep slopes, with contributing factors including excessive rainfall, improper land use, and geological formations.

The level of landslide hazard is classified into three classes (Figure 7). Selopamioro Village has 59.2% high hazard zones, 21.8% medium hazard zones and 19% low hazard zones. The high landslide hazard in Selopamioro Village is affected by its steep slope. The higher the hazard and vulnerability level, the higher the area's risk level. In line with research by Budha et al. (2020), which states that the class of factors that have a greater influence on higher landslide hazards include land with an altitude range of 1,000 m to 1,500 m and slopes steeper than 30°.

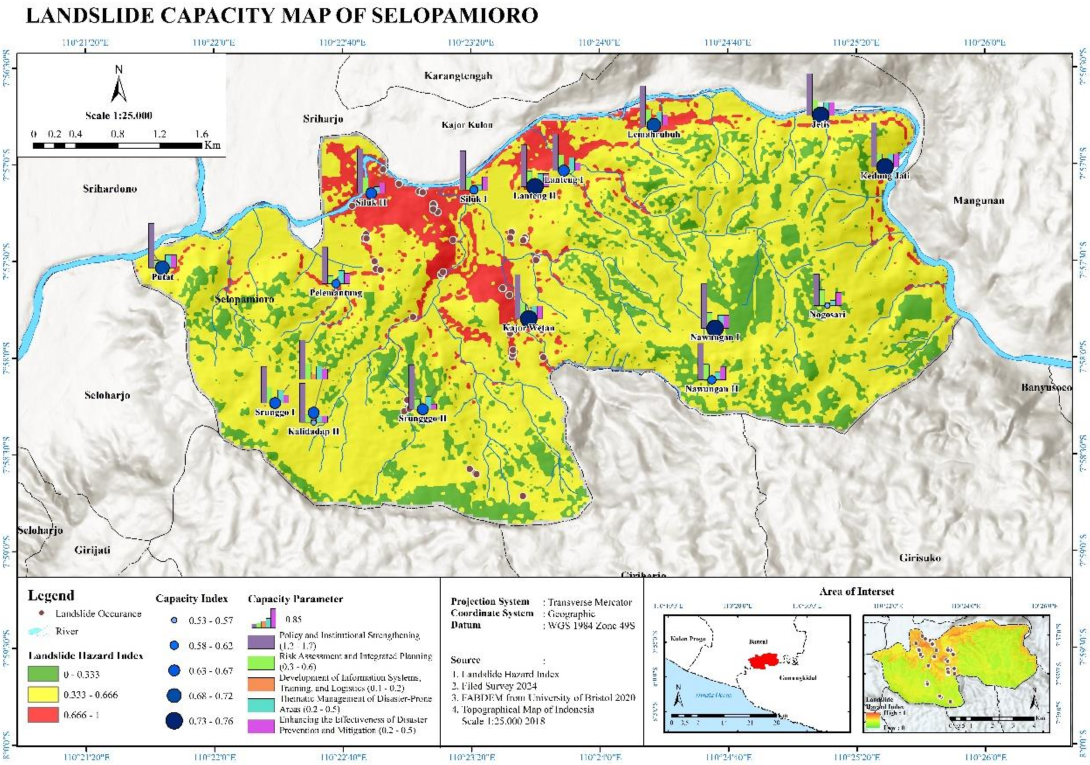

Figure 7. Landslide capacity map of Selopamioro

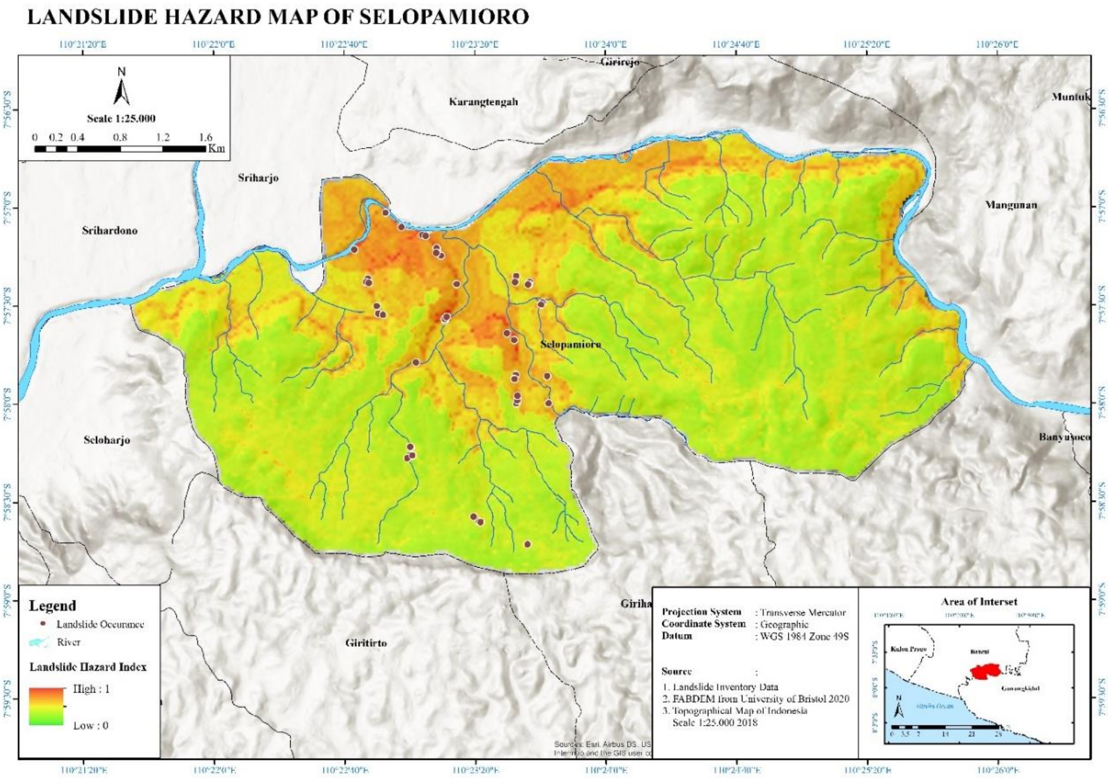

Figure 8. Landslide hazard maps with frequency ratio

Based on the analysis of the map in Figure 7, the hazard risk in Selopamioro Village ranges from moderate to high. The dominant risk level is high, which covers Pelemantung Hamlet, Kalidadap I, Kalidadap II, Kajor Kulon, Kajor Wetan, and Jetis. In areas with a high level of danger, based on the Landslide Inventory, there are landslide points in each area. Based on the distribution of SMAEs, areas with a high level of danger are areas with a low number of SMAEs. Landslides are one of the most destructive hazard processes causing loss of life and damage to the built environment (Luo et al., 2023). Therefore, the establishment of business buildings in areas with high landslide hazard levels is very risky for the sustainability of SMAEs. Establishing business infrastructure in high-risk zones poses significant challenges to the sustainability of SMAEs. Policymakers must prioritize comprehensive land-use planning, integrating slope stabilization projects and drainage improvements to enhance safety and minimize risk (Cheung, 2021).

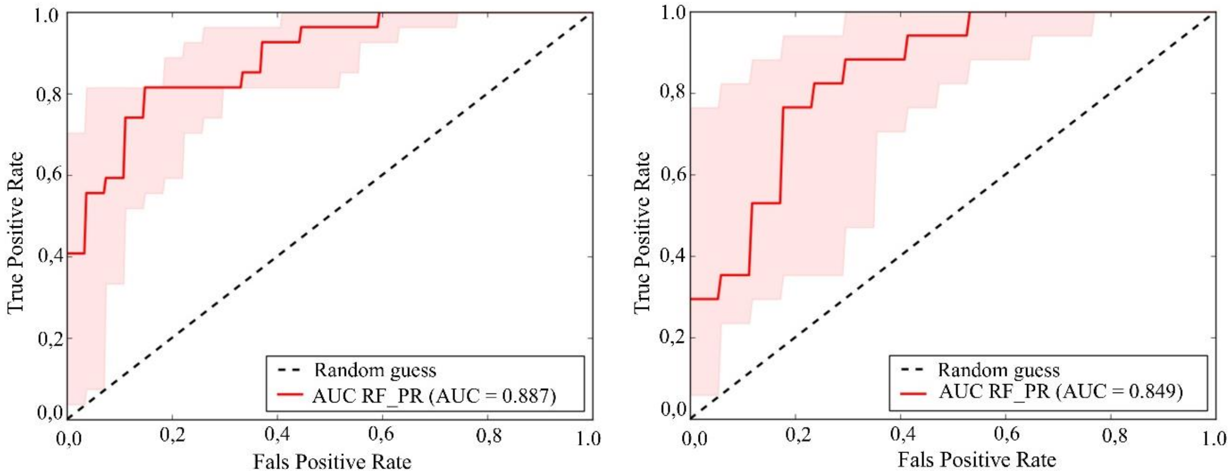

Figure 9. (a) Succes rate training data sample, (b) Prediction rate testing data sample

The study emphasizes the significance of community-based disaster risk management (CBDRM) in addressing landslide hazards. It suggests that local communities should be involved in participatory planning processes to develop effective mitigation strategies. The village government and villagers have been implementing mitigation measures such as strengthening slopes and forming the Disaster Risk Reduction Forum (FPRB). The study also highlights the role of climate change in exacerbating landslide hazards (Holcombe et al., 2013). Rainfall induces changes in surface and groundwater dynamics that reduce the slope stability conditions and cause landslides (Guzzetti et al., 2022). The study suggests that integrating modern technologies like remote sensing, GIS, and AI for hazard prediction and management is crucial. CNN-based landslide susceptibility mapping has demonstrated high accuracy in predicting vulnerable areas (Yi et al., 2020).

Future research should focus on the socio-economic impacts of landslides on SMAE and explore long-term strategies to increase resilience. Steps such as terracing, improving land use practices, and vegetation restoration can significantly reduce risk (Mujiyo et al., 2024). By implementing these recommendations, policymakers and stakeholders can support sustainable development in disaster-prone rural areas. For example, in Sambak Village, Magelang, research conducted by Wibawanti et al. (2023) has implemented mitigation activities in controlling landslides vegetatively. This program is called “Climate Village Program (ProKlim)” involves planting vegetation in landslide-prone areas. This activity can serve as a reference for Selopamioro Village.

4. CONCLUSION

This study assessed the risk of landslides to small and medium agro-industry enterprises (SMAEs) in Selopamioro village, Indonesia. The findings indicate that the current level of vulnerability of SMAEs to landslides is relatively low across the village, suggesting that existing landslides do not significantly impact the sustainability of these businesses. However, the capacity for disaster response in Selopamioro village is only moderate, highlighting a potential gap in preparedness for future landslides.

These findings offer valuable insights for both SMAEs and local authorities. While the current vulnerability of SMAEs appears low, proactive measures to mitigate future landslide risks are still recommended. SMAEs can explore options such as improving infrastructure resilience, implementing early warning systems, and developing evacuation plans. Local authorities should focus on strengthening disaster preparedness efforts in Selopamioro Village. This may involve capacity building initiatives for local communities, investing in critical infrastructure, and developing comprehensive landslide risk management plans. The hazard risk in Selopamioro Village ranges from moderate to high. The dominant risk level is high, which covers Pelemantung Hamlet, Kalidadap I, Kalidadap II, Kajor Kulon, Kajor Wetan, and Jetis.

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AUTHORS CONTRIBUTION

Experimental run and Data Collection Ngadisih, Ismi N. Puspitaningrum; Methodology, Validation, Supervision and Writing Original Draft Preparation Ngadisih, Bambang Purwantana, Devi Yuni Susanti, Guruh Samodra, Peter Strauss; Formal Analysis Ngadisih, Guruh Samodra, Ismi N. Puspitaningrum; Data Curation, Visualization, Writing - Review and Editing, Ngadisih, Guruh Samodra; other authors are SMAEs supervisors.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

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Physico-Mechanical Properties of Two Native Tree Species in the Philippines and Their Potential as Alternatives to Exotic Industrial Tree Plantation Species

Oliver S. Marasigan[1*], Shereyl A. Daguinod[1], and Jayric F. Villareal[2]

[1]*The Forest Products Research and Development Institute (FPRDI), Department of Science and Technology (DOST), Laguna, Philippines*
[2]*Mindanao State University-Maguindanao, Bangsamoro Autonomous Region in Muslim Mindanao (BARMM), Philippines*

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*** Corresponding author:**
E-mail: oliver.marasigan@fprdi.dost.gov.ph

ABSTRACT

The potential of Bagalunga (*Melia azedarach* L.) and Kalumpit (*Terminalia microcarpa* Decne) as alternatives to Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Gmelina (*Gmelina arborea* Roxb. ex Sm.), and Mahogany (*Swietenia macrophylla* King) were evaluated by assessing their physico-mechanical properties in accordance with ASTM D143-52: 2019 standards. Results showed that Mahogany had the lowest green moisture content (MC) at 90.60% and the highest basic relative density (RD_b) at 0.52, while Falcata exhibited the highest green MC (193.98%) and the lowest RD_b (0.29). Bagalunga displayed the highest shrinkage values [tangential shrinkage (TS): 6.63%, radial shrinkage (RS): 4.48%, volumetric shrinkage (VS): 10.81%], whereas Mahogany showed the lowest shrinkage (TS: 3.59%, RS: 3.11%, VS: 6.81%) but the highest longitudinal shrinkage (LS) (0.42%). Mahogany recorded the highest modulus of rupture (MOR) (63.65 MPa and 66.96 MPa at green and 12% MC, respectively), and excelled in compression [parallel (27.28 MPa and 35.62 MPa), perpendicular (7.14 MPa and 7.89 MPa)], hardness [side (4.67 kN and 4.20 kN), end (5.48 kN and 5.49 kN)], and shear strength (8.37 MPa and 10.37 MPa). Kalumpit exhibited the highest toughness in both green and 12% MC conditions (48.51 J/Spec and 42.62 J/Spec), along with the highest SPL (33.42 MPa) and MOE (8.58 GPa) at 12% MC. Gmelina had the highest MOE (7.12 GPa), while Mahogany showed the highest SPL (25.50 MPa) in the green condition. Height levels significantly affected TS and VS, while mechanical properties showed minimal variation. Farmers may consider Bagalunga and Kalumpit as alternative species. The application of silvicultural practices is essential for improving growth, optimizing rotation cycles, and ensuring sustainability for native tree species.

1. INTRODUCTION

The nation's wood industry depends on the best species and management techniques for productive forest plantations that offer farmers the highest possible returns. Forest plantations should aim to optimize volume returns in the shortest rotation period, provided they comply with Executive Order No. 23, which governs logging limitations in natural forests. Due to their ability to grow quickly and reach merchantable sizes in a short time, industrial tree plantation species are favored by farmers (Nath et al., 2016). These species are not endangered in the wild, allowing for harvesting with proper permits and compliance with minor requirements (Marquez et al., 2021). These species are primarily composed of exotic tree species, namely Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Mahogany (*Swietenia macrophylla* King), and Gmelina (*Gmelina arborea*

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Roxb. ex Sm.). In 2022, these three species accounted for the highest recorded annual log production volumes, totaling 613,821.88 m^3, 65,870.62 m^3, and 26,599.08 m^3, respectively (DENR-FMB, 2022).

Exotic tree plantations are often criticized for their negative impacts, such as introducing new pests and diseases, affecting native species, and altering both the micro and macro ecosystems of the area (Aguilos et al., 2020). Once established, some exotic species can displace or replace native plant species, disrupt nutrient cycles and biodiversity, and alter plant succession patterns, hastening soil nutrient depletion and affecting long-term site productivity (Marquez et al., 2021).

Native species have historically been outpaced by the widespread introduction of exotic species into plantations since they are considered less productive (Marquez et al., 2021). Nonetheless, interest in fast-growing native species that can sustain biodiversity and replicate natural forest conditions has recently increased due to ecological concerns (Ratsirarson et al., 2002). Furthermore, it has been discovered that native tree plantings are more successful in preserving soil productivity because they promote organic processes such as soil carbon sequestration (Kerdraon et al., 2019).

This study explored the potential of the two native tree species as alternatives to industrial tree plantation species (ITPS) by comparing their physical and mechanical properties. These two species are Bagalunga (*Melia azedarach* L.) and Kalumpit (*Terminalia microcarpa* Decne). Bagalunga was one of the identified fast-growing species of native tree species in the Philippines that can compete with the ITPS (Aguilos et al., 2020). It is a deciduous tree that typically reaches heights of 20-25 m, with a diameter at breast height (dbh) ranging from 40 to 70 cm (Venson et al., 2008).

Kalumpit, a native fruit-bearing tree, is part of the National Greening Program (NGP) of the Philippines. Engay-Gutierez et al. (2023) reported that in 2012, Kalumpit was included in the 862,181 native species produced by the Department of Environment and Natural Resources (DENR) as part of the 3.7 million indigenous planting materials. They also noted that Kalumpit was a priority species for State Universities and Colleges (SUCs) in the Philippines, such as Mariano Marcos State University (MMSU) and Southern Luzon State University (SLSU), and is featured in the NGP demonstration farm.

In the ex-situ performance evaluation of different native tree species in Bohol, Philippines, Kalumpit was one of the top-performing species among the 25 evaluated species, demonstrating exceptional adaptability (Bullecer and Socorin, 2013). Senile and unproductive Kalumpit trees can be used as alternative materials to ITPS (Alipon and Bondad, 2008). It is a semi-deciduous tree that can grow to 25 m in height and has a diameter of 100 cm (Tomas-Carig, 2020).

According to Aguilos et al. (2020), the diameter and height growth rates per year of Bagalunga and Kamlupit were higher compared to the exotic species like *S. macrophylla*, *Schizolobium parahyba*, and *Acacia mangium*. Their results showed that Bagalunga and Kalumpit could potentially grow and survive at a rate close to that of exotic species.

Research on Bagalunga wood has been conducted in several countries. Venson et al. (2008) reported a basic relative density of 0.55 in Mexico, with tangential and radial shrinkage rates of 7.90% and 4.10%, respectively. In China, Vietnam, Malaysia, and Brazil, the basic relative density ranges from 0.34 to 0.47 (Botero, 1956; Pun, 1969; Do Van Ban, 1997). Venson et al. (2008) found its strength similar to *S. macrophylla*, though Alipon and Bondad (2008) reported low strength. Kalumpit has a basic relative density of 0.53 (Reyes et al., 1992) and medium strength (Alipon and Bondad, 2008), suitable for construction, furniture, cabinetry, veneers, and plywood.

The lack of research on the properties of native tree species in comparison with those of exotic species limits the potential of native tree species to promote higher yields and utilization. Hence, this study aims to evaluate the viability of Bagalunga and Kalumpit as sustainable alternatives to exotic ITPS based on their physical and mechanical properties.

2. METHODOLOGY

2.1 Plant materials and wood samples collection

Three trees from each of the following species were collected: Bagalunga (*Melia azedarach* L.), Kalumpit (*Terminalia microcarpa* Dence), Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Gmelina (*Gmelina arborea* Roxb. ex Sm.), and Mahogany (*Swietenia macrophylla* King). Descriptions for each species were shown in Table 1. The age of Falcata, Gmelina, and Mahogany represents the recommended age at which farmers utilize these species. The trunks were sectioned into three parts: butt (2.4 m from the base), middle (4.8 m), and top (7.2 m). A total of 45 discs each 152 mm thick, and 45 billets, each 2.4 m long, were cut. The discs were used to assess physical properties, while the billets were used for mechanical properties testing. Figure 1 illustrates the sampling scheme of the study, which was adopted from Alipon et al. (2019).

