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Milicia excelsa in Rau Nature Forest Reserve, photo by Wildlife Safari in Tanzania

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Introduction is about 600 words, covering the aims of the research and provide an adequate background, avoiding a detailed literature survey or a summary of the results. **Materials and Methods** should emphasize on the procedures and data analysis. **Results and Discussion** should be written as a series of connecting sentences, however, for a manuscript with long discussion should be divided into subtitles. Thorough discussion represents the causal effect mainly explains why and how the results of the research were taken place, and do not only re-express the mentioned results in the form of sentences. **Concluding** sentence should be given at the end of the discussion. **Acknowledgements** are expressed in a brief; all sources of institutional, private and corporate financial support for the work must be fully acknowledged, and any potential conflicts of interest are noted.

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Journal:

Saharjo BH, Nurhayati AD. 2006. Domination and composition structure change at hemic peat natural regeneration following burning; a case study in Pelalawan, Riau Province. Biodiversitas 7: 154-158. DOI: 10.13057/biodiv/d070213.

The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Diversity, structure, and carbon storage of Rau catchment forest reserve in Moshi District, Tanzania

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Abstract. *Mwakalukwa EE, Masisi B. 2024. Diversity, structure, and carbon storage of Rau catchment forest reserve in Moshi District, Tanzania. Asian J For 9: 1-11.* The effects of anthropogenic activities and the dominance of exotic tree species on the Rau Catchment Forest Reserve (RCFR) in Moshi District, northern Tanzania, have been poorly documented. This study assessed (i) the current status of species composition, stand structure, and diversity, (ii) threats to biodiversity posed by anthropogenic activities and exotic tree species, and (iii) the carbon stock of RCFR. Data were gathered from 45 circular sample plots, identifying 29 woody plant species. The forest exhibited high woody species diversity (H'=2.91), with a density of 185±81 stems ha^{-1}, a standing volume of 405.75±227.16 m^3 ha^{-1}, and a basal area of 23.05±12.37 m^2 ha^{-1}. Evidence of human activities, particularly tree cutting and the dominance of exotic species, was prevalent, with illegal harvesting affecting 23 species. The mean above-ground and below-ground carbon stocks were estimated at 107.48±61.28 Mg C ha^{-1} and 21.50±12.26 Mg C ha^{-1}, respectively. The high diversity of woody species suggests that the forest may be recovering from past illegal logging. However, the increasing dominance of exotic species highlights the urgent need for measures to control their spread.

Keywords: Anthropogenic activities, biodiversity, exotic species, groundwater forests, urban forests

INTRODUCTION

Forests play a crucial role in global well-being by providing diverse ecosystem goods and services, including biodiversity conservation, climate regulation, economic resources, air and water purification, and recreational and aesthetic benefits (Aju et al. 2015; Bhatta et al. 2015; FAO 2022, 2024). In urban environments, forests contribute significantly to human well-being by mitigating air pollution, improving air quality, sequestering carbon to address climate change, reducing stormwater runoff, lowering urban temperatures, and offering green spaces for recreation (Patarkalashvili 2017; Massawe et al. 2019; Bushesha 2020; Pataki et al. 2021; Dickinson and Ramalho 2022; O'Brien et al. 2022).

Despite their importance, urban-proximate forests face numerous challenges (Güneralp et al. 2017). These include encroachment and loss of forest areas due to urban expansion into ecologically significant regions (Mutuga 2009; Addae and Oppelt 2019; Massawe et al. 2022), forest degradation resulting from unsustainable wood utilization leading to a decline in ecosystem services (Kilcullen et al. 2015; Sembosi 2019), and complete deforestation for conversion to alternative land uses (Güneralp et al. 2017; Massawe et al. 2019). Biodiversity loss occurs through habitat fragmentation, the disappearance of rare species, and reduced habitat quality caused by edge effects (Wade et al. 2003; McKinney 2008; Massawe et al. 2022). Illegal activities such as logging, mining, cultivation, and fire further open the canopy, facilitating the invasion and spread of non-native species. These invasive species disrupt biodiversity, alter forest structure, and reduce the provision of ecosystem services (Mavimbela et al. 2018; Kilawe et al. 2023). The replacement of natural forests with exotic species, which typically store less carbon, further diminishes the carbon sequestration capacity of these forests (Agboola et al. 2021).

Carbon stock assessments are critical for informed management and policy development, as forests are pivotal in climate regulation by reducing atmospheric CO_2 concentrations (Joshi et al. 2021). Accurate carbon stock data enable forest managers to negotiate favorable carbon credit terms, generate revenue for conservation, and strengthen their positions in global carbon markets (Biadgligne et al. 2022; Daba et al. 2022).

The Rau Catchment Forest Reserve (RCFR), located approximately 3 km from the Moshi municipality center in the Kilimanjaro region of Tanzania (Falck and Roponen 1994), exemplifies urban-adjacent forests under threat. Surrounded by six villages, RCFR faces challenges such as agricultural expansion, grazing, illegal logging, and the dominance of exotic tree species (Lovett and Poc′s 1993; Falck and Roponen 1994; Mkiramweni 2015; Mhache 2019; Güneralp et al. 2017; Massawe et al. 2022). However, the extent of these impacts on forest biodiversity, structure, and function remains unclear. Understanding these effects is essential for biodiversity conservation and habitat management planning.

This study hypothesized that anthropogenic activities and the spread of exotic tree species negatively impact species diversity and forest structure, thereby reducing the forest's carbon storage and sequestration capacity (Agboola et al. 2021; Kilawe et al. 2023). The study aimed to evaluate the condition of RCFR under the influence of anthropogenic activities and exotic species and to estimate its current carbon stock. The specific objectives were to assess the status of (i) species composition and diversity of living and harvested trees, including indigenous and exotic species, (ii) stand structure of living and harvested trees, (iii) threats posed by exotic tree species to indigenous species, and (iv) above- and below-ground biomass and carbon stock of RCFR.

MATERIALS AND METHODS

Study area

Rau Catchment Forest Reserve (RCFR) is situated in Moshi District, Kilimanjaro Region, at coordinates 3°23' S and 37°22' E (Figure 1). Established in 1951 (GN. No. 127 of 25/5/1951) with an initial area of 1,427 ha, RCFR's boundaries were later adjusted to its current 570 ha due to extensive illegal logging during the late 1950s (Rogers 1983; Lovett and Pocʼs 1993; Falck and Roponen 1994). The reserve lies at an elevation of 730-765 meters above sea level and receives an average annual rainfall of 870 mm, with a dry season spanning from June to February. Its soil is volcanic in origin, comprising alluvial sand and loam, and enriched with gleysols and fluvisoils (Lovett and Pocʼs 1993).

RCFR is classified as a lowland, groundwater forest with characteristics of riverine and freshwater swamp forest types (Hermansen et al. 1985). It is also described as a tropical ombrophilous alluvial swamp forest (Falck and Roponen 1994), supported by a high water table that sustains semi-deciduous and swamp vegetation. The forest exhibits greater ecological affinities to Afromontane regions than to the Zanzibar-Inhambane Regional Mosaic (Falck and Roponen 1994). Its catchment function is significant, supplying water for irrigation of approximately 50,000 ha of rice farms in the dry lowland areas south of Mt. Kilimanjaro (Falck and Roponen 1994).