Table 1. Characteristics of the collection sites and the different tree species

Characteristics	Bagalunga (*Melia azedarach*)	Kalumpit (*Terminalia microcarpa*)	Gmelina (*Gmelina arborea*)	Falcata (*Falcataria falcata*)	Mahogany (*Swietenia macrophylla*)
Region	IV-A	IV-A	XIII	XIII	III
Province	Quezon province	Quezon province	Agusan del Sur	Surigao del Sur	Zambales
Municipality	Unisan	Guinayangan	Baguyan City	Bislig City	Botolan
Barangay	Malvar	Danlangan-Batis	Wawa	Maharlika	San Juan
Number of trees collected	3	3	3	3	3
Elevation (m.a.s.l.)	10.0	71.7	68.5	100.5	26.7
Climatic type	IV	IV	II	II	I
Average tree diameter (cm)	26.23	22.83	24.3	28	20
Average merchantable height (m)	7.32	8.10	9.58	10.33	12.19
Estimated tree age (year)	15-25	15-20	7	7	15

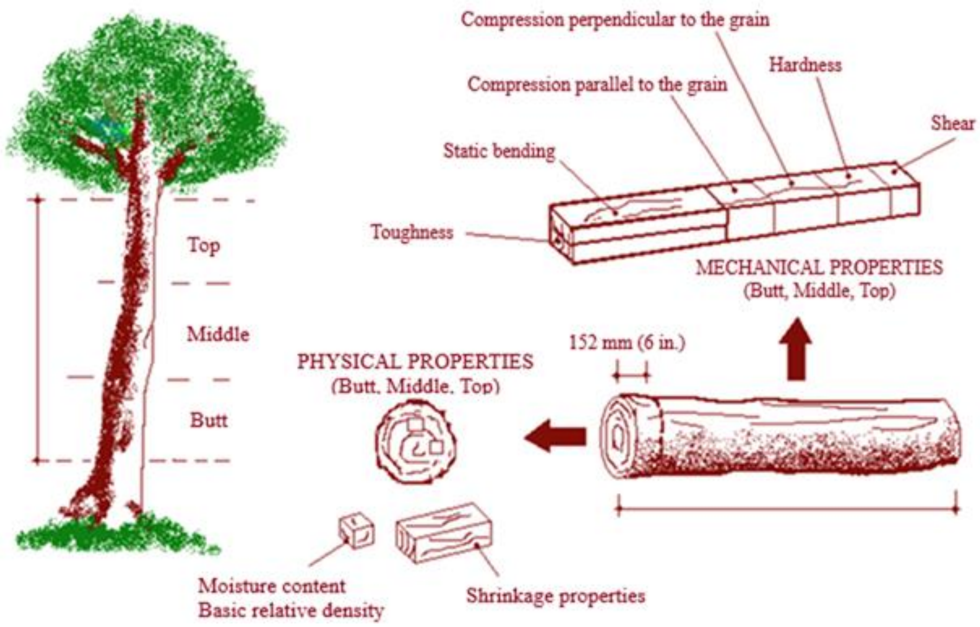

Figure 1. Sampling scheme used in the study (Alipon et al., 2019)

2.2 Determination of physical properties

Physical properties were evaluated using ASTM D143-52: Standard Test Methods for Small Clear Specimens of Timber (ASTM, 2019). A 25 mm × 25 mm × 25 mm sample was cut from the disc to analyze green moisture content (MC) and basic relative density (RD_b). Initially, the sample's weight as recorded, followed by volume measurement using the water displacement method. The samples were then oven-dried at 103±2ºC until they reached a constant weight, after which the oven-dry weight was measured. The green MC was calculated as the percentage loss in weight relative to the oven-dry weight. RD_b was determined by dividing the sample's weight by its volume. In total, 270 samples (54 per species) were tested to assess green MC and RD_b. These were calculated using the following equations:

$$MC\ (\%) = \left(\frac{W_i - W_o}{W_o}\right) \times 100 \quad (1)$$

$$RD_b = \frac{W_o}{V_g} \quad (2)$$

Where; MC: green moisture content, RD_b: basic relative density, W_i: initial weight (g), W_o: oven-dry weight (g), V_g: volume from displaced water (g).

Shrinkage values from green to oven-dry conditions were measured using blocks with dimensions of 25 mm (T) × 25 mm (R) × 102 mm (L). The tangential (T), radial (R), and longitudinal (L) dimensions of each sample were marked and measured with a dial gauge that has a precision of 0.0254 mm. A total of 270 samples, with 54 samples per species, were used to determine the shrinkage properties. The shrinkage properties (i.e., directional, and volumetric shrinkage) were calculated using the following equation:

$$S_a(\%) = \frac{D_i - D_o}{D_i} \times 100 \quad (3)$$

Where; S_a: shrinkage from green to oven-dry conditions, D_i: initial dimension (mm), and D_o: oven-dry dimension (mm).

2.3 Determination of mechanical properties

Mechanical properties were assessed according to ASTM D143-52 (ASTM, 2019). For each species, two sets (18 samples per set) of samples were prepared: green condition and 12% MC. These samples were tested for various properties including static bending [modulus of rupture (MOR), modulus of elasticity (MOE), stress at the proportional limit (SPL)], compression both perpendicular and parallel to the grain, shear strength, hardness (side and end), and toughness. Testing was carried out using the Shimadzu Universal Testing Machine UH-300 kNx series, with loading rates set at 1.3 mm/min for static bending, 0.30 mm/min for compression, 0.6 mm/min for shear, and 6.0 mm/min for hardness.

2.4 Statistical analysis

Statistical analysis was conducted using R Studio version 4.2.1 (R Core Team, 2022). Prior to performing the Analysis of Variance (ANOVA), the Kolmogorov-Smirnov normality test indicated a non-significant result (p=>0.05), suggesting that the data followed a normal distribution. ANOVA was then applied to assess whether there were significant differences in means among species, height levels, and their interactions. To identify which means differed significantly, Tukey's Honestly Significant Difference (HSD) test was employed.

3. RESULTS AND DISCUSSION

3.1 Physical properties

3.1.1 Moisture content and basic relative density

The descriptive statistics (mean, standard deviation, and analysis of variance) for the physical properties of different species at various height levels were presented in Table 2. The ANOVA results indicated statistically significant differences in green moisture content (MC) (p=0.0001) and basic relative density (RD_b) (p=0.0001). A significant interaction between species and height levels was observed in RD_b (p=0.0001), suggesting that this interaction contributed to the variability in this property.

For green MC, Falcata had the highest value at 193.98%, significantly higher than that of the other species, followed by Kalumpit (152.30%), Bagalunga (150.74%), and Gmelina (146.64%). Mahogany had the lowest significant green MC with 90.60%. In terms of RD_b, Mahogany had the highest value at 0.52, significantly higher than that of the other species. Gmelina was the second highest RD_b with 0.44, comparable to Bagalunga (0.43) and Kalumpit (0.42). Falcata, on the other hand, had a significantly lower RD_b of 0.29 compared to the other species.

These results suggested that species with higher green MC, such as Falcata, may require longer drying times. In contrast, Mahogany, having a lower green MC, could dry faster compared to other species. Based on their basic RD_b, Falcata was classified as low-density, while Gmelina, Kalumpit, and Bagalunga were classified as medium density. Mahogany, on the other hand, was classified as moderately high-density (Alipon and Bondad, 2008). These findings suggested that Kalumpit and Bagalunga could potentially be used as alternatives to Gmelina based on their RD_b.

Despite the older age of the Bagalunga compared to Mahogany, it exhibited higher MC and lower RD_b, but it was comparable to that of younger age Gmelina and Kalumpit (Tables 1 and 2). The variation in green MC and RD_b observed among the species can be attributed to differences in their anatomical and chemical properties. Mahogany, for instance, may have thicker cell walls, fewer vessels, and narrower vessel diameters, contributing to its lower MC and higher RD_b (Shmulsky and Jones, 2019).

Table 2. Physical properties of the different species at different height levels

Species	Basic relative density	Green moisture content (%)	Shrinkage properties (%)			
			Tangential	Radial	Longitudinal	Volumetric
Bagalunga	0.43b (±0.05)	150.74b (±20.85)	6.63a (±1.38)	4.48a (±0.97)	0.28b (±0.23)	10.81a (±1.66)
Falcata	0.29c (±0.06)	193.98a (±49.63)	4.41c (±0.81)	2.96d (±0.74)	0.27b (±0.22)	7.23d (±1.09)
Gmelina	0.44b (±0.04)	146.64b (±24.54)	5.16b (±0.96)	3.30c (±0.87)	0.28b (±0.16)	8.3c (±0.94)
Kalumpit	0.42b (±0.04)	152.30b (±19.62)	5.39b (±0.76)	3.76b (±0.61)	0.25b (±0.19)	8.95b (±0.88)
Mahogany	0.52a (±0.05)	90.60c (±13.73)	3.59d (±0.59)	3.11cd (±0.51)	0.42a (±0.50)	6.81d (±0.88)
Height levels						
Butt (2.4 m)	0.42a (±0.06)	148.38a (±30.17)	5.40a (±1.04)	3.45a (±0.95)	0.34a (±0.33)	8.71a (±1.43)
Mid (4.8 m)	0.41a (±0.04)	148.52a (±24.34)	4.87b (±0.85)	3.70a (±0.70)	0.28a (±0.25)	8.43ab (±0.96)
Top (7.2 m)	0.42a (±0.05)	143.65a (±22.51)	4.83b (±0.81)	3.41a (±0.58)	0.28a (±0.20)	8.12b (±0.88)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

No significant differences among the species along the height levels were observed in the green MC ($p=0.156$) and RD_b ($p=0.442$). Regarding green MC, different trends along the height levels were documented. For Falcata, Kalumpit, and Mahogany, an increasing trend towards the top portion was recorded, while a decreasing trend was observed in the other species (Figure 2). Regarding RD_b, an increasing trend towards the top portion was documented in Bagalunga and Mahogany, while a decreasing trend was observed in the remaining species (Figure 3).

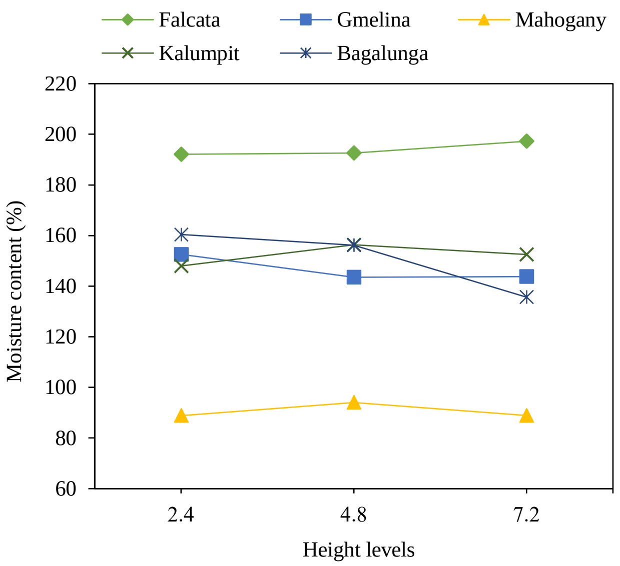

Figure 2. Moisture content along the height levels of the species

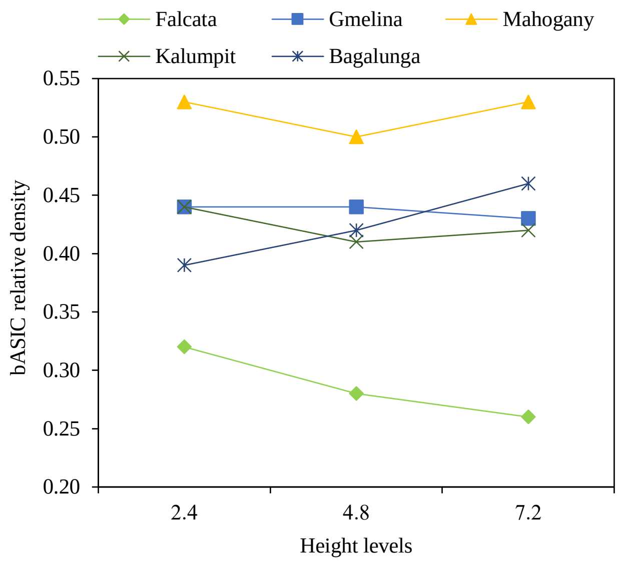

Figure 3. Basic relative density along the height levels of the species

According to Hussin et al. (2014), the variation in green MC along the height levels was due to differences in relative density associated with anatomical properties such as cell wall thickness, vessel diameter, and fiber length. Similarly, the present study observed a negative correlation between MC and RD_b (Table 3). Additionally, Moya et al. (2012) observed the negative effect of these anatomical characteristics on green MC. This finding is supported by Van Duong and Matsumura (2018),

Table 3. Correlation matrix of the physical and mechanical properties.

PROPERTIES	RD	MC	TAN	RAD	LONG	VOL	MOR	MOE	SPL	COMPPAR	COMPPER	SHEAR	SIDE	END
MC	-0.93***	-												
TAN	-0.04	0.19	-											
RAD	0.19	-0.08	0.51***	-										
LONG	0.23*	-0.26*	-0.13	-0.12	-									
VOL	0.1	0.06	0.91***	0.82***	-0.13	-								
MOR	0.77***	-0.71***	-0.1	0.13	0.13	0.01	-							
MOE	0.57***	-0.49***	0.09	0.15	0.1	0.15	0.75***	-						
SPL	0.68***	-0.56***	-0.02	0.15	0.11	0.08	0.78***	0.59***	-					
COMPPAR	0.75***	-0.72***	-0.33**	-0.08	0.14	-0.24*	0.81***	0.55***	0.79***	-				
COMPPER	0.73***	-0.73***	-0.31**	-0.07	0.23*	-0.22*	0.67***	0.40***	0.63***	0.81***	-			
SHEAR	0.81***	-0.76***	-0.12	0.06	0.29**	-0.03	0.77***	0.57***	0.66***	0.67***	0.70***	-		
SIDE	0.79***	-0.77***	-0.30**	-0.12	0.17	-0.23*	0.76***	0.55***	0.73***	0.88***	0.86***	0.78***	-	
END	0.78***	-0.78***	-0.39***	-0.16	0.2	-0.30**	0.73***	0.44***	0.69***	0.88***	0.86***	0.78***	0.93***	-
TOUGHNESS	0.32**	-0.13	0.58***	0.49***	-0.04	0.62***	0.23*	0.23*	0.44***	0.11	0.05	0.15	0.04	-0.02

Note: *p<0.05, **p<0.01, ***p<0.001; RD=relative density, MC=moisture content, TAN=tangential shrinkage, RAD=Radial shrinkage, LONG=longitudinal shrinkage, VOL=Volumetric shrinkage, MOR=Modulus of rupture, MOE=Modulus of elasticity, SPL=stress at the proportional limit, COMPPAR=compression parallel-to-grain, COMPPER=Compression perpendicular-to-grain, END=Hardness: End, SIDE=Hardness: Side who observed a direct relationship between fiber length, cell wall thickness, and relative density in *M. azedarach*. Van Duong et al. (2021) found that the relative density was positively correlated with the diameter of earlywood and latewood vessel lumens, as well as the thickness of earlywood and latewood cell walls. However, it is negatively correlated with the diameter of earlywood and latewood fiber lumens. In a previous study by Van Duong et al. (2018), they reported that the tree with the longest fiber length and low microfibril angle has the highest relative density. Moreover, the proportion of sap, heartwood, earlywood, and latewood deviations along the height levels could also contribute to the variability of MC and RD (Shmulsky and Jones, 2019).

3.1.2 Shrinkage properties

The five species showed significant differences in directional (i.e., tangential, radial, and longitudinal) (p=<0.05) and volumetric shrinkage (p=0.001). Bagalunga exhibited the highest shrinkage values for tangential shrinkage (TS), radial shrinkage (RS), and volumetric shrinkage (VS), with averages of 6.63%, 4.48%, and 10.81%, respectively. In contrast, Mahogany had the lowest shrinkage values for TS, RS, and VS, with averages of 3.59%, 3.11%, and 6.81%, respectively. However, Mahogany exhibited the highest longitudinal shrinkage (LS) at an average of 0.42%, while the other species showed no significant differences in LS.

Based on the classification of Alipon et al. (2005), Bagalunga falls under medium shrinkage, while Gmelina and Kalumpit are categorized as moderately low shrinkage, and Mahogany and Falcata exhibited low shrinkage. The results highlight Bagalunga's susceptibility to drying defects such as checking, warping, and splitting compared to other species, as evidenced by its higher VS values. In contrast, Mahogany shows the lowest tendency for these issues. To address these challenges in Bagalunga, it is crucial to establish an appropriate drying schedule. Based on RD_b, the drying schedule used for Gmelina can be applied for Bagalunga to lessen the occurrence of shrinkage defects (Bergman, 2021). While Kalumpit demonstrated a promising shrinkage property classified under moderately low shrinkage. By considering the TS and RS observed during lumber manufacturing, the study's findings can offer an estimation of a better shrinkage allowance.

A significant effect of the height levels was observed in TS (p=0.000) and VS (p=0.004). In all the species butt portion displayed the highest TS and it decreases towards the top portion (Figure 4). On the other hand, various trend was observed in the VS, for Kalumpit, Gmelina, and Falcata, the butt portion showed the highest VS, and it decreases towards the top portion. For the Mahogany and Bagalunga, the top and middle portions showed the highest VS values, respectively.

The differences in shrinkage properties observed along the height levels could be attributed to differences in the anatomical properties of the trees. According to Hamdan et al. (2020), the shrinkage properties of wood are also positively correlated with the fiber length and fiber cell wall thickness. A high microfibril angle (MFA) and low extractive content can also contribute to the high shrinkage of wood (Drozdzek et al., 2017; Shmulsky and Jones, 2019). The effects of anatomical and chemical properties on the shrinkage properties of these trees can be considered in future studies.

3.2 Mechanical properties

Table 4 presents the mean and analysis of variance obtained for the mechanical properties of the trees under the green and 12% MC conditions. The analysis revealed that the species significantly affected the mechanical properties of the trees under both conditions (p=<0.05). For static bending under green conditions, Mahogany displayed a significantly higher MOR (63.65 MPa) and SPL (25.50 MPa) than other species. Gmelina (50.23 MPa), Bagalunga (48.36 MPa), and Kalumpit (46.16 MPa) exhibited no significant differences in MOR. In terms of SPL, Mahogany (25.50 MPa) exhibited the highest value, followed by Kalumpit (25.24 MPa), and Gmelina (24.64 MPa). While the lowest value was observed in Falcata (11.60 MPa). In terms of MOE, Gmelina (7.12 GPa), Bagalunga (6.72 GPa), and Mahogany (6.64 GPa) displayed significantly higher values than the other species, while Falcata (4.33 GPa) had the lowest values.

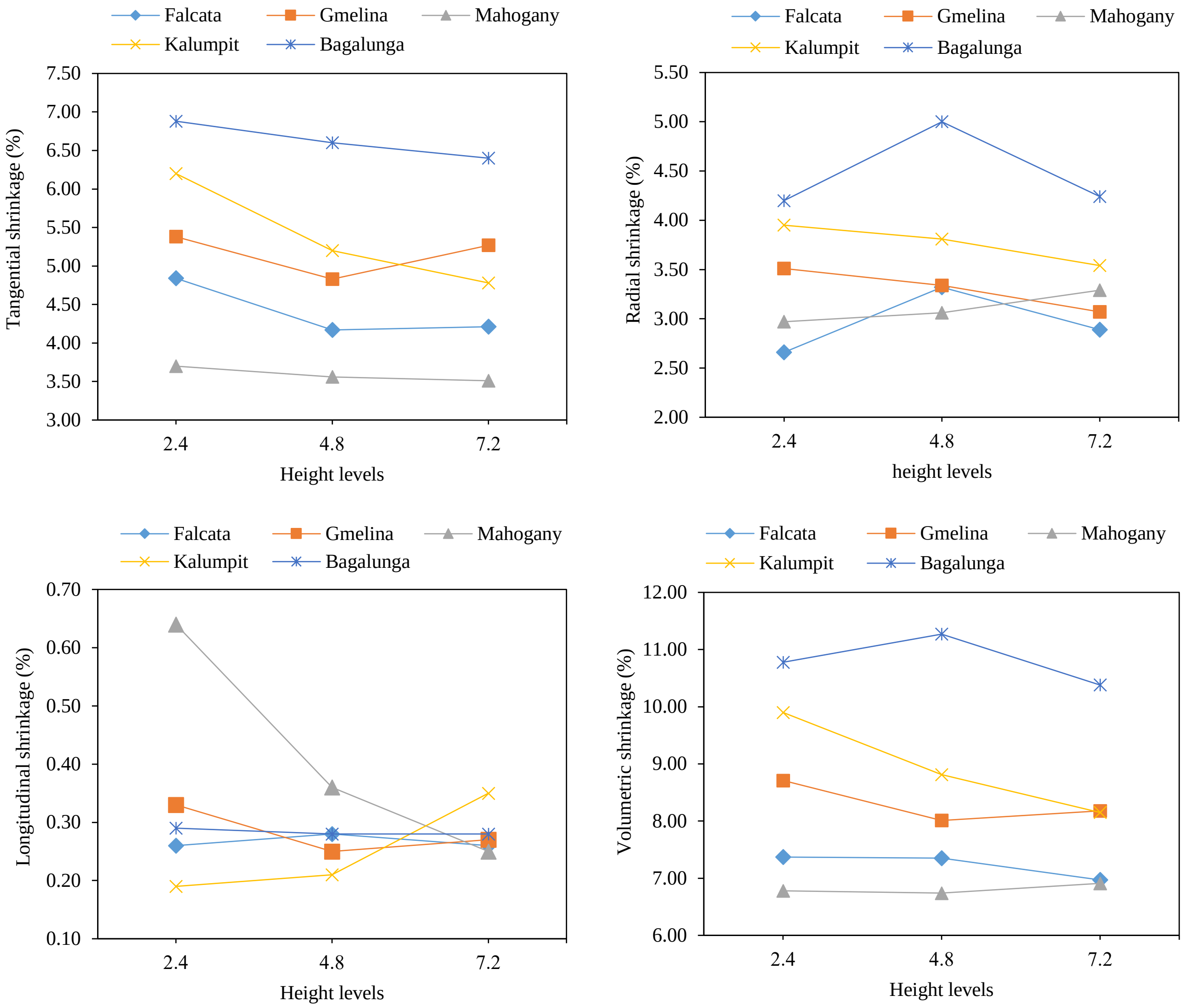

Figure 4. Shrinkage properties along the height levels of the species

Table 4. Mechanical properties at the green and 12% MC condition of the different tree species

Species	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendi-cular to the grain	Side	End		
Green condition									
Bagalunga	48.36b (±7.51)	6.72a (±0.97)	19.60b (±3.90)	15.15c (±2.03)	3.02c (±0.93)	1.97d (±0.39)	2.35d (±0.45)	6.01b (±0.83)	48.51a (±4.85)
Falcata	27.36c (±7.44)	4.33c (±1.29)	11.60c (±4.67)	13.03d (±3.36)	1.94d (±0.70)	1.22e (±0.51)	1.78e (±0.49)	3.03d (±0.68)	13.55d (±4.73)
Gmelina	50.23b (±7.43)	7.12a (±0.78)	24.64a (±3.34)	22.69b (±3.85)	5.10b (±1.74)	3.91b (±0.66)	3.78b (±0.39)	6.45b (±0.79)	36.17b (±10.06)
Kalumpit	46.16b (±6.27)	5.33b (±1.40)	25.24a (±2.28)	22.00b (±2.23)	4.42b (±0.64)	2.68c (±0.35)	3.38c (±0.55)	5.25c (±0.57)	52.73a (±2.34)
Mahogany	63.65a (±8.24)	6.64a (±0.96)	25.50a (±2.88)	27.28a (±1.99)	7.14a (±1.37)	4.67a (±0.45)	5.48a (±0.41)	8.37a (±1.33)	24.20c (±3.97)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Table 4. Mechanical properties at the green and 12% MC condition of the different tree species (cont.)

Species	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendi-cular to the grain	Side	End		
12% MC condition									
Bagalunga	65.36a (±22.41)	7.34b (±2.23)	21.23b (±12.53)	21.65c (±5.77)	4.79c (±2.52)	2.51c (±1.34)	2.83c (±0.86)	9.20b (±2.09)	42.62a (±15.31)
Falcata	35.46b (±10.81)	4.82c (±1.11)	13.94c (±7.18)	21.56c (±4.49)	2.84d (±1.45)	0.99d (±0.45)	2.24d (±0.69)	4.83e (±0.99)	11.76c (±8.96)
Gmelina	64.72a (±6.98)	6.97b (±1.34)	28.05a (±3.47)	34.80a (±3.00)	4.16c (±1.41)	3.20b (±0.62)	2.87c (±0.52)	6.62d (±1.21)	31.26b (±18.02)
Kalumpit	64.30a (±8.71)	8.58a (±1.96)	33.42a (±6.41)	29.62b (±5.74)	6.53b (±1.09)	2.80bc (±0.50)	3.98b (±0.52)	7.85c (±1.09)	47.43a (±4.15)
Mahogany	66.96a (±7.35)	7.11b (±0.84)	29.69a (±5.50)	35.62a (±4.13)	7.89a (±1.72)	4.20a (±0.82)	5.49a (±0.81)	10.37a (±0.77)	17.90c (±7.27)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

At 12% MC, the MOR of Mahogany (66.96 MPa) displayed the highest value, but was not significantly higher than those of Bagalunga (65.36 MPa), Gmelina (64.72 MPa), and Kalumpit (64.30 MPa), whereas Falcata (35.46 MPa) displayed significantly lower strength. In terms of SPL, Kalumpit displayed the highest value at 33.42 MPa, followed by Mahogany and Gmelina with values of 29.69 MPa and 28.05 MPa, respectively. The differences between these species were not statistically significant. In terms of MOE, Kalumpit (8.58 GPa) had a significantly higher value than the other species. This was followed by Bagalunga (7.34 GPa), Mahogany (7.11 GPa), and Gmelina (6.97 GPa), however, no significant differences were observed among these three species. Falcata had the significantly lowest value at 4.82 GPa.

In terms of compression strength parallel (27.28 MPa) and perpendicular (7.14 MPa) to the grain, shear strength (10.37 MPa), side hardness (4.67 kN), and end hardness (5.48 kN) in the green condition, Mahogany displayed significantly higher values than other species. This was followed by Gmelina and Kalumpit showing comparable values in terms of compressive strength.

At 12% MC, Mahogany exhibited significantly higher values for compression strength both parallel (35.62 MPa) and perpendicular (7.89 MPa) to the grain, shear strength (10.37 MPa), side hardness (4.20 kN), and end hardness (5.49 kN). Kalumpit ranked second in compression perpendicular (6.53 MPa), side hardness (2.80 kN), end hardness (3.98 kN), and shear strength (47.43 MPa), while Gmelina followed in compression parallel (34.80 MPa) and side hardness (3.20 kN). Both in the green and 12% MC conditions, Falcata had the lowest strength values across all properties. However, Bagalunga and Kalumpit displayed significantly higher toughness strengths than ITPS.

Despite its older age, Bagalunga displayed lower mechanical properties than Mahogany, though it showed comparable strength to younger Gmelina and Kalumpit. In contrast, the higher mechanical properties demonstrated by Mahogany under various conditions can be attributed to its RD. As shown in Table 2 and Table 3, the RD_b of Mahogany was significantly higher than those of other tree species and was positively correlated with the strength properties, respectively.

Similar findings were also documented by Hamdan et al. (2020) and Nordahlia et al. (2014) in *F. falcata*, *Balakata baccata*, *Macaranga gigantea*, *Endospermum diadenum*, and *Azadirachta excelsa*, respectively. Other studies have also reported that the mechanical properties of wood are significantly affected by fiber length, fiber wall thickness, and vessel diameter (Nordahlia et al., 2014; Hamdan et al., 2020). However, the effects of these factors were not explored in the present study and present an interesting opportunity for future research.

The mechanical properties of the trees in this study generally increased in strength as they were conditioned from green to 12% MC, except for toughness (Figure 5), while some species also exhibited reductions in hardness. Bagalunga displayed the highest overall average increase in mechanical properties averaging 50.23%, followed by Kalumpit (30.75%) and Falcata (25.12%), while the lowest was observed in Mahogany (6.41%) and Gmelina (2.48%). The increase in strength can be attributed to the shortening and strengthening of hydrogen bonds between the microfibrils, resulting in enhanced mechanical properties (Desch and Dinwoodie, 1996). However, the decrease in toughness can be attributed to the decrease in MC, which makes the wood brittle (Shmulsky and Jones, 2019).

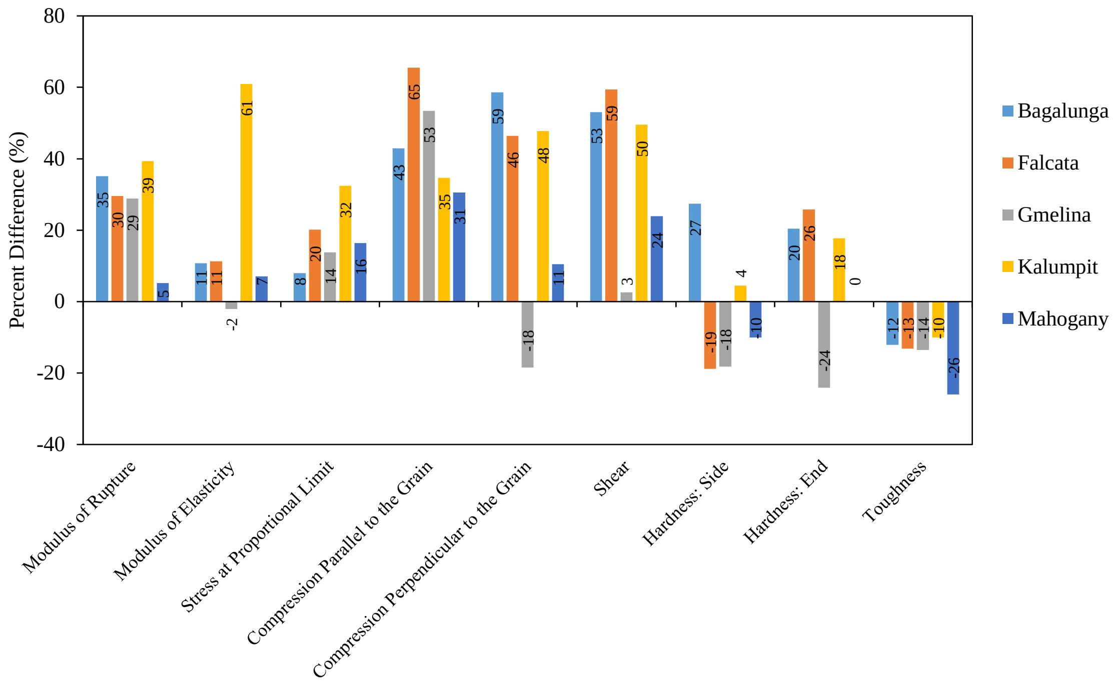

Figure 5. Percent difference in mechanical properties of different species after conditioning from green to 12% MC condition

Based on the classification of Alipon and Bondad (2008), Mahogany was classified under moderately high strength, Bagalunga, Kalumpit, and Gmelina under medium strength, and Falcata under low strength. The recommended uses for these species are listed in Table 5. The results of the study indicated that Bagalunga and Kalumpit can be used as alternatives to Gmelina, consistent with the recommendations of Natividad (2016) and Venson et al. (2008).

Table 5. Strength classification of native and industrial tree plantation species and their recommendations

Strength classification*	Species	Recommended uses*
Moderately high	Mahogany (*Swietenia macrophylla*)	Medium-heavy construction such as heavy-duty furniture, cabinets, medium-grade beams, flooring, door panels, frames, tool handle, veneer, and plywood production
Medium	Bagalunga (*Melia azedarach*) Gmelina (*Gmelina arborea*) Kalumpit (*Terminalia microcarpa*)	General construction, doors, framing, paneling, flooring, planking, medium-grade furniture, cabinet, veneer, and plywood (face and core).
Low	Falcata (*Falcataria falcata*)	Light construction where strength hardness and durability are not critical requirements such as door and panel cores, moldings, ceiling, pulp and paper, and core veneer. It can also be used for interior construction, cheap types of furniture, window frames (treated), flooring, planking, and packing cases.

Source: *Alipon and Bondad (2008)

Along the height levels, significant variations in mechanical properties across species under both green and 12% MC conditions were observed (Tables 6 and 7). In the green condition, significant differences in toughness were observed along the height levels (p=<0.001). The interaction of species × height levels was significant for MOR (p=0.007). Tukey's HSD test revealed that the MOR of the middle portion of the Kalumpit was significantly higher than that of the top portion, while the toughness of the butt portion of the Gmelina was significantly higher than those of the other portions.

In the 12% MC condition, the interaction of species × height levels showed significant differences in MOR (p=<0.001), MOE (p=0.003), compression parallel to the grain (p=0.004), shear strength (p=0.000), and hardness (end) (p=<0.001). Tukey's HSD revealed that the MOR and shear strength of the top portion of Bagalunga were significantly higher than those of the butt and middle portions. The top and butt portions of the Bagalunga and Kalumpit, on the other hand, showed significantly higher compression parallel to the grain than the other portions. In terms of end hardness, the Kalumpit top portion displayed significantly lower strength than the butt and middle portions. The variations in the mechanical properties between different height levels can be attributed to the differences in RD_b (Figure 3 and Table 3). Similar observations have been reported in other species, such as *F. falcata* (Marasigan et al., 2022), *Eucalyptus gomphocephala*, *E. cladocalyx*, and *E. grandis* × *camaldulensis* (Wessels et al., 2016), where the sections with the highest RD exhibited the highest mechanical properties.

Table 6. Mechanical properties at the green condition at different height levels

Species	Height levels	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
		Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendi-cular to the grain	Side	End		
Bagalunga	Butt	43.33a (±3.84)	5.92a (±0.74)	19.44a (±2.60)	14.23a (±1.09)	2.98a (±0.84)	1.83a (±0.32)	2.26a (±0.30)	5.58a (±0.58)	50.84a (±3.62)
	Mid	52.23a (±4.99)	6.75a (±0.91)	21.25a (±2.16)	16.56a (±1.80)	2.56a (±1.17)	1.99a (±0.49)	2.35a (±0.50)	6.17a (±0.78)	46.47a (±6.59)
	Top	49.53a (±13.70)	7.51a (±1.28)	18.12a (±6.96)	14.66a (±3.19)	3.50a (±0.78)	2.09a (±0.35)	2.45a (±0.54)	6.28a (±1.14)	48.21a (±4.33)
Falcata	Butt	28.87a (±10.75)	4.23a (±1.69)	11.47a (±6.23)	12.95a (±4.40)	2.09a (±0.94)	1.43a (±0.50)	1.75a (±0.46)	3.09a (±0.58)	14.38a (±5.37)
	Mid	27.64a (±7.35)	4.41a (±1.47)	11.93a (±6.58)	13.64a (±3.77)	2.14a (±0.77)	1.31a (±0.60)	1.90a (±0.65)	3.11a (±0.92)	14.35a (±5.77)
	Top	25.56a (±4.21)	4.35a (±0.70)	11.41a (±1.20)	12.49a (±1.91)	1.59a (±0.40)	0.92a (±0.44)	1.69a (±0.36)	2.90a (±0.53)	11.92a (±3.04)
Gmelina	Butt	50.36a (±6.94)	7.63a (±0.86)	25.91a (±4.22)	23.10a (±2.04)	5.35a (±2.11)	4.26a (±0.65)	4.00a (±0.53)	6.26a (±0.89)	42.02a (±12.31)
	Mid	55.05a (±8.23)	7.71a (±0.68)	25.77a (±3.37)	22.96a (±4.06)	5.65a (±2.32)	4.04a (±0.83)	3.77a (±0.29)	6.70a (±0.67)	33.28b (±5.35)
	Top	45.28a (±7.11)	6.02a (±0.79)	22.25a (±2.41)	22.00a (±5.46)	4.30a (±0.80)	3.44a (±0.51)	3.58a (±0.35)	6.38a (±0.80)	33.20b (±12.53)
Kalumpit	Butt	48.66ab (±8.15)	4.92a (±1.60)	26.13a (±2.94)	21.73a (±2.69)	4.46a (±0.70)	2.88a (±0.32)	3.55a (±0.60)	5.70a (±0.60)	51.58a (±4.93)
	Mid	53.04a (±1.99)	5.81a (±1.15)	25.55a (±3.78)	23.13a (±2.12)	4.72a (±0.49)	2.79a (±0.44)	3.41a (±0.33)	5.51a (±0.82)	51.53a (±1.42)
	Top	36.79b (±8.67)	5.27a (±1.46)	24.05a (±0.11)	21.14a (±1.90)	4.07a (±0.72)	2.35a (±0.29)	3.19a (±0.73)	4.52a (±0.29)	55.07a (±0.68)
Mahogany	Butt	63.80a (±5.70)	6.77a (±0.69)	28.27a (±2.13)	27.59a (±0.63)	7.00a (±0.80)	4.66a (±0.44)	5.47a (±0.39)	8.89a (±0.77)	28.86a (±3.17)
	Mid	58.41a (±12.04)	6.27a (±1.36)	23.32a (±2.14)	24.96a (±3.52)	7.49a (±2.56)	4.51a (±0.68)	5.73a (±0.38)	8.77a (±0.53)	20.70a (±5.49)
	Top	68.74a (±6.98)	6.88a (±0.83)	24.92a (±4.36)	29.30a (±1.80)	6.93a (±0.76)	4.85a (±0.22)	5.25a (±0.45)	7.44a (±2.68)	23.04a (±3.26)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Table 7. Mechanical properties at 12% MC condition at different height levels

Species	Height levels	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
		Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendicular to the grain	Side	End		
Bagalunga	Butt	49.40b (±24.52)	6.09a (±2.28)	15.70a (±11.34)	17.65b (±6.54)	4.67a (±2.74)	1.75a (±1.34)	2.09a (±0.95)	7.40b (±2.83)	47.63a (±9.77)
	Mid	56.86b (±29.06)	7.72a (±2.98)	18.45a (±10.82)	19.57b (±8.69)	4.28a (±2.30)	2.79a (±1.62)	3.01a (±0.71)	9.14b (±2.43)	44.39a (±11.08)
	Top	89.82a (±13.64)	8.22a (±1.42)	29.54a (±15.43)	27.72a (±2.07)	5.42a (±2.52)	2.98a (±1.05)	3.39a (±0.93)	11.07a (±1.02)	35.84a (±25.07)
Falcata	Butt	35.17a (±13.69)	4.97a (±1.37)	11.67a (±8.12)	24.54a (±7.25)	3.55a (±1.70)	1.15a (±0.57)	2.62a (±1.00)	4.88a (±1.70)	14.56a (±12.82)
	Mid	35.33a (±12.50)	4.70a (±1.13)	15.05a (±7.62)	18.94a (±3.31)	2.32a (±1.68)	0.81a (±0.39)	2.07a (±0.36)	4.87a (±0.52)	12.27a (±10.51)
	Top	35.88a (±6.22)	4.79a (±0.83)	15.10a (±5.80)	21.19a (±2.91)	2.66a (±0.95)	1.01a (±0.38)	2.03a (±0.70)	4.74a (±0.74)	8.44a (±3.53)
Gmelina	Butt	68.50a (±7.05)	5.71a (±2.60)	29.93a (±5.35)	37.16a (±3.05)	4.78a (±2.11)	3.91a (±0.54)	3.35a (±0.57)	7.62a (±0.82)	37.45a (±26.20)
	Mid	59.26a (±11.06)	6.47 (±0.64)	25.21a (±2.82)	32.96a (±3.59)	4.45a (±0.78)	2.77a (±0.71)	2.59a (±0.64)	5.90a (±1.97)	30.38a (±19.59)
	Top	66.39a (±2.83)	8.74a (±0.79)	28.99a (±2.24)	34.28a (±2.37)	3.26a (±1.33)	2.93a (±0.60)	2.65a (±0.35)	6.33a (±0.84)	25.94a (±8.27)
Kalumpit	Butt	67.42a (±11.98)	10.22a (±3.09)	38.73a (±5.80)	32.76a (±6.24)	7.61a (±0.92)	3.32a (±0.73)	4.57a (±0.52)	8.58a (±0.67)	45.98a (±2.20)
	Mid	72.50a (±7.40)	8.46a (±1.62)	34.33a (±6.14)	29.85ab (±5.45)	6.60a (±0.85)	2.99a (±0.47)	4.40a (±0.59)	8.04a (±0.85)	44.46a (±6.90)
	Top	52.98a (±6.75)	7.07a (±1.18)	27.20a (±7.30)	26.25b (±5.52)	5.37a (±1.48)	2.10a (±0.30)	2.98b (±0.46)	6.92a (±1.75)	51.85a (±3.36)
Mahogany	Butt	63.99a (±10.00)	6.86a (±1.24)	34.06a (±4.89)	34.12a (±3.51)	7.38a (±2.37)	4.28a (±0.87)	5.16a (±0.97)	9.56a (±0.69)	20.23a (±8.48)
	Mid	70.35a (±3.50)	7.63a (±0.52)	28.82a (±6.51)	37.91a (±1.87)	8.38a (±1.95)	3.94a (±0.85)	5.29a (±0.84)	10.49a (±0.59)	16.45a (±4.69)
	Top	66.55a (±8.55)	6.85a (±0.76)	26.21a (±5.11)	34.83a (±7.03)	7.90a (±0.83)	4.39a (±0.75)	6.01a (±0.61)	11.06a (±1.04)	17.03a (±8.64)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Anatomical properties, such as fiber cell wall thickness, fiber length, vessel frequency, and diameter, may also account for the differences in strength properties across the height levels (Lundqvist et al., 2017). In addition, Nasser et al. (2010) reported that the mechanical features of *M. azedarach*, such as MOR, MOE, compression strength, and hardness, are positively correlated with the extractive content. Their study revealed that extractives reinforce cell walls and improve the mechanical properties of wood. In the case of *A. mangium*, the extractive content increased from the butt to the top (Amini et al., 2017).