Human pressure on RCFR began as early as the 1950s, significantly altering the species structure and composition (Lovett and Pocʼs 1993; Rogers 1983; Falck and Roponen 1994). In response, part of the degraded forest was rehabilitated through reforestation with exotic species during the 1950s (Lovett and Pocʼs 1993). Logging was officially prohibited in the early 1980s as a conservation measure (Rogers 1983; Falck and Roponen 1994). About 216 ha of plantations were established within the reserve, including 10 ha of *Prioria msoo* (Harms) Breteler. Only 50 ha of natural forest remain intact.

Plantation species include *Tectona grandis* L.f., *Cedrela odorata* L., *Cedrela mexicana* M.Roem, *Lagerstroemia speciosa* (L.) Pers, *Eucalyptus* spp., *Cassia* sp., *Gmelina arborea* Roxb. ex Sm, and *Senna siamea* (Lam.) H.S. Irwin and Barneby. Among these, *G. arborea*, *S. siamea*, and *T. grandis* have become dominant (Lovett and Pocʼs 1993; Mhache 2019). These exotic species contribute to ongoing ecological challenges in the reserve.

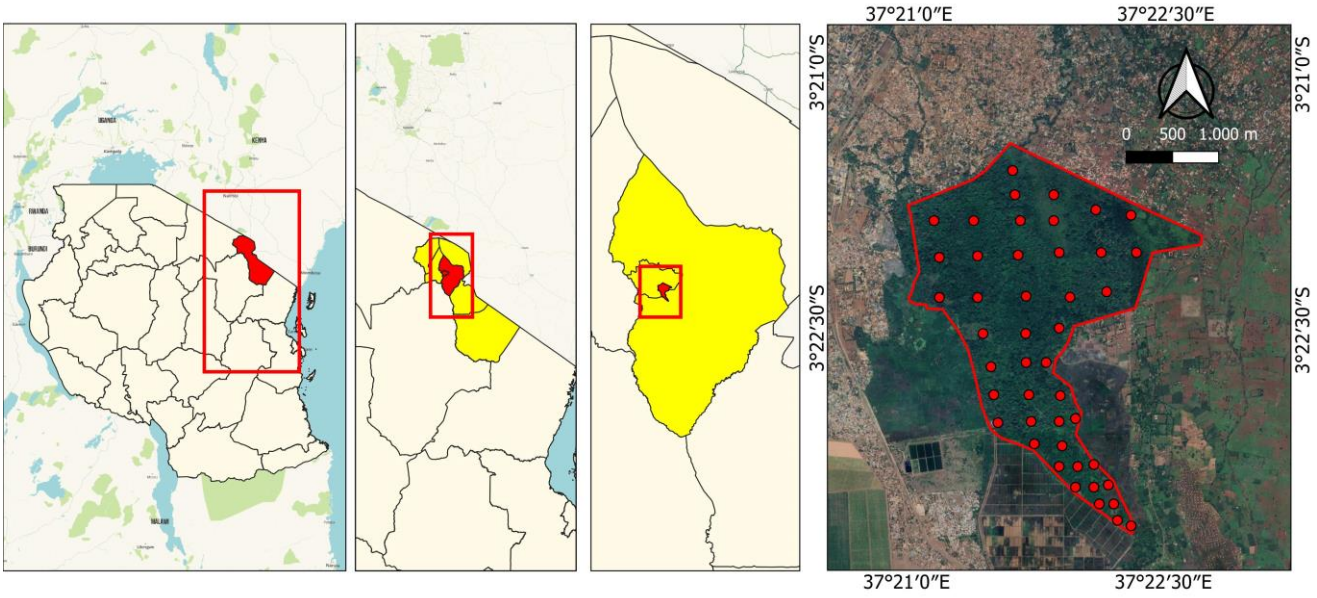

Figure 1. Map of Moshi District, Tanzania, showing the location of a lowland groundwater forest of Rau Catchment Forest Reserve (RCFR) and the layout of sample plots in the reserve (filled circles)

Data collection

A field survey was conducted in November 2017, utilizing 45 circular-shaped sample plots, each covering an area of 0.071 ha with a radius of 15 m. Circular plots were chosen for their ease of implementation, reduced edge effects, and minimized counting errors for border trees during inventory (Krebs 1989). A sampling intensity of 0.56% was adopted for this survey, aligning with the range of 0.5 to 0.7% recommended by Synnott (1979) for tropical natural forest inventories. This sampling intensity yielded 45 plots, deemed sufficient based on time constraints, inventory objectives, and resource availability (Synnott 1979; Mwakalukwa et al. 2023).

The sample plots were systematically distributed at 250 m intervals along transects spanning the 570 ha of the Rau Catchment Forest Reserve (RCFR). This systematic design ensured an even distribution of plots throughout the forest, minimizing bias and enabling a comprehensive assessment of forest composition. Within each plot, the following measurements were recorded: (i) Diameter at Breast Height (DBH): Measured for all trees with DBH ≥ 5 cm, using diameter tape or calipers depending on tree size, at 1.3 m above ground; (ii) Total Height and Basal Diameter: Recorded for three selected sample trees (small, medium, and large) at 15 cm above ground to capture size variation within species. Total height was measured with a Suunto hypsometer; (iii) Stump Diameter: Measured for all stumps with a diameter ≥ 5 cm, at 15 cm above ground.

The three sample trees within each plot were selected based on predefined diameter ranges to represent the existing size variation among tree species in the forest. Plant species identification was conducted in the field to ensure accurate taxonomic data. This methodical approach enabled a detailed and systematic inventory of the RCFR's structural and compositional attributes.

Data analysis

The data analysis focused on species richness, diversity, forest structure, and carbon stock across the 45 study plots. Total species richness was computed as the total number of species observed (Kent 2012). Species diversity was determined using the Shannon-Wiener diversity index, calculated as (H') = -∑Pi*(ln(Pi)), where: Pi represents the relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals (Ni) in the plot (ni/N), and ln denotes the natural logarithm (Kent 2012; Agboola et al. 2021; Ayele et al. 2024). The values of H' typically fall between 1.5 and 3.5, rarely exceeding 4.5 (Kent 2012). An H' value greater than 2 suggests medium to high diversity, according to Magurran (2004), with higher values indicating greater species diversity.

The Importance Value Index (IVI) was calculated as the sum of relative frequency, relative density, and relative dominance (basal area), expressed as a percentage (Kent and Coker 1992; Agboola et al. 2021; Ayele et al. 2024). Forest structure was analyzed by determining stem density, basal area, and volume for each species, categorized by diameter class (Mwakalukwa et al. 2023; Ayele et al. 2024). To predict tree heights (Ht) of non-sampled trees, data on Ht from three trees of different sizes per plot (small, medium, and large) were used. A non-linear regression equation was developed (Winsor 1932; Mwaluseke et al. 2023).