4. CONCLUSION

Bagalunga and Kalumpit are viable alternatives to exotic industrial plantation species in the Philippines. Bagalunga exhibits characteristics suitable for plantation development, including a relatively straight bole, large diameter, high merchantable height, and fast growth. Kalumpit, primarily cultivated for its fruit, also features a straight bole, large diameter, and high adaptability. The physical and mechanical properties of Bagalunga and Kalumpit were comparable to Gmelina and Mahogany and higher than those of Falcata. Their MC and RD_b values were similar to Gmelina, with Bagalunga showing the highest shrinkage, classifying it under the medium category, while Kalumpit exhibited moderately low shrinkage, similar to Gmelina. The mechanical properties of both species fell under the medium-strength, making them suitable for general construction applications such as doors, flooring, furniture, and plywood veneer. Both species also demonstrated a significant increase in strength after conditioning to 12% MC.

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AUTHOR CONTRIBUTIONS

Conception and design of study: Oliver S. Marasigan, Shereyl A. Daguinod, Jayric F. Villareal; Acquisition of data: Oliver S. Marasigan, Shereyl A. Daguinod; Analysis and/or interpretation of data: Oliver S. Marasigan, Shereyl A. Daguinod, Jayric F. Villareal; Drafting the manuscript: Oliver S. Marasigan and Jayric F. Villareal; Revising the manuscript for significant intellectual content: Oliver S. Marasigan, Shereyl A. Daguinod, Jayric F. Villareal; Approval of the version of the manuscript to be published: Oliver S. Marasigan, Shereyl A. Daguinod, Jayric F. Villareal

DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

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Heavy Metals Contamination Assessment Using Pollution Indices for Spring Water in Barwari Bala Villages, Duhok, Kurdistan Region-Iraq

Mohammed Jalil Qasim[1*], Hajar Ameen Ameen[2], and Azzedin Ali Marouf[2]

[1]*Department of Agricultural Project Techniques, Amedi Technical Institute, Duhok Polytechnic University, Kurdistan Region-Iraq*
[2]*Department of Soil and Water Science, College of Agricultural Engineering Science, University of Duhok, Kurdistan Region-Iraq*

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*** Corresponding author:**
E-mail:
mohammed.jalil@dpu.edu.krd

ABSTRACT

Regular quality monitoring of drinking water resources is crucial for ensuring a safe drinking water supply for various users. Thus, this study was carried out to assess water safety for human drinking in terms of heavy metal content using pollution indices for spring water in Barwari Bala Villages located in Duhok City, Kurdistan Region of Iraq. Six spring water samples were collected at 10 to 15 day intervals from 10 areas during the summer of 2023. All 60 samples were analyzed in the laboratory to evaluate heavy metal concentrations, including manganese (Mn), chromium (Cr), iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and lead (Pb). The overall quality of water was then assessed by utilizing pollution indices, including the degree of contamination (Cd), the heavy metal evaluation index (HEI), and the heavy metal pollution index (HPI). The results revealed that the concentrations of all the selected heavy metals found in spring water samples were lower than the permissible limits based on Iraqi standards, except for Pb in sites SW1 (Kyle Baze), SW2 (Kani Mazne), and SW8 (Derishke), which had higher concentrations of Pb depending on the prescribed limits (10 µg/L). According to metal pollution indices, the values of all the indices were lower than their critical ranges of contamination, indicating that the water of every site was safe for drinking. However, greater concentrations of Pb in spring water at sites SW1, SW2, and SW8 might have an adverse impact on human consumption in the long term. Thus, the treatment of spring water at these sites before utilization is highly recommended to ensure safe water for consumption. Further research is needed to determine the causes and contributing factors behind the rising lead (Pb) levels observed at those locations, as well as to develop appropriate treatment strategies to mitigate contamination.

1. INTRODUCTION

Water is considered one of the most valuable natural resources as it is necessary for all life forms and vital for various human activities. In recent years, freshwater demand has dramatically increased due to rapid growth in the human population (Alobaidy et al., 2010; Saleh et al., 2022). However, with the ever-increasing demand for water and the impact of various anthropogenic activities and climate change, the quality of water resources is under constant threat (Ameen, 2019; Poudel and Duex, 2017). Moreover, many nations, particularly developing countries, have faced a scarcity in freshwater resources because of climate change (Postel, 2000). For a healthy lifestyle and a sufficient supply of clean drinking water, it becomes crucial to assess and monitor water quality effectively.

Groundwater springs are considered vital lifelines for millions of mountain people around the world, providing the main supply of household water and local food security (Gurung et al., 2019; Hosseinifard and Mirzaei Aminiyan, 2015). In recent years, from the important issues that the environment has been facing is the contamination of water

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resources. The quality of groundwater and spring water is generally good; however, it is affected by many factors. Agricultural practices, urbanization, industrial activities, climate change, and remnants of war are considered significant threats to the quality of water (Li et al., 2021; Patil et al., 2022; Swain, 2024). It has been stated that the pollution of groundwater by pollutants such as heavy metals, pesticides, hydrocarbons, trace organic contaminants, microplastics, nanoparticles, and other emerging pollutants has a serious impact on human health and the quality of water, making it extremely important to assess and understand the quality of water (Li, 2020; Tran et al., 2023; Wang et al., 2023; Badar et al., 2024).

One of the effective approaches for assessing heavy metal contamination in aquatic systems is through the application of heavy metal pollution indices (Ameen et al., 2019; Kamali Maskooni et al., 2020; Majeed and Ibraheem, 2024). These indicators are considered very important tools for water quality assessment, as they provide a summarized numerical value or rating that represents the water quality based on multiple water quality parameters (Ameen et al., 2019; Prasad Ahirvar et al., 2023; Shigut et al., 2017). Moreover, water quality indices facilitate the interpretation and communication of water quality information to policymakers, water resource managers, and the general public (Banda and Kumarasamy, 2020; Lukhabi et al., 2023). Consequently, various water quality and pollution indexes have been proposed and accepted globally. The most widely used indices for such purposes include the heavy metal evaluation index (HEI), the heavy metal pollution index (HPI), and the degree of contamination (Cd) (Backman et al., 1998; Brown et al., 1970; Edet and Offiong, 2002; Raja et al., 2021; Shigut et al., 2017; Terry and Stone, 2002).

Numerous studies across the globe have used these indices to evaluate the quality of water. For instance, in Damascus, Syria, researchers found that 74% of groundwater samples have an HPI lower than the mean value of 8.58. Whereas 26% of the samples exceed this mean and only one sample reaches the limit of low pollution by heavy metal (Abou Zakhem and Hafez, 2015). The same study reported that high HPI values are concentrated in the southeastern to central parts of Damascus, especially in the northeast, due to industrial, agricultural, and urban activities, as well as heavy metal leaching from a sewage treatment station. Similarly, a study in Iraq's Maysan Province found values below the critical threshold of 100, indicating minimal pollution, though with localized risks due to industrial and agricultural activities (Jazza et al., 2022). Conversely, the Shatt Al-Arab River, Basrah-Iraq, exhibited HPI values ranging from 130.41 to 196.97, far exceeding safe limits (100), pointing to severe pollution from industrial and human activities (Al-Hejuje et al., 2017).

The vast majority of rural people in the Kurdistan Region of Iraq use groundwater and spring water for drinking without any type of treatment. The necessity of the identification and elimination of heavy metals from spring water cannot be understated because the water from these springs is utilized for a variety of purposes, including providing drinking water to villages and for agricultural purposes. Thus, the quality evaluation of spring water is needed to supply clean drinking water for any purpose. Although Ameen (2019) researched to assess the water quality in these springs for drinking, only the major elements were taken into account in this study, and heavy metal elements were not examined. To the best of the researchers' knowledge, no research has yet been undertaken using pollution indicators to assess the quality of spring water in this location; therefore, some form of indication of their concentration and variation ranges is needed to more correctly examine the quality of water. The current study was, therefore, aimed at evaluating the drinking water contamination by heavy metals and presenting the use of pollution indices as a possible monitoring tool for the drinking water quality of springs existing in Barwari Bala villages in the Amedi district in the Kurdistan Region of Iraq.

2. METHODOLOGY

2.1 Study area

This study was conducted in the ten villages of the Barwary Bala Region, located in the northern part of the Kurdistan Region of Iraq, alongside the Iraq-Turkey border. This area is roughly 100 kilometers from Duhok City. It lies at 37°10'03" N and 37°16'11" N latitudes and 43°10'08" E and 43°29'46" E longitudes. The region has a mountainous topography and a semiarid climate, which is distinguished by a dry and hot summer as well as a wet and cold winter that typically includes snow and higher rainfall. The geology of the region is completely of sedimentary origin and is made primarily of limestone (Ameen, 2019). It receives an annual rainfall of between 760 mm and 950 mm. Springs from ten villages were identified in the study. The main springs from each village were selected for investigation in case the villages have more than one spring. The symbols, names, and geographical locations of the selected springs are presented in Figure 1 and Table 1.

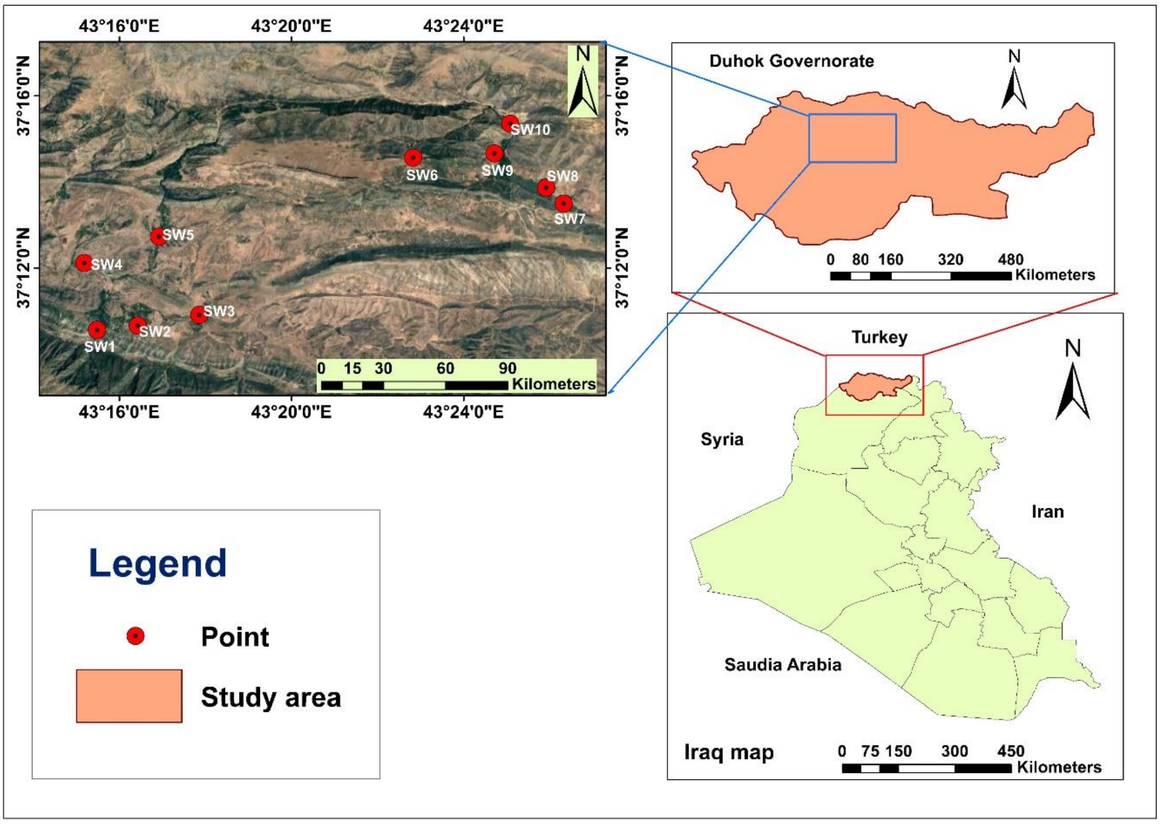

Figure 1. The study area and sample locations are shown on a map of Iraq with a satellite picture

Table 1. The symbol, names, and geographic location of the investigated water springs

Location	Sample symbol	Latitude	Longitude
Kyle Baze	SW1	37°10′31.29″N	43°15′28.78″E
Kani Mazne	SW2	37°10′39.73″N	43°16′26.10″E
Miska	SW3	37°10′54.36″N	43°17′50.88″E
Xshxasha	SW4	37°12′06.3″N	43°15′11.44″E
Beqolke	SW5	37°12′44.13″N	43°16′54.83″E
Bnavi	SW6	37°14′33.55″N	43°22′50.46″E
Kani Mase	SW7	37°13′29.3″N	43°26′18.86″E
Derishke	SW8	37°13′51.57″N	43°25′54.93″E
Maye	SW9	37°14'38.33"N	43°24'40.85"E
Bedhi	SW10	37°15′10.07″N	43°25′08.26″E

2.2 Sample collection and analysis

Spring water samples were obtained during the summer season of 2023 from June to October, as during this period, most of the people visit their villages and return to their original homes in cities during the winter. In the present study, six water samples were taken from each area at intervals of 10 to 15 days using stopper-fitted polyethylene bottles with a 450 mL capacity. Before collection, the sample collecting bottles were washed with distilled water multiple times and then with spring water. To reduce the precipitation and heavy metals adsorption, samples were then acidified with 5 mL of concentrated HNO_3 (50%) to a pH below 2 in accordance with national standard procedures (Rice et al., 2012). The obtained water samples were transported to the lab and stored at 4°C for further examination. All water samples were then analyzed to determine the concentrations of the following heavy metals manganese (Mn), chromium (Cr), iron (Fe), zinc (Zn), copper (Cu), Cadmium (Cd), and lead (Pb) by using the GBC Atomic Absorption Spectrophotometer (A.A.S.), Model 932 AA, Australia.

2.3 Pollution evaluation methods

Water pollution by heavy metals is typically estimated by heavy metal pollution or contamination indices. Various pollution indices are available worldwide for this purpose, and the three documented indexes used in the present research are the heavy metal pollution index (HPI), degree of contamination (C_d), and heavy metal evaluation index (HEI). These indices are calculated to assess the quality of drinking water concerning the content of heavy metals (Brraich and Jangu, 2015).

2.3.1 Heavy metal pollution index (HPI) calculation

This index, which indicates the collective effect of various heavy metals on the water quality, can be evaluated by employing the weighted arithmetic index technique applied by Brown et al. (1970) after minor adjustments. HPI is a rating technique that indicates the combined impact of several heavy metals on the water quality generally. This rating method is an arbitrarily chosen value between zero and one, and its selection relies on the relative significance of specific quality factors and is inversely proportional to the proposed rating standard (S_x) for each parameter (Prasad and Bose, 2001; Reza and Singh, 2010). In this research, HPI calculations were performed on seven important heavy metals, as shown in Table 2. The Iraqi Standard (COSQC, 2001) and WHO (2017) standards have been deployed to assess the samples in terms of water quality. The HPI was calculated based on the relative importance and its significant role on the overall quality of water, each of the chosen heavy metal parameters has been allocated a weight (W_x). As mentioned previously, the rating is a number between 0 and 1, representing the importance of selected heavy metals, and it is inversely proportional to the approved standards (S_x) for each heavy metal (Table 2). The unit weight (W_x) can be measured utilizing the following formula:

$$W_x = K/S_x \quad (1)$$

Where; W_x refers to the unit weightage of the parameters, S_x refers to the dependent standards, and K refers to the constant of proportionality, which was considered one in the current study. Then, the concentration of measured values for each parameter (Mv) was divided by its corresponding standard to get a quality rating score (Q_n) or sub-index, which was then multiplied by 100 as follows:

$$Q_n = M_V/S_x \times 100 \quad (2)$$

Where; M_v=the measured value of heavy metal of the ^{it}h parameter; S_x=the standards value for the ^{i}th parameter. Finally, utilizing the formula (Mohan et al., 1996; Prasad and Bose, 2001), the HPI for every sample was calculated as follows:

$$\text{HPI} = \frac{\sum_{i=1}^{n} W_x Q_n}{\sum_{i=1}^{n} W_x} \quad (3)$$

Where; Q_n=the quality rating of the ^{n}th water quality parameter; W_x=the unit weightage of the ^{i}th parameter; n= the number of parameters considered. Typically, the critical contamination indicator of the HPI value for water for drinking is 100 (Prasad and Bose, 2001). The value of HPI<100 represents low pollution by heavy metals. If the HPI value is greater than 100, it indicates that the water is not drinkable (Edet and Offiong, 2002; Mohan et al., 1996; Prasad and Bose, 2001).

2.3.2 Degree of contamination (C_d)

The degree of contamination (C_d) quantifies the combined harmful impacts of C_d based on numerous parameters that are thought to be possibly dangerous for drinking water (Backman et al., 1998). C_d is a sum of the pollution influences of the different parameters that surpass their admissible values and is calculated as follows:

$$C_d = \sum_{i=1}^{n} C_{fi} \quad (4)$$

$$C_{fi} = \frac{C_i}{C_n} - 1 \quad (5)$$

Where; C_{fi}, C_i, and C_n refer to contamination factor, measured value, and upper permissible concentration of the ^{i}th component or parameter, respectively. For the current study, C_n was considered as the maximum permissible limit (MPL), as shown in Table 2. The C_d values, which describe the degree of contamination (Backman et al., 1998; Edet and Offiong, 2002), are divided into three groups: low (C_d<1), medium (1<C_d<3), and high (C_d>3).

Table 2. Unit weight of individual heavy metals with recommended standards (µg/L) used for index calculation

Heavy metals	Unit	(WHO, 2017) Drinking water (Gv)[a]	Iraqi standards (COSQC, 2001) (MPL)[b] (S_x)	Units weight (W_x)
Cr	µg/L	50	50[c]	0.020
Mn	µg/L	400	100[c]	0.010
Fe	µg/L	-	300[c]	0.003
Cu	µg/L	2,000	1,000[c]	0.001
Zn	µg/L	-	3,000[c]	0.000
Pb	µg/L	10	10[c]	0.100
Cd	µg/L	3	3[c]	0.333
				$\Sigma W_i = 0.468$

(Gv)[a]=Guideline value; (MPL)[b]=Maximum permissible limit, [c] depended standards.

2.3.3 Heavy metal evaluation index (HEI)

Similar to the HPI, the HEI measures the water quality in terms of heavy metals (Edet and Offiong, 2002). According to Mohan et al. (1996), the following equation is used to determine the HEI:

$$HEI = \sum_{i=0}^{n} \frac{H_C}{H_{max}} \quad (6)$$

Where; H_c and H_{mac} stand for both the measured value and the maximum admissible concentration (MAC) of the [i]th parameter. According to Edet and Offiong (2002) procedure, HEI is divided into three categories: low (HEI<10), middle (10<HEI<20), and high (HEI>20).

2.4 Statistical analysis

A one-way ANOVA following the GLM procedure was used for measuring the significant differences in the selected heavy metals among the studied sites. The significant differences in heavy metal means were found by Tukey's HSD (Honestly Significant Difference) test at p<0.05. One sample t-test (right-tailed t-test) was used to determine if the measured values were greater than the recommended standards. Minitab software version 18 was used to analyze the Data of the research.

3. RESULTS AND DISCUSSION

3.1 Sidewise distribution of heavy metals and their comparison to standards

The statistical results [mean±standard error (SE) and p-values] of measured heavy metals in the collected spring water samples at 10 sites and Iraq water quality standards are provided in Table 3.

Chromium (Cr) is one of the elements that is widely distrusted in the earth's crust and can exist in forms (valences) of +2 to +6 (WHO, 2017). The sources of Cr in water could be natural or anthropogenic (Bhardwaj et al., 2017). Chromium (III) is considered an essential nutrient for humans, according to the World Health Organization (WHO, 2017). Chromium, a toxicological and carcinogenic substance, can be a reason for dermatitis and skin ulcers (Saha and Paul, 2016). However, the results showed that the chromium (Cr) concentration in water samples ranged from 0.12 to 2.81 µg/L. It was observed that the concertation of Cr was significantly (p<0.001) varied among the studied sites. Significantly higher concentrations of Cr were found at sites SW3, SW7, and SW8, followed by sites SW1, SW2, SW6, and SW10, while concentrations of Cr were found at the rest of the sites (Table 3). These differences in the concentration of heavy metals among the studied locations could be due to the differences in the lithological structure of these locations or some of these sites may contain potentially contaminated sources such as residential wastewater, septic tank effluent, and fertilizers. However, the concentration of Cr in every sample was lower than the maximum acceptable value (50 µg/L) of Iraq's standards (COSQC, 2001) for drinking.

Iron (Fe) and manganese (Mn) are considered from important substances that the human body needs in small amounts because of their crucial roles in the formation of hemoglobin and cell function (Gautam et al., 2014). Although Fe and Mn are necessary for enzyme function, their undesirable concentrations in drinking water might be harmful to human health (Gautam et al., 2014; Saha and Paul, 2016). Iron is among the most prevalent metals in the crust of the earth. Mn is also present in the earth's crust, however, in smaller proportions. According to Ameen et al. (2019), there are several ways for these two elements to get into the water, including the weathering of rocks, leachate from landfills, wastewater from the metal industries, and agricultural runoff, including pesticides and fertilizers. Nevertheless, in the current investigation, the concentration of iron was from 17.12 to 96.5 µg/L (Table 3). The study showed a significant difference ($p<0.001$) in the concentration of Fe among the tested sites. The Fe concentration was significantly greater at site SW4, followed by sites SW2, SW3, SW7, SW8, and SW10, and the Fe concentration was significantly lower at site SW5, followed by sites SW1, SW6, and SW9. Furthermore, Mn concentrations also ranged from 2.15 to 3.22 µg/L. Higher concentrations of Fe were observed in the samples from SW4, SW5, SW7, and SW8, while the rest of the sites had a lower concentration of Mn. These variations in the concentrations of Fe and Mn (as discussed previously) might be related to the variation in geological rocks or a certain anthropogenic source, e.g., domestic effluents, irrigation discharge, and sewage effluent. Although no health-based guideline value is proposed for Fe and Mn in drinking water, according to Iraq's standards (COSQC, 2001), the concentrations of Mn and Fe in all spring water samples were documented to be beneath the established thresholds.

Copper (Cu) is another essential trace metal that is required by biological systems to activate certain enzymes and facilitate bone repair, but in larger quantities, it may have negative effects on human health, particularly infants (Gautam et al., 2014; WHO, 2017). The presence of copper in spring water can be influenced by geological factors and the surrounding environment. However, as illustrated in Table 3 the Cu value in the tested spring water samples varied from 6.06 and 77.28 µg/L. The Cu concentrations also varied according to the various places, and higher concentrations were found at sites SW4 and SW6, followed by sites SW9 and SW10, and a lower value was found at site SW3. The value of Cu in water samples was lower than the prescribed limit (1,000 µg/L) depending on the described standard (COSQC, 2001).

Zinc (Zn) is regarded as an important element for human nutrition, however, higher levels of zinc might be unhealthy (WHO, 2017). Zinc toxicity at excessive doses results in vomiting and nausea in children (Gautam et al., 2014), even though WHO (2017) has not established a health-based guideline value for this element in drinking water. Zinc can enter spring water naturally from geological rocks and through human activities such as the application of zinc-containing fertilizers or pesticides (Ameen et al., 2019; Gautam et al., 2014). However, the analyzed data revealed there was a significant difference ($p<0.001$) in Zn concentrations among the studied sites. Sites SW8 and SW10 had the highest concentrations of Zn, followed by site SW9, and lower concentrations of Zn were recorded at sites SW1 and SW5 (Table 3). The ranges of Zn detected in spring water samples were significantly lower ($p<0.001$) than the maximum permissible limits (3,000 µg/L) of Iraqi standards (COSQC, 2001).

Lead (Pb) is considered a non-beneficial element and has no nutritional value for living things; instead, it has been classified as a toxic metal (Gautam et al., 2014; WHO, 2017). Nevertheless, the Pb concentrations found in the water samples analyzed in the present study were in the range of 5.14 to 16.9 µg/L. A significant effect was recorded ($p<0.001$) on the concentration of Pb in spring water samples analyzed in the current study (Table 3). This effect showed that there were significantly greater concentrations of Pb at sites SW1 and SW8, followed by SW2 and SW4, while there were significantly lower concentrations of Pb at sites SW3 and SW6. The values of Pb in all tested samples were significantly lower than the acceptable limits (10 µg/L) according to Iraqi standards (COSQC, 2001), except for sites SW1, SW2, and SW8, where the concentrations of this metal were greater than the acceptable limits. The higher concentration of Pb in sites SW1, SW2, and SW8 could be due to the higher population and higher human activities in these areas. Thus, serious measures need to be considered in these areas, including the careful application of agricultural inputs as well as the use of wastewater and sewage sludge in agriculture. Additionally, Pb concentration in water may also depend on the period in which the water has been in contact with the lead-containing materials (WHO, 2017).

Cadmium (Cd) metal, a hazardous trace metal that is thought to contribute to the development of cancer and cardiovascular disease, is thought to increase with age, particularly in the kidney (Saha and Paul, 2016; WHO, 2017). Cadmium enters the water system through wastewater (Terry and Stone, 2002). Cadmium may also enter water bodies through the application of phosphate fertilizer or insecticide (Kubier et al., 2019). Nevertheless, interestingly, no concentrations of Cd were detected in the spring water samples collected in the current study.

Table 3. Mean±SE values of the studied heavy metals measured in spring water at the studied sites (μg/L)

Locations	Cr	Mn	Fe	Cu	Zn	Pb	Cd
SW1	1.42±0.03[cd]	2.15±0.08[f]	60.43±2.99[cd]	19.66±5.25[ef]	8.95±0.64[e]	15.35±0.58[ab]*	0.00
SW2	1.65±0.08[c]	2.47±0.12[def]	76.35±3.19[b]	19.46±0.22[f]	62.00±6.22[d]	12.72±0.95[bc]*	0.00
SW3	2.45±0.08[ab]	2.68±0.17[cde]	78.86±2.37[b]	11.40±2.32[fg]	85.61±14.4[cd]	6.83±0.23[ef]	0.00
SW4	0.62±0.02[ef]	3.03±0.08[abc]	96.50±0.56[a]	71.41±1.45[a]	83.44±0.02[cd]	10.13±0.44[cd]	0.00
SW5	0.12±0.01[f]	3.22±0.09[a]	17.12±0.36[e]	6.06±0.15[g]	8.40±0.02[e]	8.16±0.47[de]	0.00
SW6	1.86±0.13[cb]	2.25±0.04[ef]	48.54±1.45[d]	77.28±1.77[a]	94.65±0.17[c]	5.14±0.37[f]	0.00
SW7	2.81±0.33[a]	2.83±0.06[a-d]	76.13±2.60[b]	29.45±1.04[de]	106.35±1.84[c]	9.28±0.69[de]	0.00
SW8	2.53±0.29[ab]	3.13±0.12[ab]	78.58±4.11[b]	32.84±0.34[cd]	171.37±2.26[a]	16.90±0.89[a]*	0.00
SW9	0.73±0.00[def]	2.55±0.08[def]	54.20±4.47[d]	50.00±0.80[b]	143.06±2.77[b]	7.67±0.31[def]	0.00
SW10	1.31±0.23[cde]	2.77±0.06[bcd]	72.39±4.00[bc]	40.65±2.07[bc]	175.27±1.08[a]	8.17±0.27[de]	0.00
p-values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Iraqi standards (MPL)	50	100	300	1,000	3,000	10	3

Means in each column sharing different letters are significantly different at $p<0.05$.
Mean±SE denotes *=measured values are significantly higher than standards at $p<0.05$.
Mean±SE without *=measured values are significantly lower than the standards ($p<0.05$.

3.2 Metal pollution indices

Pollution indices have been applied in the current study to assess the overall quality of spring water samples, such as HPI, Cd, and HEI, based on the measured concentrations of the nominated metals (Cr, Fe, Mn, Zn, Cu, Pb, and Cd). The calculation of heavy metal pollution indices in water samples is the most commonly used technique for water quality testing because it demonstrates the combined impact of individual heavy metals on the overall water quality (Ameen et al., 2019; Reza and Singh, 2010). However, the summarized values of pollution indices (HPI, Cd, and HEI) used in the current study of water samples for each site are presented in Table 4. The values of the indices HPI, Cd, and HEI calculated for all spring water samples ranged from 11.32 to 36.56, 6.16 to -4.88, and 0.84 to 2.12, respectively (Table 4). Depending on the values of the HPI, all of the examined spring water samples were below the threshold for contamination index value of 100 and not polluted critically with respect to the heavy metals used in the present study. The results of the Cd measured for all the studied spring water samples belong to a low degree of contamination (Cd<1). The HEI index also showed that all the analyzed water samples belonged to the low-heavy metal class (HEI<10). Comparing pollution indices among different studied sites, it was observed that the values of all the used indices were greater at site SW8, followed by sites SW1 and SW2, whereas the lower values of these indices were observed at site SW6, followed by sites SW3 and SW9 (Table 4). Higher values of indices at the latter sites might be due to the elevated concentration of Pb detected in the sites as well as the higher unit weight (W_x) given to this parameter.

Comparing to previous studies, Issa and Alshatteri (2018) recorded lower HPI than the threshold value, ranging from 24.564 to 54.986 during their study on surface and groundwater in different sites of the Garmian Area, Kurdistan Region of Iraq. However, in some sites, they observed higher HEI than the critical value (HEI>2.45). The maximum value recorded in site 8 (Kalar drinking water project) was 8.441. The results of Jazza et al. (2022) study also recorded lower HPI than the critical polluted value, which was done in Misan Province of Iraq on samples collected from different sites of treating water for drinking. According to Khalid et al. (2020), the results are in agreement with the current research in terms of HPI and HEI, which were below the threshold values with the averages 54.442 and 0.221 respectively. The study was done in Erbil City, Kurdistan Region of Iraq, to evaluate the drinking water quality in schools selected randomly. In addition, more recent studies around the Kurdistan Region of Iraq (North of Iraq) on evaluating the quality of drinking water with heavy metal contaminations such as Salih et al. (2015), Salim et al. (2017), Majid et al. (2018), and Ameen et al. (2019) recorded the results lower than threshold values which agreed with the current study results.

Table 4. Summarized values of metal pollution indices in spring water samples for all the studied sites

Locations	HPI		Cd		HEI	
	Value	Critical pollution category	Value	Degree of pollution	Value	Degree of pollution
SW1	33.11	Not polluted	-5.19	Low	1.81	Low
SW2	27.54	Not polluted	-5.38	Low	1.62	Low
SW3	15.05	Not polluted	-5.94	Low	1.06	Low
SW4	22.00	Not polluted	-5.52	Low	1.48	Low
SW5	17.55	Not polluted	-6.08	Low	0.92	Low
SW6	11.32	Not polluted	-6.16	Low	0.84	Low
SW7	20.31	Not polluted	-5.67	Low	1.33	Low
SW8	36.56	Not polluted	-4.88	Low	2.12	Low
SW9	16.64	Not polluted	-5.91	Low	1.09	Low
SW10	17.82	Not polluted	-5.79	Low	1.21	Low

4. CONCLUSION

Based on the findings of the current research, it can be concluded that the values of heavy metals and pollution indices measured in spring water samples varied from region to region. The results of the metal pollution indices also concluded that the quality of the spring water samples collected in the present study is safe for drinking purposes, as all the calculated pollution indices were lower than critical levels of contamination according to metal pollution indices. Moreover, based on individual heavy metal parameters, the concentration of all the selected heavy metals detected in spring water samples was lower than the maximum permissible limits according to Iraqi standards, except for Pb in sites SW1, SW2, and SW8, where the concentration of Pb in these sites was higher than the permissible limits. The higher lead concentrations in these locations might be a sign of leakage of this metal from anthropogenic activity that should be controlled. Nevertheless, care should be taken by the people of this area when utilizing the water from these springs. Furthermore, it is highly recommended that water be treated or filtered before utilization to ensure safe drinking water.

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The Impact of Community Participation on Tourism Village Management and Sustainability: A Case Study in Wonokitri Village, Pasuruan

Alfi Muflikhah Lestari*, Moh Khusaini, Qomariyatus Sholihah, and Gatot Ciptadi

Graduate School, University Brawijaya, Malang, Indonesia

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*** Corresponding author:**
E-mail: alfilestari7@ub.ac.id

ABSTRACT

This research explores the impact of community participation in tourism village management –represented through motivation, opportunity and ability - and its implications for sustainability. Tourism villages, as a local community participation movement, play an important role in promoting economic, social, environmental, and cultural welfare. This study uses a quantitative approach with Partial Least Square-Structural Equation Modeling (PLS-SEM) analysis techniques and was conducted in Wonokitri Village, Tosari District, Pasuruan Regency, East Java, Indonesia. Data were collected through questionnaires from 100 local community respondents. The results showed that motivation, opportunity, and ability had a significant impact on tourism village management, with an r-square contribution of 61.4%. However, only tourism village management had a significant influence on sustainability, with an r-square contribution of 85.2%. These findings emphasize the importance of tourism village management through strategic planning, technology, innovation, and community involvement in creating tourism village sustainability. In addition, the main driving factors in effective management include motivation indicators such as awareness of preserving culture and the environment, as well as job and economic opportunities, and increased income. This research provides theoretical contributions by expanding the sustainability model based on tourism village management and providing operational guidelines for the government, managers, and local communities to encourage tourism villages as centers of sustainable economic growth, as well as cultural and environmental preservation.

1. INTRODUCTION

Tourism is a strategic sector that plays an important role in global economic growth, improving people's welfare, and preserving culture and the environment. In Indonesia, Law Number 10 of 2009 concerning Tourism states that tourism development aims to increase economic growth, create jobs, and reduce poverty. The National Tourism Development Master Plan (RIPPN) 2010-2025 also emphasizes the importance of community-based and sustainable tourism as a direction of development that is oriented towards economic equality, environmental preservation, and improving the quality of life of local communities (Kemenparekraf, 2021; Kemendagri, 2009). However, various studies show that the tourism industry is not free from negative impacts, such as environmental degradation and loss of local cultural values (Gonzalez et al., 2018; Peeters et al., 2018; Perkumienė and Pranskūnienė, 2019). Therefore, a responsible and community-based tourism development approach is a relevant solution to reduce these negative impacts (Hwang and Stewart, 2017; Lee and Jan, 2019; Okazaki, 2008).

Tourism villages are one form of sustainable tourism implementation, and they alsoprovide space for local communities to manage natural and cultural

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resources independently, while improving their economic welfare. In Indonesia, the development of tourism villages is supported by Law Number 6 of 2014 concerning Villages, which encourages initiatives, participation, and empowerment of village communities to explore local potential for shared welfare. Tourism villages have unique characteristics, such as the preservation of nature, traditions, and local culture, which can then be the main pillars in community-based economic development (Cawley and Gillmor, 2008; López-Sanz et al., 2021; Pasanchay and Schott, 2021). In addition, tourism villages play a role in motivating communities to protect the environment and preserve their cultural values (Cetin and Kalaycı, 2012; Gao et al., 2019).

One of a successful community-based tourism village is Wonokitri Village in Pasuruan Regency, East Java Province, Indonesia. This village developed the Edelweiss Park as a sustainable conservation tourism destination. This initiative involved a local farmer group, Hulun Hiyang, working together under the auspices of the Bromo Tengger Semeru National Park (TNBTS). In addition to preserving Edelweiss as a rare plant, this initiative also provides economic impacts for the community through the sale of souvenirs and participation in tourism activities. The local culture of the Tengger Tribe also supports the preservation of Edelweiss through its use in traditional rituals such as Yadnya Kasada and Karo, which are cultural tourism attractions (Ernawati et al., 2023). With TNBTS branding as “Land of Edelweiss”, community participation in the management of Edelweis Park shows a real contribution to the sustainability of the tourist village.

Community participation in managing tourism villages is influenced by three main factors, namely Motivation, Opportunity, and Ability, known as the MOA Model. Community motivation arises from awareness of the importance of preserving the environment and local culture, while opportunity is multi-faceted and generally created through economic benefits, employment, and increased welfare. Community ability in planning, management, and supervision is largely considered the key to the success of sustainable tourism development (Cawley and Gillmor, 2008; Gao et al., 2019; Lee and Jan, 2019; López-Sanz et al., 2021; Pasanchay and Schott, 2021; Utama and Trimurti, 2021). However, community participation is often influenced by differences in individual characteristics, behavior, and local context, so a more in-depth approach is needed in analyzing these factors (Hung et al., 2010; Jepson et al., 2014; Kunasekaran et al., 2022).

Previous studies on the MOA Model have mostly focused on the global context, while studies that specifically analyze the application of this model in the management of tourist villages in Indonesia are still limited. Therefore, this study analyzes the impact of community participation (based on the MOA Model) on the management of tourist villages and their sustainability in Wonokitri Village. By exploring the relationship between community motivation, opportunity, and ability in the context of Edelweis Park management, this study is expected to provide theoretical and practical contributions to the development of sustainable community-based tourism.

2. METHODOLOGY

2.1 Area of study

The research location in Wonokitri Village, Tosari District, Pasuruan Regency, East Java Province, Indonesia are presented in Figure 1. The village covers an area of approximately 1,290.294 hectares and has a population of 2,792 people. Wonokitri is known for its conservation-based tourism potential, represented by The Edelweiss Park. Conservation efforts in Wonokitri focus on Edelweiss plant protection, cultural heritage preservation, and economic empowerment through the development of sustainable tourism villages.

Figure 1. The Edelweiss Park, author documentation, 2024

2.2 Data collection and sample determination

This study employed a data collection method using a purposive sampling technique. Respondents were selected based on the criterion that they must be local residents holding a Population Identification

Card (KTP) of Wonokitri Village. This requirement ensured that only officially registered residents were included, as they were more likely to be directly involved by Tourism Village Management. Having a KTP indicates legal residency, which is relevant for understanding the participation, perceptions, and contributions of local people to the development of tourism in the village. Primary data were collected through questionnaires, which directly gathered information from respondents regarding their experiences, involvement, and perspectives on tourism management. Secondary data were obtained through literature studies, including reviews of relevant research, government reports, and other published sources that provided context and theoretical support for the study. The population size in this study is 2,792 people, which serves as the basis for determining the sample size using the Slovin formula. The population number was obtained from official village records and statistical data from the local government of Wonokitri Village. Based on the Slovin formula, the sample is $n = \frac{2792}{1+2792\ (10\%)^2}$, so that a minimum sample of 97 respondents is obtained. To increase representativeness, the number of samples was enlarged to 100 respondents. An error rate of 10% was chosen by considering the limitations of budget, time, and research resources.

2.3 Methods

Structural Equation Modeling (SEM) analysis with Smart Partial Least Square (PLS) version 4.0. The structural equation model tested was:

$$Y1 = \gamma 1 X1 + \gamma 2 X2 + \gamma 3 X3 + \zeta$$

$$Y2 = \gamma 4 X1 + \gamma 5 X2 + \gamma 6 X3 + \beta 1 Y1 + \zeta$$

Where: γ (Gamma) is The coefficient of influence of independent variables on dependent variables; β (Beta) is the coefficient of influence of the dependent variable on the latent variable; ζ (Zeta) is the model error; X1=motivation; X2=opportunity; X3=ability; Y1=tourism village management; Y2=sustainability.

These steps are designed to ensure that the research model is valid, reliable, and capable of providing statistically significant results, thereby supporting scientific contributions to sustainable tourism village management.