Tree volume was estimated using DBH and Ht data, with volume equations applied at plot and forest levels. Additionally, biomass estimation incorporated DBH, Ht, and wood basic density (WD). Biomass was then used to estimate carbon stock at both plot and forest levels. Models from Mugasha et al. (2016) for lowland forests in Tanzania were applied to estimate forest volume and biomass using an equation from the Rondo site. Biomass was converted into carbon density per hectare, with below-ground biomass estimated as 20% of total above-ground biomass. The equations used were:

Height (m) or Ht (m) = $(-0.00365\times DBH^2) + (0.7916\times DBH) + 3.5451$ ($R^2 = 0.79$; AIC =509; n = 122; Ht range: 4m to 47.8m with mean 21 m)

Volume ($m^3\ tree^{-1}$) = $0.000076 \times DBH^{2.3488}\times Ht^{0.3848}$ ($R^2 = 0.95$; RMSE = 0.90; AIC=91.648)

Biomass ($kg\ tree^{-1}$) = $0.07511\times (WD \times DBH^2 \times Ht)^{0.9477}$ (R^2= 0.92; RMSE= 462.47; AIC= 396.58)

Where:
DBH: Diameter at Breast Height (cm)
Ht: Total tree height (m)
WD: Wood Basic Density ($g\ cm^{-3}$)
RMSE: Root Mean Square Error
AIC: Akaike's Information Criterion
R^2: Coefficient of determination.

Wood basic density values for each species were sourced from Reyes et al. (1992), Brown (1997), and Orwa et al. (2009). Carbon stock was calculated per hectare (Mg C ha^{-1}) by multiplying biomass with a conversion factor of 0.49 (Manyanda et al. 2020). All data analyses were performed using Excel spreadsheets and R (version 4.2.0).

RESULTS AND DISCUSSION

Species composition and diversity

A total of 29 tree and shrub species, with diameters ranging from 5 to 240 cm, were identified in RCFR, belonging to 28 genera and 15 plant families (Table 1). Of these species, trees contributed 93% (13 plant families), while shrubs accounted for 7% (2 plant families). The Fabaceae family had the highest number of tree species (19%), followed by the Myrtaceae family (15%), while the shrub species were primarily from the Boraginaceae and Salicaceae families. The most frequently encountered species were *Macaranga kilimandscharica* Pax (49% of plots), *Tabernaemontana ventricosa* Hochst. ex A.DC. (40%), *Ficus sycomorus* L. (36%), *Trichilia emetica* Vahl (31%), and *Milicia excelsa* (Welw.) C.C.Berg (29%) (Table 1). The average number of species per plot was four, with a range of 1 to 9 species per plot (Figure 2). Among the ten most important species, based on the Importance Value Index (IVI) and Shannon-Wiener diversity index (H') scores, *Gmelina arborea*, *Senna siamea*, and *Tectona grandis* emerged as key species (Table 1).

The study identified a total of 23 tree and shrub species with basal diameters ranging from 5 to 104 cm, belonging to 21 genera and 14 plant families in the Rau Catchment Forest Reserve (RCFR). Of these, trees comprised 91% (12 plant families) and shrubs 9% (2 plant families). The most abundant families in terms of harvested species were Fabaceae (17%) and Myrtaceae (13%). *Senna siamea* (exotic) was the most frequent species among the harvested individuals, occurring in 16% of plots, followed by *M. excelsa* (11%), *M. kilimandscharica* (11%), and *Cordia africana* (11%). *G. arborea*, *S. siamea*, and *T. grandis* were also important species according to the Importance Value Index (IVI) and Shannon-Wiener diversity index (H').

The species richness of 29 tree and shrub species reported in this study (9 exotic and 20 indigenous) is lower than that of other tropical lowland, groundwater, riverine, and freshwater swamp forests, with the exception of Kacholi (2019). The lower species richness could be attributed to the smaller number of sample plots used (45 plots) and the applied diameter limit of ≥ 5 cm. The results, however, align closely with those presented by Mkiramweni (2015), who found 38 species in the same forest using more than twice the number of plots (114). In contrast, Falck and Roponen (1994) identified 92 species across all vascular plants with no diameter limit. This suggests that RCFR has relatively low species richness, which may be influenced by ongoing illegal activities and the dominance of exotic species, which suppress the regeneration of indigenous species (Mhache 2019). According to Mkiramweni (2015), major threats to the RCFR vegetation include firewood collection (25.5%), illegal timber harvesting (14.3%), pole cutting (11.7%), fodder collection (9%), grazing (8.2%), and encroachment (7.9%). The reported harvested stem density of 55±35 stems ha^{-1} in this study supports the occurrence of these anthropogenic activities.

The lower Shannon-Wiener index (H'=2.91) for trees and shrubs in this study compared to other tropical forests suggests that the RCFR has been impacted by past disturbances (Lovett and Pocʹs1993; Mkiramweni 2015). Kent (2012) notes that a forest is considered rich when its H' value exceeds 3.5, while a value above 2 suggests medium to high diversity (Magurran 2004). Therefore, the H' value of 2.91 in this study indicates that RCFR is a relatively high-diversity forest with an even distribution of species.

Species from the genera *Milicia*, *Macaranga*, and *Cordia* were the most frequently harvested, valued for timber, charcoal, firewood, and medicine (Lovett and Pocʹs 1993; Mkiramweni 2015). Interestingly, the rare species *P. msoo* was also included in the list of harvested species, prized for its straightness and durability, particularly in broom handle production. The frequent harvesting of *S. siamea*, an exotic species, highlights how human preferences shape the composition of harvested tree species. A targeted tree planting program could help meet local needs and reduce pressure on the forest by encouraging the cultivation of preferred species outside the reserve.

Stand structure

The total mean stem density, basal area, and volume for standing and harvested trees and shrubs in RCFR are detailed in Tables 1 and 2. Regarding stem density, four exotic species—*S. siamea*, *G. arborea*, *T. grandis*, and *Eucalyptus* sp.—dominate the forest. Exotics contribute 63 ± 36 stems ha^{-1} (34%) to the total stem density of standing trees and shrubs, while indigenous species contribute 122±45 stems ha^{-1} (66%) (Figure 3, Table 1). Exotic species predominantly occupy the lower diameter classes (below 30.0 cm), although a few individuals are found in diameter classes greater than 30.0 cm (Figure 4).

For stumps, *G. arborea* (14 stems ha^{-1}), *S. siamea* (12 stems ha^{-1}), and *T. grandis* (8 stems ha^{-1}) are the most abundant exotic species (Table 2). The distribution of trees across size classes follows the typical reverse J shape, with a higher number of smaller individuals (Figure 5). Most of the harvested individuals also fall below the 30.0 cm basal diameter, and the majority of these harvested individuals are exotic species (Figure 6).

In terms of basal area, the trend in stem density is reflected similarly, with exotic trees and shrubs occupying 5.93±4.28 m^2 ha^{-1} (26%) of the basal area, while indigenous trees and shrubs occupy 17.12±8.09 m^2 ha^{-1} (74%) (Table 1). *G. arborea*, *Eucalyptus* sp., and *S. siamea* contributed the most to the basal area of standing exotic species (Figure 7), while the species contributing most to the basal area of stumps are shown in Figure 8. The distribution of trees to size classes follows a normal "J" shape (Figure 9), indicating that trees with a diameter greater than 70.1 cm contribute significantly to the per-hectare basal area of the forest.

In terms of volume, the species contributing most to the stand volume of standing individuals were *F. sycomorus* (31%), *G. arborea* (11%), *M. excelsa* (10%), and *Newtonia buchananii* (8%) (Table 1). Exotic species contributed 22% (88.38 ± 66.60 m^3 ha^{-1}), while indigenous trees and shrubs contributed 78% (317.37 ± 160.57 m^3 ha^{-1}) (Table 1). As with basal area, most exotic species occur in the lower diameter classes (below 30.0 cm), though a few are found in diameter classes greater than 30.0 cm (Figure 4). The distribution of standing trees to size classes follows a near-normal "J" shape, with trees in larger diameter classes (>40.1 cm) contributing significantly to the mean total standing volume of the forest (Table 1).

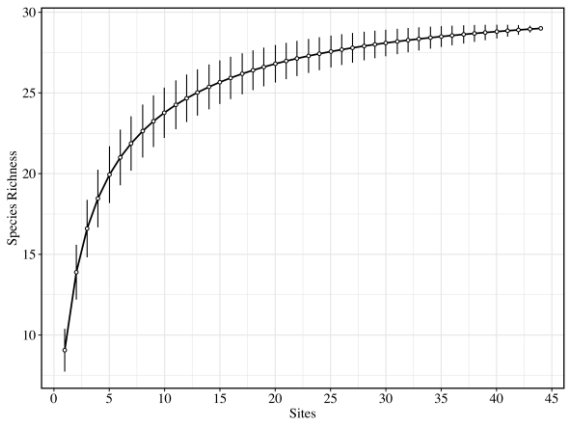

Figure 2. Species accumulation curve of tree species in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania. The curve depicts the expected number of species as a function of the sampled area, with the upper and lower bounds representing the 95% confidence intervals

Table 1. List of standing tree and shrub species with a minimum DBH of 5 cm sorted by Importance Value Index (IVI) identified in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

Species name	Plant family	Habit	Category	Frequency (%)	*Rf (%)	RDe (%)	RDo (%)	IVI	*H'*	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Stand Volume (m^3ha^{-1})	AGC ($Mgha^{-1}$)	BGC ($Mgha^{-1}$)
Ficus sycomorus L.	Moraceae	Tree	IND	36	8.5	5.3	25.1	38.8	0.16	10±3	5.78±2.23	124.31±50.62	18.56±7.37	3.71±1.47
Macaranga kilimandscharica Pax	Euphorbiaceae	Tree	IND	49	11.6	8.2	7.2	27.0	0.20	15±3	1.66±0.47	25.76±8.00	6.28±1.92	1.26±0.38
Tabernaemontana ventricosa Hochst. ex A.DC.	Apocynaceae	Tree	IND	40	9.5	15.0	2.0	26.5	0.28	28±8	0.45±0.20	4.02±2.06	1.92±0.97	0.38±0.19
Gmelina arborea Roxb. ex Sm.	Lamiaceae	Tree	EXT	9	2.1	8.3	11.1	21.5	0.21	15±9	2.55±1.84	44.18±33.15	11.00±8.03	2.20±1.61
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	Tree	EXT	24	5.8	10.7	4.3	20.9	0.24	20±7	0.99±0.37	11.64±4.48	5.06±1.94	1.01±0.39
Milicia excelsa (Welw.) C.C.Berg	Moraceae	Tree	IND	29	6.9	4.8	9.0	20.6	0.15	9±3	2.07±1.07	39.56±23.48	12.65±6.68	2.53±1.34
Trichilia emetica Vahl	Meliaceae	Tree	IND	31	7.4	5.8	2.1	15.3	0.16	11±3	0.49±0.21	6.42±3.26	2.38±1.18	0.48±0.24
Syzygium guineense (Willd.) DC.	Myrtaceae	Tree	IND	13	3.2	4.6	5.0	12.8	0.14	8±5	1.15±0.59	21.38±11.38	8.67±4.51	1.73±0.90
Tectona grandis L.f.	Lamiaceae	Tree	EXT	9	2.1	7.2	3.2	12.4	0.19	13±8	0.73±0.48	9.04±6.31	3.11±2.17	0.62±0.43
Newtonia buchananii (Baker) G.C.C.Gilbert & Boutique	Fabaceae	Tree	IND	11	2.6	2.0	6.9	11.6	0.08	4±2	1.58±0.93	31.68±18.96	8.35±4.92	1.67±0.98
Bridelia micrantha (Hochst.) Baill.	Phyllanthaceae	Tree	IND	13	3.2	2.4	5.9	11.5	0.09	4±2	1.37±0.99	26.57±20.76	6.98±5.23	1.40±1.05
Eucalyptus sp.	Myrtaceae	Tree	EXT	2	0.5	4.4	5.9	10.8	0.14	8±8	1.35±1.35	19.62±19.62	7.21±7.21	1.44±1.44
Vachellia xanthophloea (Benth.) Banfi & Galasso	Fabaceae	Tree	IND	13	3.2	3.4	2.8	9.4	0.12	6±3	0.66±0.38	9.64±5.92	5.18±3.15	1.04±0.63
Sorindeia madagascariensis DC.	Anacardiaceae	Tree	IND	22	5.3	2.9	0.6	8.8	0.10	5±2	0.14±0.07	1.30±0.64	0.42±0.21	0.08±0.04
Albizia schimperiana Oliv.	Fabaceae	Tree	IND	13	3.2	1.5	3.8	8.5	0.06	3±1	0.88±0.45	16.55±9.30	4.54±2.43	0.91±0.49
Prioria msoo (Harms) Breteler	Fabaceae	Tree	IND	11	2.6	3.1	1.3	7.0	0.11	6±3	0.31±0.21	3.95±2.79	1.24±0.88	0.25±0.18
Croton macrostachyus Hochst. ex Delile	Euphorbiaceae	Tree	IND	18	4.2	1.7	0.9	6.8	0.07	3±1	0.20±0.09	2.42±1.11	0.77±0.35	0.15±0.07
Cordia africana Lam.	Boraginaceae	Shrub	IND	16	3.7	2.0	0.5	6.2	0.08	4±2	0.11±0.05	1.08±0.47	0.56±0.25	0.11±0.05
Rauvolfia caffra Sond.	Apocynaceae	Tree	IND	9	2.1	1.0	0.3	3.4	0.05	2±1	0.07±0.04	0.63±0.41	0.22±0.14	0.04±0.03
Syzygium cumini (L.) Skeels	Myrtaceae	Tree	IND	9	2.1	1.0	0.3	3.4	0.05	2±1	0.06±0.04	0.61±0.36	0.27±0.16	0.05±0.03
Cedrela odorata L.	Meliaceae	Tree	EXT	9	2.1	1.0	0.1	3.3	0.05	2±1	0.03±0.02	0.23±0.16	0.06±0.04	0.01±0.01
Casuarina equisetifolia L.	Casuarinaceae	Tree	EXT	7	1.6	0.5	0.7	2.8	0.03	1±1	0.17±0.11	2.60±1.87	1.28±0.91	0.26±0.18
Fagaropsis angolensis (Engl.) H.M.Gardner	Rutaceae	Tree	IND	7	1.6	0.7	0.5	2.8	0.03	1±1	0.11±0.07	1.36±0.90	0.37±0.24	0.07±0.05
Dovyalis caffra (Hook. f. & Harv.) Warb.	Salicaceae	Shrub	EXT	4	1.1	0.7	0.3	2.0	0.03	1±1	0.06±0.06	0.63±0.62	0.20±0.20	0.04±0.04
Mangifera indica L.	Anacardiaceae	Tree	EXT	4	1.1	0.7	0.1	1.9	0.03	1±1	0.03±0.02	0.20±0.15	0.07±0.06	0.01±0.01
Psidium guajava L.	Myrtaceae	Tree	EXT	4	1.1	0.3	0.1	1.5	0.02	1±0	0.02±0.02	0.24±0.24	0.09±0.09	0.02±0.02
Markhamia obtusifolia (Baker) Sprague	Bignoniaceae	Tree	IND	2	0.5	0.3	0.1	0.9	0.02	1±1	0.01±0.01	0.11±0.11	0.04±0.04	0.01±0.01
Cinchona sp.	Rubiaceae	Tree	IND	2	0.5	0.2	0.0	0.7	0.01	0±0	0.00±0.00	0.01±0.01	0.00±0.00	0.00±0.00
Kigelia africana (Lam.) Benth.	Bignoniaceae	Tree	IND	2	0.5	0.2	0.0	0.7	0.01	0±0	0.00±0.00	0.02±0.02	0.01±0.01	0.00±0.00
Total				420	100	100	100	300	2.91	185±81	23.05±12.37	405.75±227.16	107.48±61.28	21.50±12.26