3. RESULTS AND DISCUSSION

3.1 Respondent characteristics results

The results of the respondent characteristics analysis (shown in Table 1) provide an important picture of the demographics of the community participating in the management of Wonokitri Tourism Village. Respondents consisted of 79% male and 21% female. This proportion reflects the dominance of men in the management of tourism village activities, which may be influenced by traditional roles in rural communities, where men are more active in economic and social activities (Ramaano, 2024). Respondent characteristics based on age range found particpants from 17 years to over 40 years. The majority of respondents are in the 31-35 age group, with 37%. The 26-30 age range is the second largest group (33%), followed by the 21-25 age range (16%). Respondents aged 36-40 years (7%) and over 40 (5%) also contributed, while the youngest group (17-20 years) only amounted to 2%. The 31-35 age group is in a productive phase with job stability and family responsibilities that allow individuals to participate in more community activities. Their emotional maturity, life experience, and economic stability also support involvement in managing tourist villages, thus becoming the main driving force in the community (Ma et al., 2022; Panić et al., 2024; Seraphin, 2024).

Most respondents had a high school/vocational education (84%). Respondents with a bachelor's degree reached 11%, while 3% had a junior high school education, and 2% had an elementary school education. The high proportion of high school graduates shows the relationship between the level of practical education and direct involvement in tourism village activities. A high school education background provides sufficient basic skills to participate in programs such as technical training or conservation activities. High school/vocational high school graduates also showed openness to further training, which can improve their technical skills and capacity in managing tourism villages sustainably (Gao et al., 2019; Utama and Trimurti, 2021). Most respondents had a monthly income in the range of IDR 2-3 million (41%). Respondents with an income of IDR 1-2 million reached 34%, while an income of IDR 3-4 million was 13%. The group with income less than IDR 1 million amounted to 5%, while income of IDR 4-5 million reached 4%, and more than IDR 5 million

Table 1. Respondent characteristics (Data processed, 2024)

Category	Sub-category	Frequency	Percentage (%)
Gender	Male	79	79
	Female	21	21
Age	17-20 years	2	2
	21-25 years	16	16
	26-30 years	33	33
	31-35 years	37	37
	36-40 years	7	7
	>40 years	5	5
Education level	Elementary School/Islamic Elementary School	2	2
	Junior High School/Islamic Junior High School	3	3
	High School/Vocational High School	84	84
	Bachelor's	11	11
Income per month (Indonesian Rupiah: IDR)	<1 million	5	5
	1-2 million	34	34
	2-3 million	41	41
	3-4 million	13	13
	4-5 million	4	4
	>5 million	3	3

only accoutned for 3%. Respondents with middle income (IDR 2-3 million) showed the potential to be actively involved in managing tourism villages because they were more open to opportunity that could improve their economic welfare (Suyatna et al., 2024). The involvement of this group is important because tourism village activities provide direct economic benefits such as increased income through small businesses or jobs related to tourism (Hariyadi et al., 2024; Jing et al., 2024; Suyatna et al., 2024). Overall, the profile of respondent characteristics shows that the group participating in the management of Wonokitri Tourism Village is dominated by individuals in the productive age group, with a practical educational background, and a middle-income level. The combination of these factors creates a community base that is responsive to economic opportunity, shows motivations for environmental conservation, and is open to cultural preservation. This is in line with the MOA Model theory which emphasizes the importance of motivation, opportunity, and ability in encouraging community participation (Utama and Trimurti, 2021).

3.2 Measurement model results

Measurement Model analysis aims to ensure that the instruments used in this study are valid and reliable. Validation was carried out through convergent and discriminant validity tests, as well as reliability using composite reliability and Cronbach's alpha values. The results of the measurement model analysis were processed using Smart PLS 4.0. The 20 measurement items in this study were developed based on a combination of previous research and contextual adjustments to fit the study's objectives. The development process included the following:

1. Literature review and theoretical basis:
   - Constructs and indicators were adapted from established studies on community-based tourism, sustainable tourism, and entrepreneurship to ensure validity and reliability.
2. Contextual adaptation:
   - Some indicators were directly adopted, while others were refined to match the specific characteristics of Wonokitri Village, ensuring relevance to the local tourism framework.
3. Expert validation and pilot testing:
   - The initial set of items was reviewed by tourism experts and tested with a small sample of local respondents to assess clarity, reliability, and applicability.
4. Finalization and model testing:
   - Factor analysis confirmed the construct validity, with most loading values exceeding 0.7, indicating strong measurement consistency.

This process ensured that the measurement items accurately capture motivation, opportunity, ability, tourism village management, and sustainability within the context of community-based tourism. The following Table 2 shows the outer loading values for each indicator in the research construct.

All indicators show a loading factor value ≥ 0.50 (Table 2 and Figure 2), which indicates that the indicators are valid in measuring the construct (Hair et al., 2019).

Table 2. Initial outer loading (Data processed with Smart PLS 4.0, 2024)

Construction	Code	Item	Loading
Motivation	M1	Awareness of preserving the environment	0.909
	M2	Awareness of preserving culture	0.866
	M3	Economic potential	0.766
	M4	There is cooperation and supporting facilities	0.716
Opportunity	OP1	There is natural and cultural potential	0.782
	OP2	There are economic opportunities	0.725
	OP3	There are job opportunities	0.743
	OP4	There is an increase in income	0.752
Ability	AB1	Have environmental management skills	0.771
	AB2	Have business management skills	0.823
	AB3	Have effective communication skills	0.826
	AB4	Have networking and partnership capabilities	0.736
Tourism village management	TVM1	Strategic planning	0.526
	TVM2	Marketing and promotion	0.773
	TVM3	Service and friendliness	0.863
	TVM4	Technology and innovation	0.887
Sustainability	S1	Environmental sustainability	0.562
	S2	Cultural sustainability	0.870
	S3	Economic welfare	0.761
	S4	Social welfare	0.848

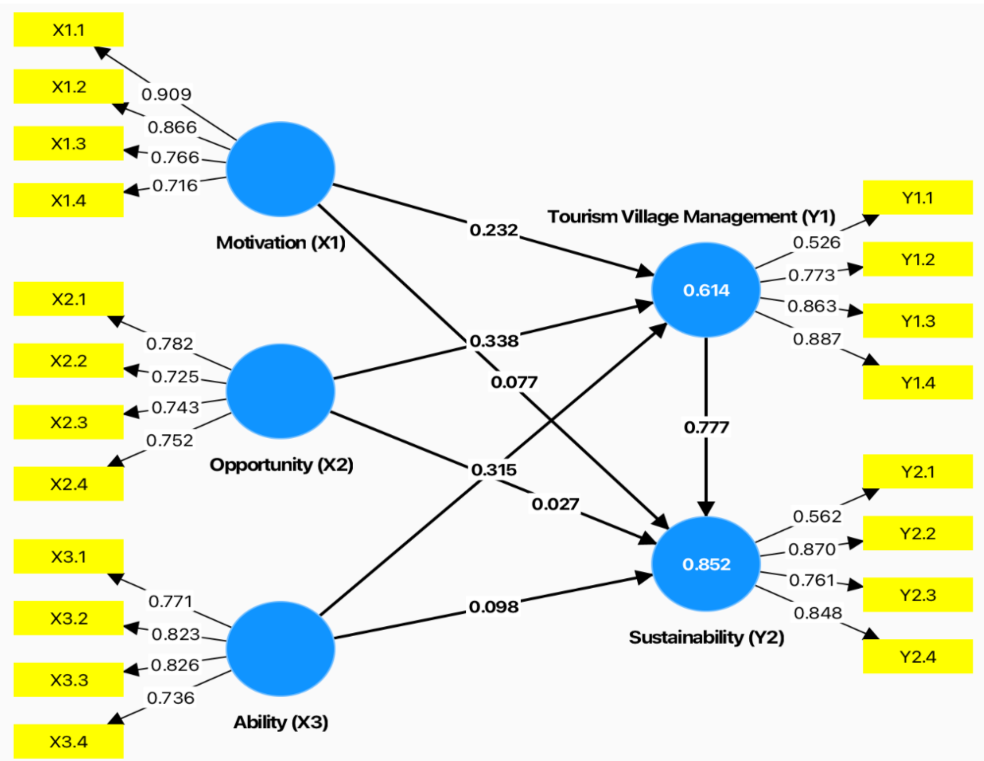

Figure 2. Path coefficients and r-square model, data processed with Smart PLS 4.0, 2024

As shown in Table 3, all constructs have composite reliability values ≥0.70 and Cronbach's alpha ≥0.70, indicating that the constructs are reliable (Hair et al., 2019). The AVE (Average Variance Extracted) value for all constructs is ≥0.50, which means that each construct is able to explain more than 50% of the variance of its indicators. Discriminant validity is tested by comparing the square root of AVE with the correlation between constructs. A higher AVE square root value compared to the correlation between constructs indicates good discriminant validity. These results support that the measured construct has clear discrimination from other constructs.

Table 3. Construct reliability and validity (Data processed with Smart PLS 4.0, 2024)

Construction	Cronbach's alpha	rho_A	Composite reliability	Average Variance Extracted (AVE)
Motivation	0.832	0.847	0.889	0.669
Opportunity	0.742	0.742	0.838	0.564
Ability	0.799	0.808	0.869	0.624
Tourism village management	0.764	0.792	0.854	0.602
Sustainability	0.761	0.787	0.850	0.593

Based on the results of the analysis, the measurement model used meets the criteria of validity and reliability. All indicators are valid with loading factor values above 0.50. The construct is reliable with composite reliability and Cronbach's alpha values above 0.70. AVE shows adequate convergent validity for all constructs. Discriminant validity is confirmed through a comparison of the square roots of AVE. These results indicate that the research instrument has met the criteria for use in further analysis, especially in testing the structural model.

3.3 Structural model results

Structural model testing is conducted to evaluate the relationship between constructs, significance values, and r-square of the research model. The r-square value is used to assess the contribution of independent variables to the dependent variable, thus providing an overview of the strength of the model in explaining data variability.

Based on Table 4, it can be seen that the r-square value for the variable of tourism village management is 0.614 which can be interpreted that the magnitude of the influence of the variables of motivation, opportunity and ability on the management of tourism village is 61.4% while the remaining 38.6% is explained by other variables outside the model. The r-square value for the sustainability variable is 0.852 which means that 85.2% of the variables of motivation, opportunity, ability, management of tourism village have a major influence on sustainability, while the remaining 14.8% is influenced by other factors outside the model.

Path relationships in the model structural which obtained with procedure *bootstrapping* have value which considered if the t-statistic value is greater than 1.96 (significance level 5%) or greater than 1.65 (significance level 10%) for each path relationship (Ghozali and Latan, 2015; Hair et al., 2019). Table 5 presents the statistical findings of this study.

Table 4. R-square value

	r-Square	r- Square Adjusted
Tourism Village Management	0.614	0.602
Sustainability	0.852	0.846

Table 5. Statistics results (Data processed with Smart PLS 4.0, 2024)

	Variables	Path coefficient	Sample mean	Standard deviation	t-statistics	p-values
H1	Motivation → Tourism Village Management	0.232	0.237	0.108	2.149	0.032
H2	Motivation → Sustainability	0.077	0.072	0.075	1.026	0.305

Table 5. Statistics results (Data processed with Smart PLS 4.0, 2024) (cont.)

	Variables	Path coefficient	Sample mean	Standard deviation	t-statistics	p-values
H3	Opportunity→ Tourism Village Management	0.338	0.344	0.117	2.897	0.004
H4	Opportunity→ Sustainability	0.232	0.031	0.060	0.452	0.651
H5	Ability → Tourism Village Management	0.315	0.311	0.130	2.418	0.016
H6	Ability →Sustainability	0.098	0.094	0.074	1.324	0.185
H7	Tourism Village Management→ Sustainability	0.777	0.781	0.076	10.161	0.000

Below are the results, as related to the original hypothesis and analysis.

H1 Motivation towards the management of tourism villages indicating that motivation has a positive and significant impact on tourism village management. The path coefficient of 0.232 indicates that increasing motivation will improve tourism village management.

H2 Motivation towards sustainability indicating that motivation does not have a significant impact on sustainability. The path coefficient of 0.077 indicates a weak and insignificant positive relationship.

H3 Opportunity in management of tourism villages indicating that opportunity has a positive and significant effect on tourism village management. The path coefficient of 0.338 indicates that greater opportunity can improve tourism village management.

H4 Opportunity to sustainability indicating that opportunity does not have a significant effect on sustainability. The path coefficient of 0.232 indicates an insignificant positive relationship.

H5 The ability to manage tourism villages indicating that ability has a positive and significant effect on tourism village management. The path coefficient of 0.315 indicates that increasing ability will improve tourism village management.

H6 Ability to sustainability indicating that ability does not have a significant effect on sustainability. The path coefficient of 0.098 indicates an insignificant positive relationship.

H7 Tourism village management on sustainability indicating that tourism village management has a positive and significant effect on sustainability. The path coefficient of 0.777 indicates a very strong relationship, where better tourism village management will strongly improve sustainability.

The structural model results, as presented in Figure 2, highlight the relationships between the independent and dependent variables. The findings confirm that motivation, opportunity, and ability significantly influence tourism village management (H1, H3, H5 are supported). Additionally, tourism village management strongly influences sustainability (H7 is highly significant with T=10.161, p=0.000). However, H2, H4, and H6 are not statistically significant, indicating that direct relationships between motivation, opportunity, and ability on sustainability require further exploration. Based on the structural model analysis, the relationship between variables shows that motivation, opportunity, and ability have a significant influence on tourism village management, while tourism village management plays a significant role in influencing sustainability. This indicates the importance of strengthening aspects of tourism village management to support environmental sustainability, culture, and socio-economic welfare.

3.4 Discussion

The results of this study provide important insights into the impact of motivation, opportunity, capability, tourism village management and sustainability. The following is an in-depth discussion of each research finding.

3.4.1 The influence of motivation on tourism village management

The results of the study indicate that motivation has a significant positive effect on the management of tourist villages (t-statistic=2.149; p-value=0.032). The original sample value of 0.232 indicates a fairly strong relationship. Motivation indicators, such as awareness of preserving the environment, culture, economic potential, and the existence of cooperation and supporting facilities, contribute significantly to the variables of tourist village management. Personal motivation, especially in awareness of preserving the environment, supports the literature which in turn showed that ecological factors play an important role in the success of community-based tourism management (Anaba et al., 2024; Darvishmotevali et al., 2024; Islam et al., 2024). Cultural awareness is also in line with research findings d'Angella and De Carlo (2024), Chinawat (2024), Cuong et al. (2024), which stated that community participation in preserving local culture improves the quality of tourist destination management. Economic potential and supporting facilities are also relevant to the study (Nguyen et al., 2023), confirming that economic opportunity does in fact motivate people to be more actively involved in managing tourist destinations. Thus, the success of tourist village management is highly dependent on understanding what motivates local people to participate. In addition, strong motivation tends to encourage sustainability within effective tourist village management. Figure 3 show the existence of facilities and information boards related to farmer groups managing the Edelweiss Park tourism area. The presence of these groups confirms that community motivation in preserving the environment and culture, as stated in previous studies (Anaba et al., 2024; Darvishmotevali et al., 2024; Islam et al., 2024), plays a crucial role in tourism village management. Their participation in maintaining the local ecosystem, such as the protected Edelweiss flower, demonstrates that environmental awareness is a key factor in managing tourism destinations.

3.4.2 The influence of motivation on sustainability

The results of the analysis show that motivation does not have a significant effect on sustainability (t-statistic=1.026; p-value=0.305). The original sample value of 0.077 indicates a weak relationship. Although motivation indicators such as awareness of preserving the environment and culture have high loading values, this does not directly affect sustainability. This finding is consistent with a study (Islam et al., 2024), which showed that although initial motivation is important, sustainability is more heavily influenced by structural factors, such as policy support and technical skills. In addition, Anaba et al. (2024) stated that individual motivation often fades if it is not balanced with a clear sustainability framework. In this context, it is important to strengthen external factors, such as training and institutional support, so that motivation can be translated into sustainable practices (Darvishmotevali et al., 2024). Although individual motivation is high - as seen in the involvement of community groups in managing Edelweiss Park (Figure 3) - it does not necessarily guarantee sustainability, especially when lacking structural support. This finding aligns with previous studies (Islam et al., 2024), which emphasized that sustainability is more influenced by policies and institutional support rather than solely by individual motivation.

3.4.3 The influence of opportunity on tourism village management

Opportunity has a significant positive effect on tourism village management (t-statistic=2.897; p-value=0.004). The original sample value of 0.338 indicates a fairly strong relationship. Indicators such as natural and cultural potential, economic opportunity, employment opportunity, and increased income contribute positively to tourism village management. The relationship of economic opportunity to tourism village management is supported by research (such as Tosun, 2006), which emphasizes that access to it increases community participation. Natural and cultural potential, meanwhile, are the main drivers of the success of community-based tourism management (Ali et al., 2022; Khanh and Phong, 2020; Thomas, 2022; Yılmaz and Anasori, 2022). In addition, increased income is in line with the results of a study (Snyman, 2014), which showed that direct economic benefits from tourism strengthen community involvement in management. Figures 3(b) and (d) highlights the utilization of natural potential and tourism infrastructure which in turn supports village tourism management. Facilities such as gazebos and plant-covered pedestrian paths confirm that natural and cultural potential are key drivers of community-based tourism success (Ali et al., 2022; Khanh and Phong, 2020). These types of infrastructure also support findings noting that access to economic opportunities increases community participation in tourism management (Tosun, 2006).

3.4.4 The Influence of Opportunity on Sustainability

Opportunity does not have a significant effect on sustainability (t-statistic=0.452; p-value=0.651). The original sample value of 0.232 indicates a weak relationship. This shows that although economic opportunity are available, they are not enough to guarantee long-term sustainability. This finding is consistent with the results of research (Gültekin and Osman, 2019; Vinodan and Manalel, 2019), which state that economic opportunity must be equipped with regulatory and monitoring mechanisms to achieve sustainability. In this context, community capacity development and integrated management policies are important factors (Diamantis, 2018; Panić et al., 2024; Rampheri and Dube, 2021; Saludadez et al., 2022). Although there are evident economic opportunity from managing Edelweiss Park, the figures do not depict a strong regulatory or monitoring system capable of ensuring long-term sustainability. This research consistent with Gültekin and Osman (2019), Vinodan and Manalel (2019), which states that economic opportunity must be accompanied by supporting policies to contribute to sustainability.

3.4.5 The influence of ability on tourism village management

Ability has a significant positive effect on tourism village management (t-statistic=2.418; p-value=0.016). The original sample value of 0.315 indicates a strong relationship. Ability indicators include environmental management, business management, effective communication, and networks and partnerships. Business management ability, in particular, supports the findings of Na thongkaew et al. (2024), Rivera et al. (2024) and Romero-Medina et al. (2024), which state that technical and managerial skills are important foundations in community-based destination management. In addition, effective communication skills are relevant (Hatma Indra Jaya et al., 2024; Kusumastuti et al., 2024; Rivera et al., 2024), which emphasizes the importance of communication in building partnerships between communities and external parties. Figure 3, showing the farmer group and village information board, indicates that community managerial abilities, such as environmental and tourism facility management, play an essential role in the success of tourism destinations. This supports the findings of Rivera et al. (2024), which highlighted that technical and managerial skills are fundamental in community-based destination management.

3.4.6 The influence of ability on sustainability

Ability has no significant effect on sustainability (t-statistic=1.324; p-value=0.185). The original sample value of 0.098 indicates a weak relationship. This shows that sustainability is not only determined by technical or managerial ability, but also by external factors, such as policy support and financial resources. Research Baloch et al. (2023), Hall (2020), Jaafar et al. (2021) shows that sustainability requires a holistic approach that includes continuing education and the formation of global networks. Therefore, capacity building must be complemented with broader resources and support. Sustainability is not solely determined by technical ability but also by external factors such as policy support and financial resources (Baloch et al., 2023; Hall, 2020).