Note: * Rf = Relative frequency, RDe = Relative density, RDo = Relative dominance (basal area), *H'* = Shannon-Wiener diversity index, AGC = Above Ground Carbon (mean ± SE), BGC = Below Ground Carbon (mean ± SE), density (mean ± SE), Basal area (mean ± SE), Stand volume (mean ± SE). Plot size = 15 m radius. SE = Standard error. EXT = Exotic, IND = Indigenous

Table 2. List of harvested tree and shrub species with a minimum basal diameter of 5 cm sorted by Importance Value Index (IVI) identified in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

Species name	Plant family	Habit	Category	Frequency (%)	*Rf (%)	RDe (%)	RDo (%)	IVI	*H'*	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Stand Volume (m^{3}ha^{-1})
Gmelina arborea Roxb. ex Sm.	Lamiaceae	Tree	EXT	7	5.6	24.7	32.9	63.1	0.35	14±10	1.39±0.98	0.77±0.54
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	Tree	EXT	16	13.0	21.3	18.5	52.8	0.33	12±5	0.78±0.46	0.33±0.17
Tectona grandis L.f.	Lamiaceae	Tree	EXT	7	5.6	14.4	11.2	31.2	0.28	8±5	0.47±0.32	0.27±0.18
Macaranga kilimandscharica Pax	Euphorbiaceae	Tree	IND	11	9.3	4.6	4.1	17.9	0.14	3±1	0.17±0.11	0.17±0.12
Cordia africana Lam.	Boraginaceae	Shrub	IND	11	9.3	4.0	4.3	17.6	0.13	2±1	0.18±0.11	0.10±0.06
Bridelia micrantha (Hochst.) Baill.	Phyllanthaceae	Tree	IND	7	5.6	4.0	6.7	16.3	0.13	2±1	0.28±0.26	1.00±0.98
Milicia excelsa (Welw.) C.C.Berg	Moraceae	Tree	IND	11	9.3	4.0	2.0	15.3	0.13	2±1	0.08±0.04	0.04±0.02
Albizia gummifera (J.F.Gmel.) C.A.Sm.	Fabaceae	Tree	IND	2	1.9	1.7	6.5	10.1	0.07	1±1	0.28±0.28	0.04±0.04
Eucalyptus sp.	Myrtaceae	Tree	EXT	2	1.9	3.4	4.7	10.0	0.12	2±2	0.20±0.20	0.08±0.08
Tabernaemontana ventricosa Hochst. ex A.DC.	Apocynaceae	Tree	IND	7	5.6	2.9	0.3	8.7	0.10	2±1	0.01±0.01	0.01±0.00
Trichilia emetica Vahl	Meliaceae	Tree	IND	7	5.6	2.9	0.3	8.7	0.10	2±1	0.01±0.01	0.01±0.00
Prioria msoo (Harms) Breteler	Fabaceae	Tree	IND	7	5.6	1.7	0.4	7.7	0.07	1±1	0.02±0.01	0.01±0.00
Croton macrostachyus Hochst. ex Delile	Euphorbiaceae	Tree	IND	4	3.7	1.1	1.8	6.6	0.05	1±0	0.07±0.07	0.02±0.01
Vachellia xanthophloea (Benth.) Banfi & Galasso	Fabaceae	Tree	IND	2	1.9	0.6	3.2	5.6	0.03	0±0	0.14±0.14	0.04±0.04
Melanopsidium nigrum Colla	Rubiaceae	Tree	IND	2	1.9	2.3	0.6	4.7	0.09	1±1	0.02±0.02	0.00±0.00
Markhamia obtusifolia (Baker) Sprague	Bignoniaceae	Tree	IND	2	1.9	1.1	1.0	4.0	0.05	1±1	0.04±0.04	0.01±0.01
Cordia africana Lam.	Boraginaceae	Tree	IND	2	1.9	0.6	1.0	3.4	0.03	0±0	0.04±0.04	0.03±0.03
Syzygium guineense (Willd.) DC.	Myrtaceae	Tree	IND	2	1.9	1.1	0.2	3.2	0.03	0±0	0.00±0.00	0.00±0.00
Ficus sycomorus L.	Moraceae	Tree	IND	2	1.9	1.1	0.1	3.1	0.05	1±1	0.00±0.00	0.00±0.00
Sorindeia madagascariensis DC.	Anacardiaceae	Tree	IND	2	1.9	0.6	0.3	2.7	0.03	0±0	0.01±0.01	0.00±0.00
Euclea divinorum Hiern	Ebenaceae	Shrub	IND	2	1.9	0.6	0.1	2.5	0.03	0±0	0.00±0.00	0.00±0.00
Kigelia africana (Lam.) Benth.	Bignoniaceae	Tree	IND	2	1.9	0.6	0.0	2.5	0.03	0±0	0.00±0.00	0.00±0.00
Syzygium cumini (L.) Skeels	Myrtaceae	Tree	IND	2	1.9	0.6	0.0	2.4	0.05	1±1	0.01±0.01	0.01±0.01
Total				120	100	100	100	300	2.41	55±35	4.22±3.11	2.94±2.33

Note: * Rf = Relative frequency, RDe = Relative density, RDo = Relative dominance (basal area), *H'* = Shannon-Wiener diversity index, density (mean ± SE), Basal area (mean ± SE), Stand volume (mean ± SE). Plot size = 15 m radius. IND = Indigenous, EXT = Exotic

Table 3. Species richness, diversity, stem density, and basal area values observed in other studies from lowland, groundwater, riverine, and freshwater swamp forests