3.4.7 The influence of tourism village management on sustainability

Tourism village management has a significant positive influence on sustainability (t-statistic=10.161; p-value=0.000). The original sample value of 0.777 indicates a very strong relationship. Management indicators, such as strategic planning, marketing, service, and innovation and technology, all make important contributions to sustainability. This finding supports the literature Abreu et al. (2024), Hariyadi et al. (2024), Rivera et al. (2024), Walkowski (2019), Dilshod et al. (2024), Khusaini et al. (2024), which emphasizes that strategic management is key to ensuring the sustainability of community-based tourism. In addition, research on good service and hospitality support (Hariyanto et al., 2020; Nugroho et al., 2021) shows that tourist satisfaction improves the economic sustainability of a destination. Well-organized tourism facilities (as in Figure 3) further indicate that proper management positively impacts the attractiveness of tourism as well as economic sustainability. This finding is in line with Abreu et al. (2024) and Hariyadi et al. (2024), who emphasized that strategic planning and high-quality services contribute to the sustainability of community-based tourism.

(a) The name board for the Edelweiss Park tourist attraction at the entrance area displays the garden landscape and ornamental plants.

(b) The gazebo area in the tourist site, situated in a foggy environment with natural architectural design.

(c) The name board of the “Hulun Hiyang” farmer group in Wonokitri Village, part of tourism village management in Bromo Tengger Semeru National Park area.

(d) The path with a net tunnel, on both sides of which are cultivated edelweiss seedlings and ornamental plants.

Figure 3. Author documentation, 2024

Overall, the results of this study provide significant contributions to the literature on tourism village management and sustainability, while also serving as a strong foundation for developing strategic policies in the future. The study highlights the importance of community participation, motivation, opportunity, and ability in fostering a sustainable tourism village ecosystem. These findings not only enrich theoretical discussions but also provide practical guidelines for implementation at different stages. To ensure effective implementation of these findings, operational steps can be taken as follows.

(1) Strengthening community capacity and infrastructure: The primary focus in the short term is to enhance community capacity and improve essential infrastructure. Education and training related to environmental conservation, cultural preservation, and business management increase community awareness and skills in managing tourism villages. Additionally, identifying local opportunities, including sources of natural, cultural, and economic potential, the first step in developing tourism villages based on local wisdom. Improving basic infrastructure, such as road access, waste management, and environmental cleanliness, is also crucial for enhancing tourist comfort and the overall attractiveness of tourism villages.

(2) Application of technology and strengthening partnerships: The focus in this phase shifts to leveraging technology and fostering innovation. Developing digital platforms for promoting tourism villages and integrating environmentally friendly technology in waste management and renewable energy can enhance operational efficiency and sustainability. Strengthening collaborations with stakeholders, including business entities, government bodies, and academic institutions, also establishes a data-driven and research-based tourism village ecosystem. Additionally, strategic marketing and

branding efforts, such as promotional campaigns and unique local experience-based tourism packages, help expand the tourism village's appeal to domestic and international markets.

(3) Sustainable Business Models and Youth Empowerment: In the long term, the sustainability of tourism villages relies on the establishment of sustainable business models and the empowerment of the younger generation. Encouraging entrepreneurship among local youth, fostering innovation in tourism products, and ensuring effective monitoring and evaluation mechanisms helps maintain positive social, economic, and environmental impacts. These steps also ensure that tourism villages continue to develop dynamically, adapting to emerging challenges while preserving their cultural and ecological integrity.

By integrating these phased strategies, this study offers a practical framework for promoting sustainable community-based tourism. The structured approach facilitates the adoption of these findings in different contexts, ensuring that tourism villages remain economically viable, socially inclusive, and environmentally sustainable for the long run.

4. CONCLUSION

The conclusion of the results of this study shows that motivation, opportunity, and ability play an important role in the success of tourism village management and sustainability. Community motivation has been shown to have a positive influence on tourism village management, especially those related to awareness of preserving the environment, culture, and economic potential. However, motivation does not have a significant effect on sustainability, which is more influenced by structural factors and supporting policies. Opportunities, such as natural and cultural potential and economic access, have a positive effect on tourism village management, although these factors do not guarantee long-term sustainability without clear regulatory support. The ability to manage and communicate effectively also shows a significant influence on tourism village management, but does not directly affect sustainability, which requires a holistic approach with broader policy and resource support. Good tourism village management, including strategic planning, marketing, service, and innovation technology, has been shown to have a very strong influence on sustainability. Overall, the results of this study emphasize the importance of community-based management, application of technology and innovation, and preservation of culture and the environment as keys to the success of sustainable tourism villages. Consistent and collaborative policy implementation also ensures that tourism villages are a model of sustainable development with a positive impact on local communities.

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AUTHOR CONTRIBUTIONS

- Lestari AM (Main Author) designed the methodology, conducted the experiments, processed the data, and wrote the main draft.
- Khusaini M (Supervisor) the main supervisor who provided conceptual guidance, reviewed the manuscript, and approved the publication.
- Sholihah Q (Supervisor) guided the analysis process and critically reviewed the article.
- Ciptadi G (Supervisor) reviewed the article and provided critical input.

DECLARATION OF COMPETING INTEREST

No potential conflict of interest was reported by the authors.

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Enhancing the Geotechnical Behavior of Expansive Soil-Coconut Fiber Mixtures with Various Agricultural Ash Waste: A Comparative Study

Anita Widianti[1*], Muhammad Hatta[1], Anita Rahmawati[1], and Dian Eksana Wibowo[2]

[1]*Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Yogyakarta, Indonesia*
[2]*Faculty of Engineering, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia*

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*** Corresponding author:**
E-mail: anitawidianti@umy.ac.id

ABSTRACT

Expansive soil is classified as problematic because it has a high plasticity index, high swelling shrinkage due to water content fluctuations, and low bearing capacity. This research focused on stabilizing it with coconut fiber and three different types of agricultural ash: sugarcane bagasse ash (SBA), rice husk ash (RHA), and coir-wood ash (CWA). Coconut fiber made up 0.75% of the material and acted as reinforcement. The three types of ash were used in varying proportions (0%, 2%, 4%, 6%, 8%, and 10% of the mixture's total weight) to reduce swelling shrinkage and enhance bearing capacity through cementation. The mixture was compacted to the soil's Maximum Dry Density and Optimum Moisture Content. Then, the specimens were cured for different durations. The California Bearing Ratio (CBR) testing specimens were cured for 7 days and 14 days, while those for Unconfined Compressive Strength (UCS) testing were cured for 14 days and 28 days. All testing complied with ASTM standards. The results showed that strengthening coconut fiber and stabilizing with three different types of ash in expansive soil increased CBR and UCS values and significantly reduced swelling. These improvements were directly proportional to increases in the ash content and curing time. Optimal outcomes were achieved with all three types of ash at a similar content level, ranging from 8% to 10%. For specimens cured for 14 days, CBR values increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil. For specimens cured for 28 days, UCS values increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil. A swelling value of 0% was achieved in the soil-coconut fiber mixture stabilized with a 10% concentration of RHA/SBA/CWA. These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling. By utilizing agricultural waste for expansive soil stabilization, significant benefits can be achieved for the government, industry, and local communities. Developing technical guidelines for using agricultural waste as a soil stabilizer will greatly facilitate its practical application in the field.

HIGHLIGHTS

This study compares three agricultural ashes from industrial waste widely available in Indonesia as stabilization materials for expansive soil-coconut fiber mixtures.

1. INTRODUCTION

Expansive soil is problematic, characterized by a high plasticity index and swelling shrinkage due to water content fluctuations. This soil swells during the rainy season and shrinks during the dry season. Consequently, structures built on such soil are prone

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to damage (Ikeagwuani, 2019). Technological advances have led to the development of various techniques for improving expansive soil, including mechanical and chemical stabilization methods (Rani and Chandra, 2021; Tamiru et al., 2025). Mechanical stabilization improves soil's mechanical properties by incorporating highly tensile materials. Chemical stabilization, on the other hand, involves adding specific chemicals to the soil, which then undergo a chemical process that produces new materials with enhanced physical and mechanical behavior. Commonly used chemicals include cement and lime, which have proven effective in improving soil quality (Al-Kalili et al., 2022). Anburuvel (2024) states that the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of soils (excluding peat), stabilized with either cement or lime at a 5% content, can reach values of 30-60% and 700-1,500 kPa, respectively. These values depend on the soil type, degree of compaction, and curing conditions. However, using cement and lime is costly and contributes to global warming due to substantial carbon dioxide emissions (Gowthaman et al., 2018; Sekar and Kandasamy, 2019). The production of one ton of Portland clinker cement releases approximately one ton of CO_2 into the atmosphere. Additionally, Portland cement is responsible for about 7% of global CO_2 emissions, contributing to the depletion of the ozone layer (Chakraborty and Roy, 2016). Indeed, the principles of sustainable development must always be considered. Environmental protection should be prioritized throughout the planning, implementation, and maintenance of infrastructure projects. Therefore, it is essential to consider environmental sustainability when employing soil stabilization materials. Utilizing recycled materials can help reduce costs and promote sustainable development (Darwis, 2017).

Using recycled materials or waste derived from natural sources has been promoted as an alternative to traditional soil-stabilizing materials. These abundant natural substances are cost-effective, environmentally friendly, and biodegradable (Alqaisi et al., 2020). Various types of agricultural waste are effective as soil-stabilizing materials (Ishola et al., 2019). Widianti et al. (2022) studied the contribution of coconut fiber waste to the mechanical characteristics of soft clay. Introducing coconut fiber into the soil randomly could improve the soil's shear, bearing, and tensile strength. The percentage of fibers with high tensile strength ranged from 0.6% to 0.8%, but it did not reduce water-induced swelling. Therefore, additional research was conducted by combining coconut fiber with agricultural ash waste to create a coir-wood ash (CWA) mixture. This combination has proven highly effective in stabilizing soft clay. When CWA is added to the soil, it can eliminate swelling and significantly improve the values of CBR, UCS, tensile strength, elastic modulus, and shear strength by up to 534%, 349%, 105%, 824%, and 210%, respectively (Widianti et al., 2023; Widianti et al., 2024).

Food and Agriculture Organization of the United Nations (2022) shows that Indonesia is the world's largest coconut producer with total production of 17.19 million tons, the world's 4th largest rice producer with total production of 54.75 million tons, and the world's 8th largest sugar producer with total production of 32.40 million tons. The waste generated from coconuts, rice, and sugarcane is 35%, 15%, and 90%, respectively (Trikarlina et al., 2018; Asfar et al., 2021; Sudibandriyo and Lydia, 2011). This waste is commonly used as a fuel source in various industries, producing ash waste. Typically, this ash waste is discarded, leading to environmental disruption (Al-Ghouti et al., 2021), even though sugarcane bagasse ash (SBA) and rice husk ash (RHA) have the potential to be soil stabilizers (Yadav et al., 2017; Daarol et al., 2023). RHA and SBA are characterized by their notable SiO_2, Al_2O_3, and Fe_2O_3 content. Silica, a primary constituent in cement manufacturing, exhibits pozzolanic characteristics, resulting in increased hardness over time when reacted with Al_2O_3 and CaO in clay soil. Apart from that, the ash grains' very loose structure makes mixing evenly with clay soil easy. Although extensive research has been conducted, the conventional approach involves combining RHA and SBA with lime or cement. Numerous experiments have been conducted, mostly involving mixtures of RHA or SBA with lime or cement (Dang et al., 2016; Eliaslankaran et al., 2021; Gandhi and Shukla, 2021; Pushpakumara and Mendis, 2022; Raja et al., 2022; Barwar et al., 2022).

Based on the studies, it is necessary to investigate the combination of reinforcing with coconut fiber and chemically stabilizing with RHA and SBA, both industrial wastes. The findings were compared with the results from Widianti et al. (2023), who used coir-wood ash (CWA) to evaluate its effectiveness and impact on expansive soil's bearing capacity and swelling.

2. METHODOLOGY

2.1 Materials

2.1.1 Soil

The physical and mechanical properties of the soil used in this investigation were analyzed by Widianti et al. (2020) according to ASTM. The analysis showed that the soil composition consisted of sand (13.36%), silt (70.58%), and clay (16.68%). Additionally, the soil exhibited a liquid limit of 89.91%, a plastic limit of 38.86%, and a shrinkage limit of 16.33%. According to AASHTO, the soil was categorized as clay (A-7-5), while USCS identified it as clay with high plasticity (CH).

Soil with a liquid limit value of >60% and a plasticity index of >35% is categorized as expansive clay with high swelling potential (National Standardization Agency, 2018). The level of potential for clay to swell can also be analyzed using the plasticity index value and the clay percentage (Skempton, 1953). This data was used to calculate the activity value (A), and a value of 3.18 was obtained. According to Das and Sobhan (2016), soil with an A value of >1.25 is categorized as active clay. According to Bowles (1992), soil with an A value between 1 and 7 is categorized as clay, containing clay minerals called montmorillonite. The unstabilized soil produced a CBR value of 1.25%, which Bowles (1992) classifies as very poor. The unconfined compressive strength (UCS) value was determined to be 41.70 kPa. Das and Sobhan (2016) classifies soil with UCS ranging from 25 to 50 kPa as soft soil.

The soil had granules passing through sieve No. 4 (for the CBR test) and sieve No. 40 (for the UCS test).

2.1.2 Coconut fiber

The coconut fiber waste exhibited tensile strength ranging from 108.6 MPa to 238.6 MPa and strain ranging from 28.70% to 34.25%. The fiber was separated from the husk and then dried in an oven at 100°C. Afterward, the fiber was cut into pieces of approximately 5 cm in length.

2.1.3 Agricultural ash

This study utilized three different types of agricultural ash: sugarcane bagasse ash (SBA), rice husk ash (RHA), and coir-wood ash (CWA). SBA is the residue from sugarcane bagasse after extraction and is used as a fuel source in sugar mills (Figure 1(a)). RHA, derived from rice husks, is used as a fuel source in brick and tile manufacturing (Figure 1(b)). CWA is a by-product of a mixture of coconut fiber and wood used as a fuel in the tofu production industry (Figure 1(c)). The combustion process carried out is categorized as uncontrolled burning. The selected ash sample was gray, consisting of grains that passed a 200-mesh sieve. Table 1 presents the SBA, RHA, and CWA oxide composition test results from the GetIn-CICERO Laboratory, Department of Geological Engineering, Universitas Gadjah Mada, Indonesia. Testing was conducted using a Spectro Xepos XRF.

The oxide composition test results for all agricultural waste indicate that SBA, RHA, and CWA are excellent pozzolanic materials due to their high combined proportions of silica (SiO_2), iron oxide (Fe_2O_3), and alumina (Al_2O_3). According to ASTM C618-22 (ASTM International, 2022), both SBA and RHA fall under Class F because they meet the criteria of having a minimum of 50% for the combined content of SiO_2, Al_2O_3, and Fe_2O_3, a maximum of 18% for CaO, and a maximum of 5% for SO_3. Materials in Class F are known for their pozzolanic properties. Conversely, CWA does not fit into Class N, F, or C because its SiO_2, Al_2O_3, and Fe_2O_3 content is only 37.42%, below the required content of 50%. However, CWA does have a high CaO content of 27.58%, exceeding the 18% limit. This high CaO content gives it cementitious properties.

Figure 1. Types of agricultural ashes (a) sugarcane bagasse ash, (b) rice husk ash, (c) coir-wood ash

Table 1. Test results for the oxide composition of SBA, RHA, and CWA

Component		Result		
		Sugarcane bagasse ash (SBA)	Rice husk ash (RHA)	Coir-wood ash (CWA) (Widianti et al., 2023)
SiO_2	Silicon oxide	81.12%	85.89%	33.52%
Al_2O_3	Aluminium oxide	6.18%	2.65%	1.93%
Fe_2O_3	Iron oxide	5.36%	2.27%	1.97%
CaO	Calcium oxide	4.29%	5.52%	27.58%
MgO	Magnesium oxide	1.84%	1.81%	4.96%
P_2O_5	Phosphorus oxide	1.33%	2.33%	3.95%
K_2O	Potassium oxide	3.62%	3.52%	15.23%
SO_3	Sulfideoxide	0.94%	1.49%	3.67%
Na_2O	Sodium oxide	0.45%	0.41%	1.21%

2.2 Laboratory testing

Soaked CBR and UCS tests were performed at the Geotechnical Laboratory of Universitas Muhammadiyah Yogyakarta, Indonesia. Table 2 lists the specimen dimensions and the standards implemented for the tests.

The coconut fiber content was 0.75% of the total mix weight. This value is based on previous studies by Widianti et al. (2020) and Widianti et al. (2021). Different ash concentrations were added to the mixtures, with ash content at 0%, 2%, 4%, 6%, 8%, and 10%. This variation refers to the research by Widianti et al. (2023). The amount of water added during mixing was based on the Optimum Moisture Content value. The mixture was compacted to the soil's Maximum Dry Density.Then, the specimens were cured for a different length of time. The specimens for CBR testing were cured for 7 days and 14 days, while those for UCS testing were cured for 14 days and 28 days. This curing time aligns with the guidelines specified by The Ministry of Public Works of the Republic of Indonesia (2007). Table 3 presents the detailed design of the specimen variations. Figure 2 shows the laboratory CBR test performed on the soaked samples. The soaked CBR testing aims to simulate rain or the most severe conditions in the field, resulting in the addition of water to the soil.

Table 2. Specimen dimensions and testing standards

Test type	Specimen dimension		Testing standard
	Height (cm)	Diameter (cm)	
Soaked CBR and swelling	17.8	15.3	ASTM D1883-07e2 (ASTM International, 2007)
Unconfined compressive strength (UCS)	7.2	3.6	ASTM D2166-06 (ASTM International, 2016)

Table 3. The design of specimen variations

Specimen variation		Sugarcane bagasse ash (SBA)		Rice husk ash (RHA)		Coir-wood ash (CWA) (Widianti et al., 2023)	
		Soaked CBR	UCS	Soaked CBR	UCS	Soaked CBR	UCS
Soil + 0.75% coconut fiber + varying types and content of ash	0%	X	•	X	•	X	•
	2%	X	•	X	•	X	•
	4%	X	•	X	•	X	•
	6%	X	•	X	•	X	•
	8%	X	•	X	•	X	•
	10%	X	•	X	•	X	•

Description: X: 7 and 14 days of curing; •: 14 and 28 days of curing

3. RESULTS AND DISCUSSION

3.1 Effects of the type and content of ash on the CBR value

Figure 3 illustrates CBR values after soaking for each specimen reinforced with 0.75% coconut fiber; stabilized with varying RHA, SBA, and CWA contents, and cured for 7 and 14 days. For CWA testing results, the data is obtained from Widianti et al. (2023).

The unstabilized soil acquired a soaked CBR value of 1.25%, falling to the extremely low-quality soil, as categorized by Bowles (1992). Figure 3 shows that after being reinforced with coconut fiber, the CBR value increased significantly to 2.12% (an increase of 0.7 times compared to the unstabilized soil). This improvement in the strength of expansive soil reinforced with coconut fiber is attributed to the interactions and interlocking between the fibers and between the fibers and soil particles within the compacted specimens. The rough surface of the fibers enhances friction between particles and helps bind soil particles together (Dang et al., 2016). These bonds transfer stress from the soil to the fibers, which possess high tensile strength (Singh and Bagra, 2013).