Reference	Location	Sample plots	Plots size (m)	Species richness	Plant families	*H'*	Density (stems ha^{-1})	Basal area (m^2ha^{-1})
Abdullah et al. (2021)	Freshwater swamp forest at Parit forest reserve in Malaysia	-	-	-	-	2.39	484	23.9
Agboola et al. (2021)	Lowland forests across Southwest (SW) Nigeria	6	25×25	55	-	2.55	770.67	23.23
Avila et al. (2021)	Six swamp forests in Southeastern Brazil	-	5×5	134 (range 29-59)	47	1.82, 2.07, 2.23, 2.28, 2.93, and 3.18	-	-
Banya et al. (2021)	Kangari Hills swamp forest reserve in Sierra Leone	15	10×10	58	30	3.63	367	33
Buragohain et al. (2023)	A lowland rain forest of Kakoi reserve forest in India	2	100×100	55	26	3.55, 3.68	582, 446	38.43, 32.63
Igu (2017)	Otuwe freshwater swamp forest in the Niger Delta in Nigeria	8	100×100	35	18	1.66	255	-
Kacholi (2013)	Kimboza lowland forest reserve in Tanzania	18	20×20	52	22	3.40	390	24
Kacholi (2014)	Kilengwe lowland forest reserve in Tanzania	18	20×20	67	26	4.02	276	7.1
Kacholi (2019)	Nongeni lowland forest reserve in Tanzania	20	20×25	24	11	2.67	751	10.8±2.6
Meragiaw et al. (2018)	Walga riparian vegetation in Ethiopia	50	10×50	99	45	3.55	356	-
Mkiramweni (2015)	Rau catchment forest reserve	114	10×50	38	22	2.99	306±12	30.1±2.5
Mligo (2015)	Namatimbili lowland riverine, coastal forest in Tanzania	-	20×50	85	31	1.64	-	73.8±21.5
Mligo (2016)	Wami river system in Tanzania at Kilosa site	-	-	-	-	1.63, 2.40, 2.55, 2.70 and 2.94	-	-
Rahmah et al. (2016)	Lowland forest in the Bukit Duabelas National Park, Indonesia	-	-	-	-	4.29	414	25.7
Yen and Cochard (2017)	Lowland evergreen rain forest of Nam Dong district in Central Vietnam	-	-	-	-	2.91	678	27
Our study	Rau catchment forest reserve	45	15	29	15	2.91	185±81	23.1±12.4

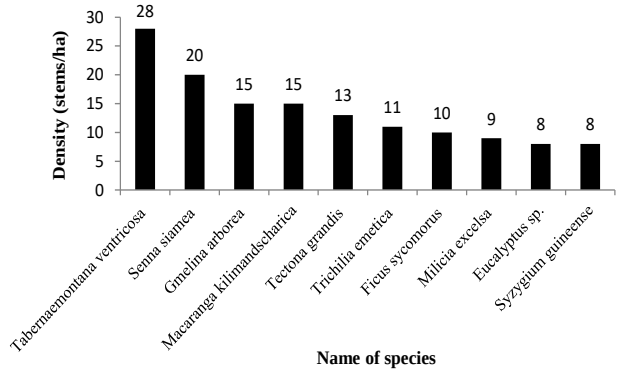

Figure 3. The 10 most abundant standing species with a high stem density were found in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

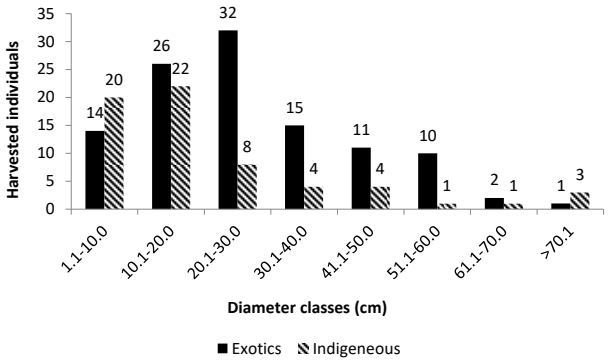

Figure 6. The distribution of harvested individuals of tree species and shrubs with ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

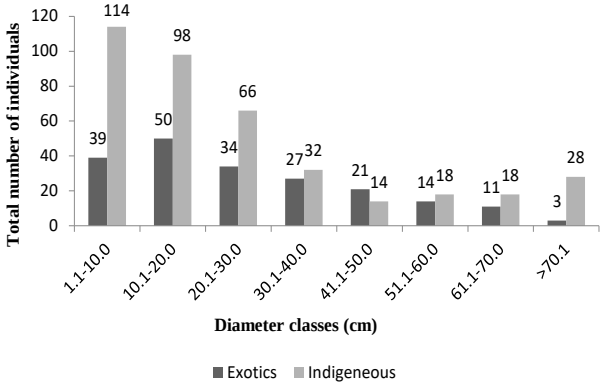

Figure 4. The distribution of total individual standing tree species and shrubs with ≥ 5 cm DBH by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

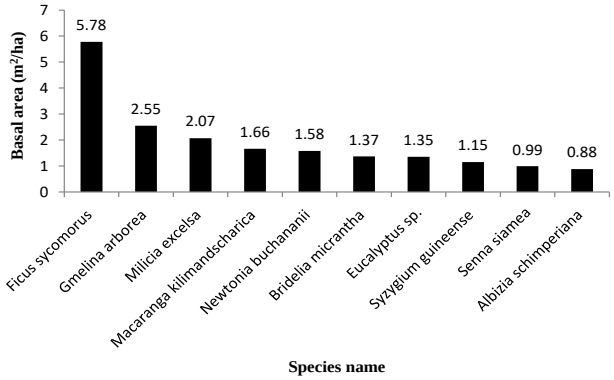

Figure 7. The 10 most abundant standing species with high basal area are found in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

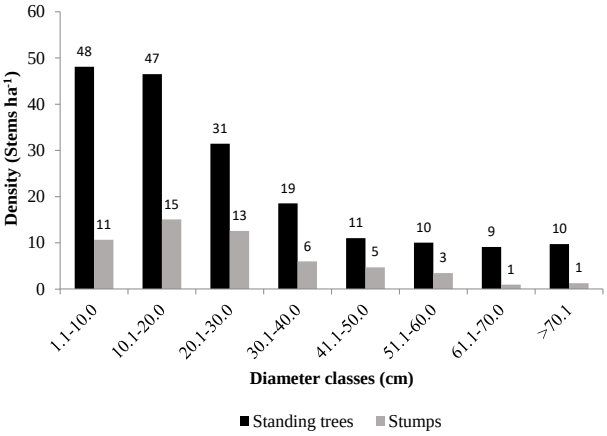

Figure 5. The distribution of density per hectare of standing tree species and shrubs with ≥ 5 cm DBH and stumps ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

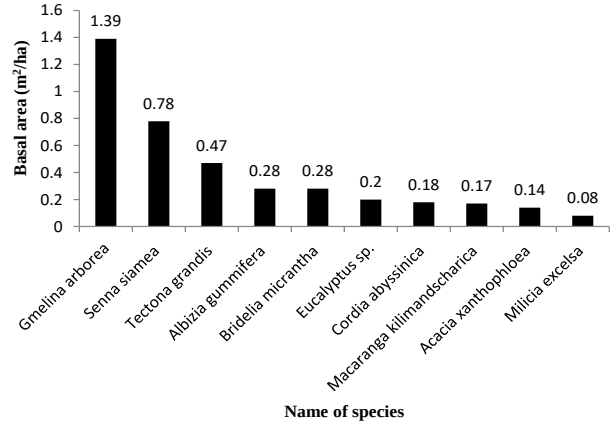

Figure 8. The 10 most abundant harvested species with high basal areas are found in Rau Catchment Forest Reserve (RCFR), Moshi district, Tanzania

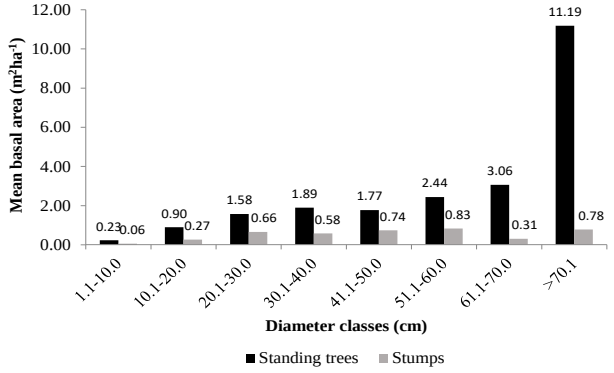

Figure 9. The distribution of basal area per hectare of standing tree species and shrubs with ≥ 5 cm DBH and stumps ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

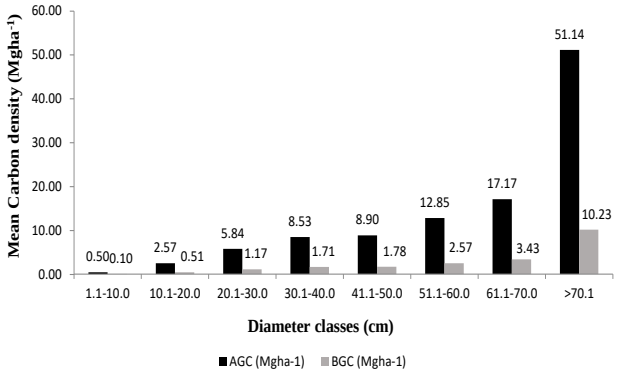

Figure 10. The distribution of above-ground and below-ground mean carbon density of standing tree species and shrubs ≥ 5 cm DBH by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi district, Tanzania

For felled trees, the species contributing most to the volume were *Bridelia micrantha* (34%), *G. arborea* (26%), *S. siamea* (11%), and *T. grandis* (9%) (Table 2). The distribution of stumps to size classes shows that trees with a basal diameter greater than 40.1 cm contributed more to the mean total harvested volume in the forest.

Generally, all stand structure attributes of RCFR (stem density, basal area, and volume) appear lower when compared to other tropical lowland, groundwater, riverine, and freshwater swamp forests (Table 3), except for the stem density of 136 stems ha^{-1} reported by Mligo (2015) from the Namatimbili lowland riverine, coastal forest in Tanzania (Table 3). Banya et al. (2021) reported a volume value of 741.3 m^3 ha^{-1} from the Kangari Hills swamp forest reserve in Sierra Leone. The lower stem density observed in this study could be due to the impact of human activities, particularly excessive tree-cutting, which has reduced the total number of stems in the reserve. This also accounts for the lower basal area and stand volume recorded in the forest. The higher density, basal area, and volume reported in other studies may be attributed to the intact conditions of those forests, which promote the occurrence of many individuals of a particular species, including those in higher DBH classes. The normal reversed "J" shape shown by the diameter class distribution indicates the dominance of small trees, suggesting a good regeneration status (Figure 5).

The dominance of *S. siamea*, *G. arborea*, *T. grandis*, *Eucalyptus* sp., and *Casuarina equisetifolia* among the standing exotic species in terms of stem density, basal area, and stand volume indicates that these species are taking advantage of open spaces created by illegal logging and other anthropogenic activities to establish themselves and grow in large numbers (Falck and Roponen 1994; Mhache 2019) (Figure 4; Table 1). These species, except for *T. grandis*, have been documented as invasive elsewhere (Binggeli et al. 1998; Witt and Luke 2017; CABI 2018), and their ability to suppress the growth of other species poses a threat to the survival of indigenous tree species in the reserve (Falck and Roponen 1994). For instance, *T. grandis* has been observed to alter forest floor conditions by producing a thick cover of old leaves, which hampers regeneration of other species (Falck and Roponen 1994). Introducing foreign species carries the risk of uncontrolled spread, which may affect soil composition, light conditions, and underground vegetation, thereby altering the overall character of the forest. Therefore, it is crucial to investigate the regeneration patterns of local species under the canopy of these exotic species to assess whether they pose a threat to the sustainability of indigenous trees in the reserve and to understand the potential consequences if these threats are not addressed.

The analysis of diameter class distribution for all exotic and indigenous species reveals that the majority of exotic species are concentrated in the lower diameter classes (<30.0 cm), indicating they are replacing indigenous species and affecting ecological succession (Figure 4). This highlights the need for measures to control the dominance and spread of exotic species to allow for the regeneration of native forest species. Efforts to prevent illegal tree cutting, which opens up the forest canopy and facilitates the spread of exotic species, should be intensified (Mavimbela et al. 2018).

Biomass and carbon storage

The mean above-ground and below-ground biomass and carbon stocks for trees and shrubs with a diameter ≥5 cm found in RCFR are presented in Table 1. The tree species contributing most to the observed above-ground carbon density were *F. sycomorus* (17%), *M. excelsa* (12%), and *G. arborea* (exotic) (10%). These same species also contributed significantly to the observed below-ground carbon density. The biomass and carbon distribution across different diameter classes exhibited a near-normal "J" shape (Figure 10), with biomass and carbon increasing as diameter size increased. Approximately 95% of the biomass and carbon were stored in large diameter classes (>70.1 cm), indicating the presence of large trees within the reserve.

Indigenous species contributed a larger share (74%) to the total mean above-ground biomass and carbon stock compared to exotic species, which contributed 26% (Table 1). Among the indigenous species, *F. sycomorus*, *M. excelsa*, *Syzygium guineense* (Willd.) DC, *N. buchananii*, and *B. micrantha* contributed the most to the observed above-ground carbon density. On the other hand, the exotic species that contributed the most to the observed above-ground carbon density were *G. arborea*, *Eucalyptus* sp., *S. siamea*, and *T. grandis* (Table 1). Similar trends were observed in the below-ground biomass and carbon stock of the forest reserve.

The total mean above-ground carbon stock of trees and shrubs with DBH ≥ 5 cm, which was found to be 107.48 ± 61.28 Mg C ha^{-1} in this study, is lower than those reported in other tropical forests (Agboola et al. 2021; Mauya and Madundo 2021; Buragohain et al. 2023). For example, Mauya and Madundo (2021) observed carbon stocks in six lowland forest reserves in the East Usambara tropical mountain forests of Tanzania, with values ranging from 128.70±23.28 Mg C ha^{-1} (Kwamngumi) to 166.20 ± 37.18 Mg C ha^{-1} (Longuza). Agboola et al. (2021) reported carbon stocks ranging from 98.67 Mg C ha^{-1} to 555.95 Mg C ha^{-1} in six lowland forests in Nigeria, while Buragohain et al. (2023) reported carbon stocks of 142.74 Mg C ha^{-1} and 185.89 Mg C ha^{-1} from the Kakoi reserve forest in India.

The higher carbon stock values reported in these studies could be attributed to the presence of numerous large trees, which contribute significantly to the overall forest carbon density. In contrast, the lower value observed in this study may be due to the dominance of trees in lower diameter classes, leading to a lower contribution to the total carbon stock (Figure 4). Other factors such as the study area, stand characteristics, sampling methodology, level of disturbance, geographical variation, and temporal variation could also contribute to the observed variability in carbon stock results.

In conclusion, the results of this study indicate that RCFR has a high diversity of woody species (H'=2.91) but low species richness (29 species), particularly when compared to other lowland, riverine, and freshwater swamp forests in Tanzania and other tropical regions. Tree density and basal area in RCFR are also lower than those reported in other tropical forests. Similarly, the carbon stock in this study was lower than values found in other lowland and groundwater forests. Among the species, *S. siamea* (exotic) was the most overexploited, appearing in 16% of the plots.

The carbon stock estimates presented here provide valuable baseline data for monitoring changes in carbon storage within the forest. To sustain or enhance the biodiversity and management of RCFR in the future, we recommend that efforts to protect the forest be intensified. This should include monitoring the dominance and spread of exotic species and safeguarding the reserve from encroachment. Furthermore, assessing the regeneration patterns of local species under the canopy of both indigenous and exotic species is crucial to determine whether the presence of exotic species threatens the sustainability of native species in the reserve. Additionally, future studies should consider quantifying carbon stock in other carbon pools to provide a more comprehensive estimate of the total carbon stock in the forest.