(a) (b) (c)

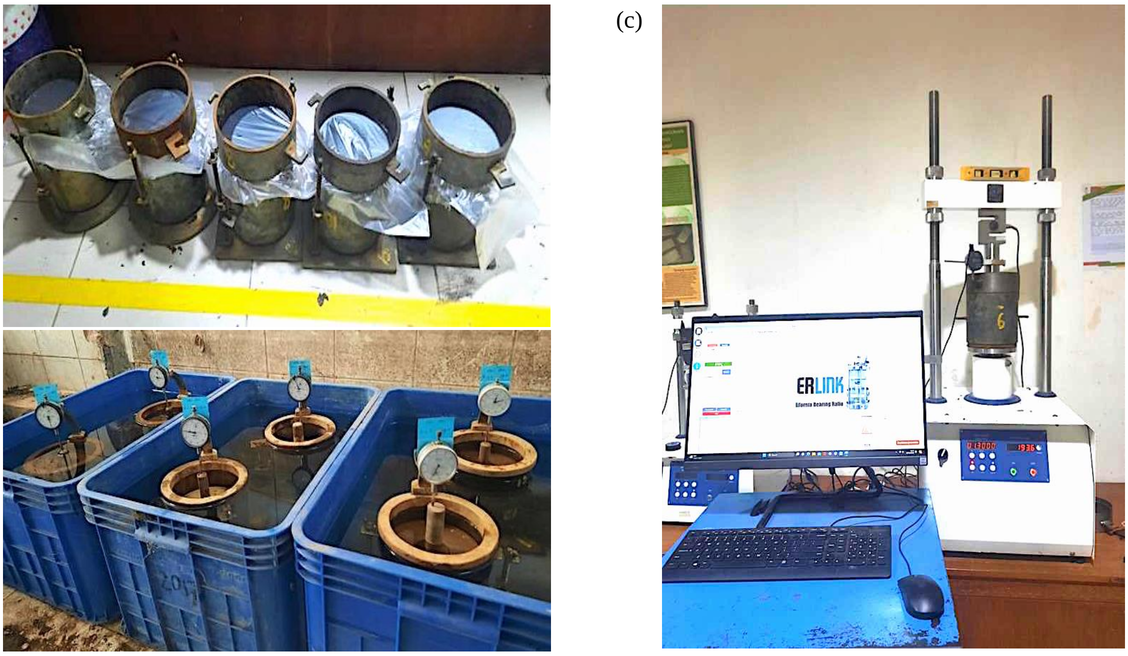


Figure 2. Soaked CBR testing: (a) curing for 7 and 14 days, (b) soaking for 4 days, (c) CBR testing

(a)

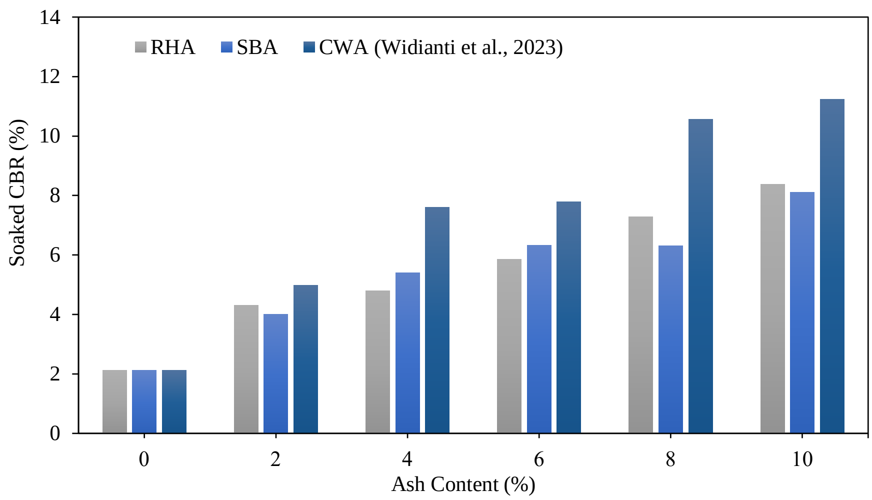


Figure 3. Effects of the type and content of ash on the CBR value of mixed soil with varying curing durations: (a) 7 days, (b) 14 days

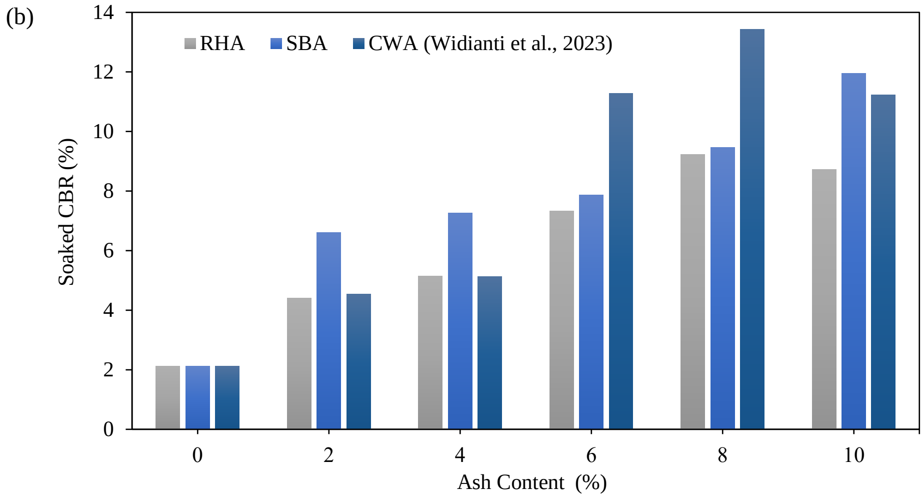


Figure 3. Effects of the type and content of ash on the CBR value of mixed soil with varying curing durations: (a) 7 days, (b) 14 days (cont.)

Figure 3 also illustrates the trend of increasing soaked CBR values upon stabilization with three different types of agricultural ash. A higher ash content and a longer curing duration resulted in higher CBR values, with 8% to 10% ash content leading to the highest values. For specimens cured for 14 days, the CBR value increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil. According to Bowles (1992), soil with a CBR value ranging from 7% to 20% is considered fair soil.

SBA and RHA have high silica (SiO_2) and alumina (Al_2O_3) content, measuring 87.30% and 88.54%, respectively. This presence of silica and alumina makes them good pozzolanic materials. With the help of water, silica and alumina will react with calcium oxide (CaO) present in the soil and ash to produce calcium silicate hydrate and calcium aluminate. These compounds are crucial parameters for cementitious behavior (Yadav et al., 2017).

Soil stabilized with CWA resulted in a higher soaked CBR value. Its silica and alumina content is only 37.42% (below 50%), but its calcium oxide (CaO) content is high, namely 27.58%. This material will function as cementitious with self-cementing properties that can subsequently harden.

As Darwis (2017) outlined, the reaction between silica-alumina and CaO is a two-stage process over time. The first stage, known as the immediate reaction, occurs within hours. Mixing CaO with water results in the formation of hydrated lime ($Ca(OH)_2$), which serves as the precursor for cementitious compound development and consequently reduces the water content in the soil. The reaction is shown below:

$$CaO + H_2O \dashrightarrow Ca(OH)_2 + heat$$

After this initial reaction, flocculation and/or agglomeration of clay particles occurs, leading to a coarser texture and decreased plasticity. This condition enhances the soil matrix's shear strength and improves the soil's workability. The second phase involves medium and long-term reactions, spanning days, weeks, months, or years. The reaction characteristic of this phase is the pozzolanic reaction, shown below:

$$Ca(OH)_2 + H_2O + SiO_2 \ \& \ Al_2O_3 \dashrightarrow C\text{-}S\text{-}H \ \& \ C\text{-}A\text{-}H$$

(cementitious materials)

Through the pozzolanic reaction, silica and alumina react with calcium to create new cementitious compounds, specifically calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). This process transforms the very fine clay particles, causing them to crystallize into relatively larger and coarser particles. As a result, the contact area between grains grows, and the bonding between them strengthens, significantly improving the bearing capacity.

3.2 Effects of the type and content of ash on the swelling behavior

The swelling value was assessed through the soaked CBR test. Figure 4 illustrates the swelling values for each specimen reinforced with 0.75% coconut fiber and stabilized with varying RHA, SBA, and CWA contents after 7-day and 14-day curing durations.

Figure 4 illustrates agricultural ash waste's significant effectiveness in reducing clay's swelling potential. The swelling value decreased as the ash content increased, and the curing duration was extended. The swelling value of expansive clay was 3.25% when reinforced with coconut fiber. Adding RHA and SBA as much as 2% resulted in a considerable reduction in the swelling value, which decreased by 79% of the initial value after a curing duration of seven days and further by 91% after 14 days. The reduction in the swelling value becomes more pronounced at higher ash percentages, reaching nearly 0% within the 8-10% ash content range. In contrast, soil reinforced with coconut fiber and stabilized with CWA showed a progressive reduction in the swelling value as the CWA concentration increased. When the concentration of CWA was raised by 2% and 4%, the swelling value decreased by 33.2% and 56.6% after seven days of curing and by 36.3% and 58.5% after 14 days of curing, respectively. At a 6% CWA content, the swelling was effectively eliminated.

The observed reduction in the swelling value is attributed to the flocculation and agglomeration of soil particles, which reduce the surface area of clay grains and make the soil less plastic and coarser. Basma and Tuncer (1991) noted that adding additives decreases the soil's swelling potential from high to low, with increased ash content and curing duration contributing to changes in the soil's physical properties. The pore spaces within the stabilized soil become significantly smaller than those in the unstabilized soil (Ikeagwuani, 2019). Based on the Scanning Electron Microscopy (SEM) analysis, unstabilized soil exhibits a loose particle arrangement, evidenced by many pores (Figure 5(a)). In contrast, the soil, fiber, and ash mixture displays a denser and more compact microstructure. The number of pore voids is substantially reduced (Figure 5(b)).

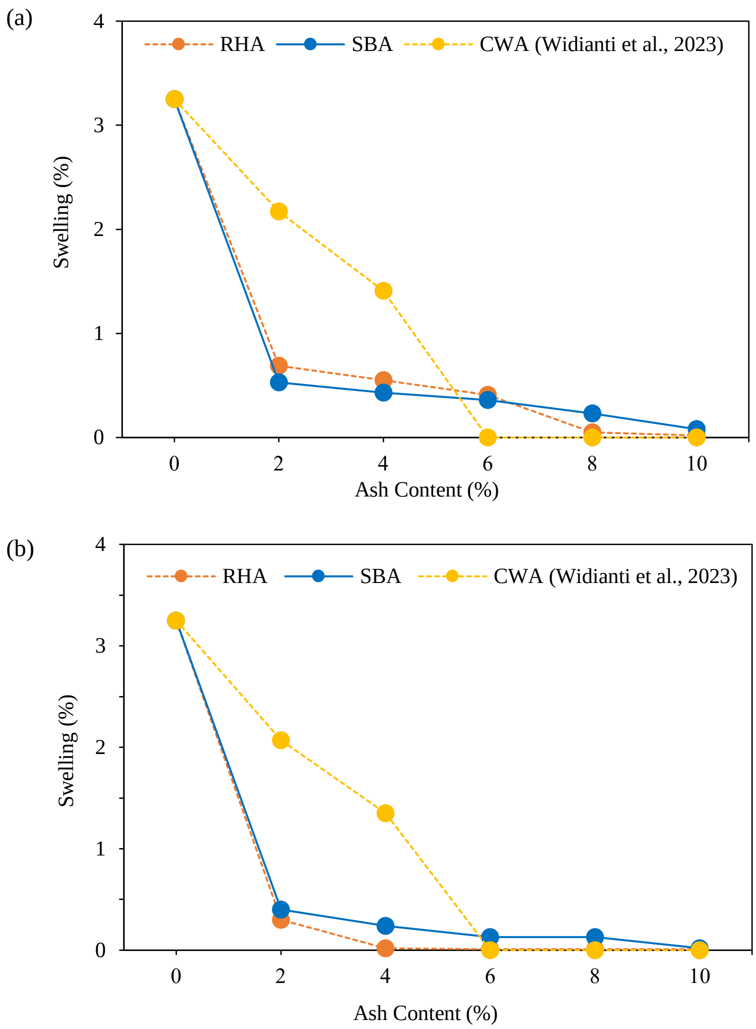
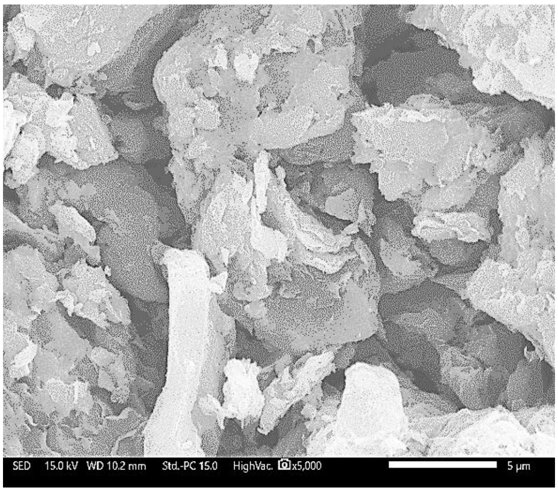


Figure 4. Effects of the type and content of ash on the swelling behavior of mixed soil with varying curing durations: (a) 7 days, (b) 14 days

(a)


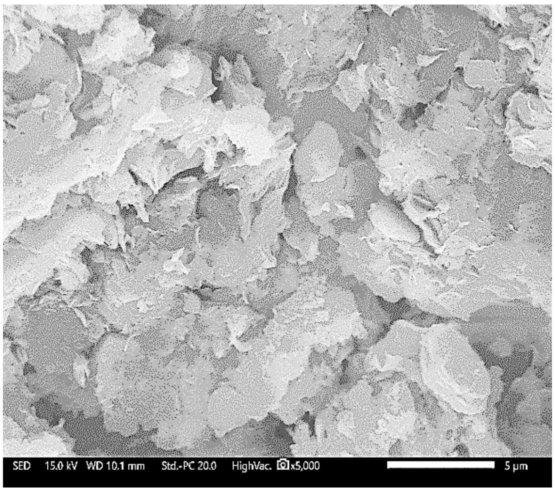
(b)


Figure 5. The microstructure of expansive soil (a) unstabilized, (b) stabilized

3.3 Effects of the type and content of ash on the UCS value

In addition to the soaked CBR test, the impact of ash was also assessed through Unconfined Compressive Strength (UCS) measurements. Figure 6 shows the UCS values for each specimen reinforced with 0.75% coconut fiber and stabilized with varying RHA, SBA, and CWA contents. The curing durations for these specimens were either 14 days or 28 days.

As shown in Figure 6, the UCS values display a consistent trend across all types of ash. The UCS value increased significantly with higher ash content and longer curing duration. This increase is attributed to the cementation between the soil and the ash, which forms agglomerates and enhances the bonding between individual soil particles. The existing voids in the soil were partially filled with a more rigid cementitious material, leading to more excellent compression resistance and reduced water permeability. The highest UCS value was recorded for soil with 0.75% coconut fiber and 8% ash content. However, at a 10% ash content, the UCS value decreased. The soil particles become larger at this concentration, and reducing soil density (Herman et al., 2021). Despite this decrease, the UCS value remains significantly higher than the soil reinforced with coconut fiber alone (Chakraborty and Roy, 2016; Yusuf and Zava, 2019).

(a)


Figure 6. Effects of the type and content of ash on the UCS value of soil mixtures with varying curing durations: (a) 14 days, (b) 28 days

Figure 6. Effects of the type and content of ash on the UCS value of soil mixtures with varying curing durations: (a) 14 days, (b) 28 days (cont.)

The classification of clay consistency was determined based on the UCS value (Das and Sobhan, 2016). The unstabilized clay soil had a UCS value of 41.70 kPa, which classified it as soft soil. Incorporating 0.75% coir fibers increased the UCS value to 98.10 kPa, representing an improvement of 1.4 times compared to the unstabilized soil, thus categorizing the soil as medium soil. Stabilization involved combining coir fibers with ash. The soil exhibited high rigidity with ash content ranging from 2% to 6% and showed significant hardness with ash content between 8% and 10%. For specimens cured for 28 days, the UCS value increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil. Hardiyatmo (2014) states that soil is hard if its UCS value exceeds 400 kPa, indicating an exceptionally high load-bearing capacity.

While the soaked CBR value was higher for soil stabilized with CWA, this treatment resulted in the lowest UCS value. These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling.

4. CONCLUSION

The study led to the following conclusions:

1) Strengthening coconut fiber and stabilizing with three different types of ash increased CBR and UCS values and significantly reduced the swelling of expansive soil. These improvements were directly proportional to increases in the ash content and curing duration.

2) Optimal outcomes were achieved with all three types of ash at similar contents, ranging from 8% to 10%.

3) For specimens cured for 14 days, CBR values increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil.

4) A swelling value of 0% was achieved in the soil-coconut fiber mixture stabilized with a 10% concentration of RHA/SBA/CWA.

5) For specimens cured for 28 days, UCS values increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil.

6) These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling.

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AUTHORS CONTRIBUTION

Conceptualization, Methodology, Validation, Supervision, and Writing Original Draft Preparation, Anita Widianti; Experimental run, Data Collection, and Formal Analysis, Muhammad Hatta; Visualization, Review and Editing, Anita Rahmawati and Dian Eksana Wibowo.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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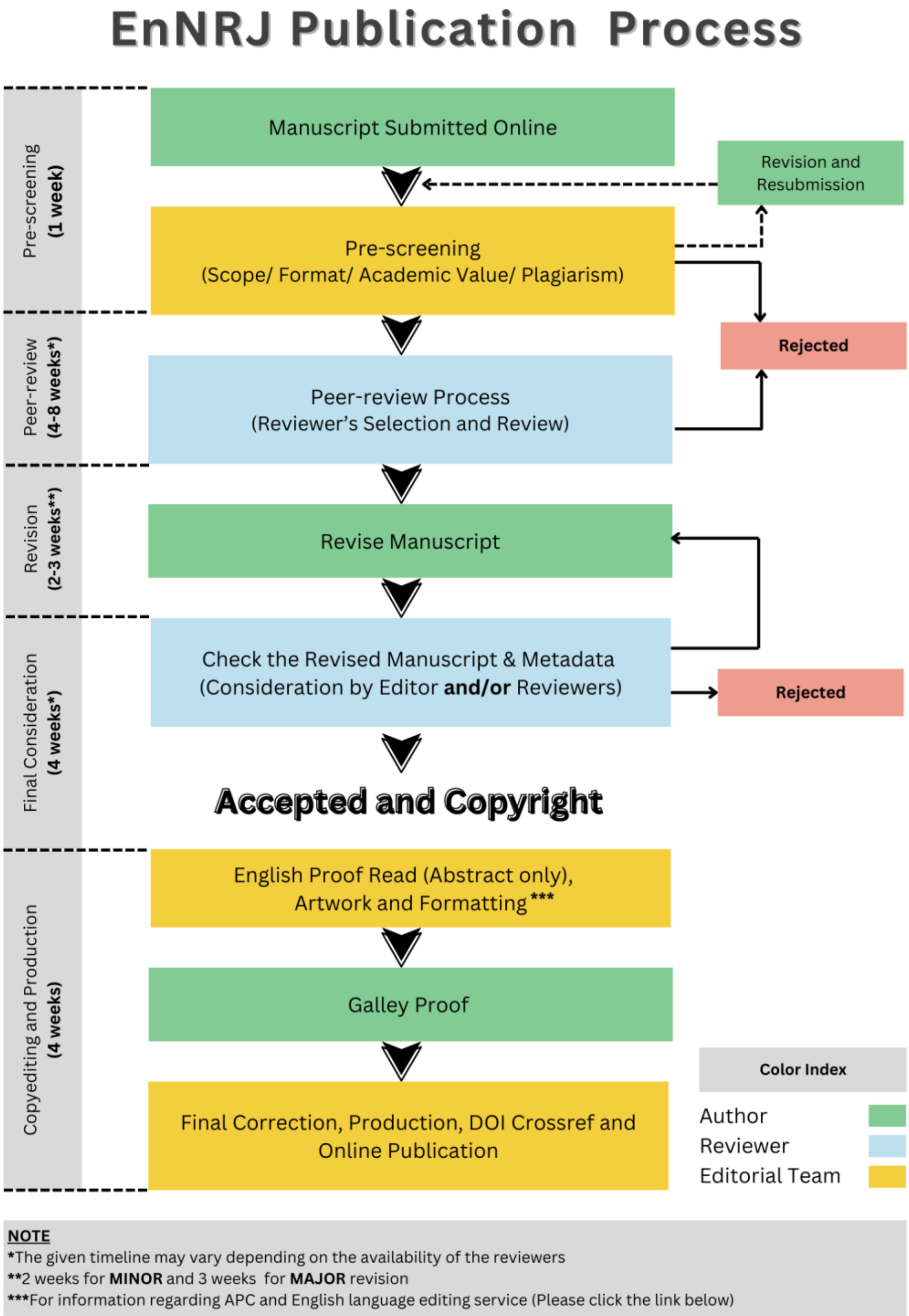

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[1]Department of Environmental Technology and Management, Faculty of Environment, Kasetsart University, Bangkok, Thailand
[2]Environmental Science and Technology Program, Faculty of Science and Technology, Phranakhon Rajabhat University, Bangkok, Thailand
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Journal article

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Journal article with Article Number

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Non-English articles

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Article in press

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Ph.D./Master thesis

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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

Royal Gazette. Promotion of Marine and Coastal Resources Management Act 2059. Volume 132, Part 21, Dated 26 Mar B.E. 2558. Bangkok, Thailand: Office of the Council of State; 2015a. (in Thai).

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999 Phutthamonthon Sai 4 Rd, Salaya, Phutthamonthon District, Nakhon Pathom 73170
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