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Developing a mud crab ecotourism business model in the mangrove forest ecosystems of Belitong UNESCO Global Geopark, Indonesia

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Abstract. *Mahbubi A, Fatoni A, Iskandar. 2025. Developing a mud crab ecotourism business model in the mangrove forest ecosystems of Belitong UNESCO Global Geopark, Indonesia. Asian J For 9: 13-23.* The traditional mud crab business model, which involves trading fresh mud crabs, exhibits limited sustainability, particularly in the Belitong UNESCO Global Geoparks (Belitong UGGp) mangrove area. *Scylla tranquebarica* (Fabricius, 1798) is more abundant than *Scylla serrata* (Forskål, 1775) and other mud crab species in the Belitong UGGp. This study aims to develop a mud crab ecotourism business model within the Belitong UGGp mangrove forest ecosystem. This study employs a qualitative approach. Data were collected through interviews with mud crab catchers and mangrove forest tourists, as well as focus group discussions with Belitong UGGp management, the Indonesian Tourism Association, and the tourism and creative economy office of the Belitong District Government. The data analysis in this study used content analysis involving the Business Model Canvas (BMC), empathy map, and value innovation framework. The qualitative analysis procedure covered the phases of data condensation, presentation, and conclusion or verification. The reliability of the study, tested using the kappa coefficient, yielded an excellent score of 0.81. Promoting innovation in business models involves creating diverse products and mud crab ecotourism programs, such as culinary offerings, snacks, souvenirs, educational tours, and tracking; fostering activities, such as mud crab processing; and establishing resources, such as mud crab galleries. In addition, it will enhance customer relationships and stakeholder collaboration, reduce the trade of fresh mud crabs with consumers outside the region, and eliminate small mud crab fishing.

Keywords: Business model, ecotourism, innovation, mangrove forest, mud crab

INTRODUCTION

Indonesia leads the global mangrove forest area, with a staggering 20% of the 147,359 km^2 (United Nations Environment Program 2023). Mangrove and seagrass forests in Indonesia are the main focus of achieving sustainable coastal ecosystems (Sidik et al. 2023). According to Karniati et al. (2021), mangrove forests are the primary habitat for numerous fishery commodities, particularly mud crabs. The mud crab is a crab from *Scylla*, comprising four species: *Scylla serrata* (Forsskål, 1775), *Scylla olivacea* (Herbst, 1796), *Scylla tranquebarica* (Fabricius, 1798), and *Scylla paramamosain* (Estampador, 1949) (Keenan et al. 1998). Mud crabs are commonly found in Indonesian mangrove forests, including Sulawesi (Hamid and Wardiatno 2018), Bali (Ginantra et al. 2021; Swasta et al. 2023), Java (Fitri et al. 2017), and Sumatra (Sari et al. 2021). In Belitong, *S. tranquebarica* was more abundant than other species of mud crabs (Sari et al. 2021). Generally, mud crabs are not extensively cultivated and are primarily traded in their live or fresh states.

The potential of mud crabs to become a leading agritourism in Indonesia has not yet been fully realized. However, the diversity of crabs in mangrove ecosystems holds considerable promise for ecotourism development in this region (Irwansyah et al. 2021). In Kenya, mud crabs have long been used as primary menu items in agro-food tourism at various local tourist attractions (Mirera 2017). Specifically, Tranter et al. (2022) reminded us that stakeholders must manage the development of fishery tourism well to avoid negative impacts on the environment and society.

The ecotourism approach can foster economic, environmental, and social sustainability. Studies have shown that ecotourism has minimal impact on ecology (Arif et al. 2022). However, mud crabs have not yet been widely promoted as a leading tourism attraction in the form of mud crab ecotourism. Adlan and Yusof (2024) have only proposed the establishment of a mud crab ecotourism center in Malaysia, focusing on the design of mud crab ecotourism products and services. The development of innovative products requires business model innovation (Visnjic et al. 2016). In order to achieve success, business actors must align product innovation, particularly in the context of mud crab tourism, which requires urgent business model innovation, including adapting product innovation to process, marketing, and organizational innovation (Tavassoli and Bengtsson 2018). Bagnoli et al. (2021) suggested that businesses should develop their business models after the covid-19 pandemic. Therefore, it is crucial to refine product innovation through the development of a business model. The concept of a business model is applicable to a diverse range of businesses (Hock-Doepgen et al. 2021). Therefore, the

business model approach can serve as a means to facilitate the advancement of Belitong UGGp.

The Belitong UNESCO Global Geoparks (UGGp) region presents a promising opportunity to establish a mud crab ecotourism business model, considering the extensive mangrove forests that are over a century old, such as those found in the granitic mangrove forest of the Kuale geosite. The Gunung Kubing Geosite is another notable mangrove forest in the Belitong UGGp area, which serves as a source of mangrove crabs for local food and commodities markets, as well as for international markets. Given the popularity of the Kuale Geosite as an ecotourism destination for old mangrove forests, it is essential to position the Gunung Kubing geosite as a mangrove crab ecotourism destination through the development of a mud crab ecotourism business model.

The development of a mud crab ecotourism business model in the Belitong UGGp area is a strategy for sustainable mud crabs that preserves the environment, provides added value to geological heritage and local communities, encourages the creative economy to create jobs, and emphasizes the authenticity of products, producers, and restaurants within the geopark area. Liu et al. (2017) noted that agri-food tourism is an eco-innovation strategy that integrates agricultural and food products with tourism services, prioritizing sustainability to meet customer values. This study aims to formulate a mud crab ecotourism business model within the Belitong UGGp mangrove ecosystem by first examining the existing business model and the perspectives of mangrove ecotourism customers.

MATERIALS AND METHODS

Study area

Indonesia ranks among the top five countries with the highest number of geoparks recognized by UNESCO. One of the geoparks is the Belitong Geopark, in Belitung District, Bangka Belitung Islands Province, Indonesia, which has attained the highest score in the history of Indonesian geopark submissions to the UNESCO Global Geopark, specifically 850 of a maximum of 1,000 points. The Belitong Geopark stands out for its exceptional integration of geological, biological, and cultural components. This distinctive landscape features an extensive mangrove forest ecosystem that provides habitat for a wide array of plant and animal species.

Kuale and Gunung Kubing geosite boast substantial mangrove ecosystems in the Belitong UNESCO Global Geopark (Belitong UGGp) area. The Kuale geosite is distinguished by its mangrove forests, which surpass 100 years old. Therefore, the Belitong UGGp management has positioned this geosite as an ancient mangrove ecotourism destination. In contrast, the Gunung Kubing Geosite is comprised of relatively young and muddy mangrove forests. This muddy mangrove forest area serves as the primary habitat for mangrove crab reproduction (Pati et al. 2023).

As a recently incorporated geosite within the Belitong UGGp, the Gunung Kubing geosite has not attained the same level of recognition as the Kuale geosite. Considering these distinct characteristics, it is strategically advantageous to develop Gunung Kubing as a specialized ecotourism site that focuses on mud crab habitat. Therefore, this study was conducted at the Gunung Kubing Geosite, Belitong UGGp (Figure 1).

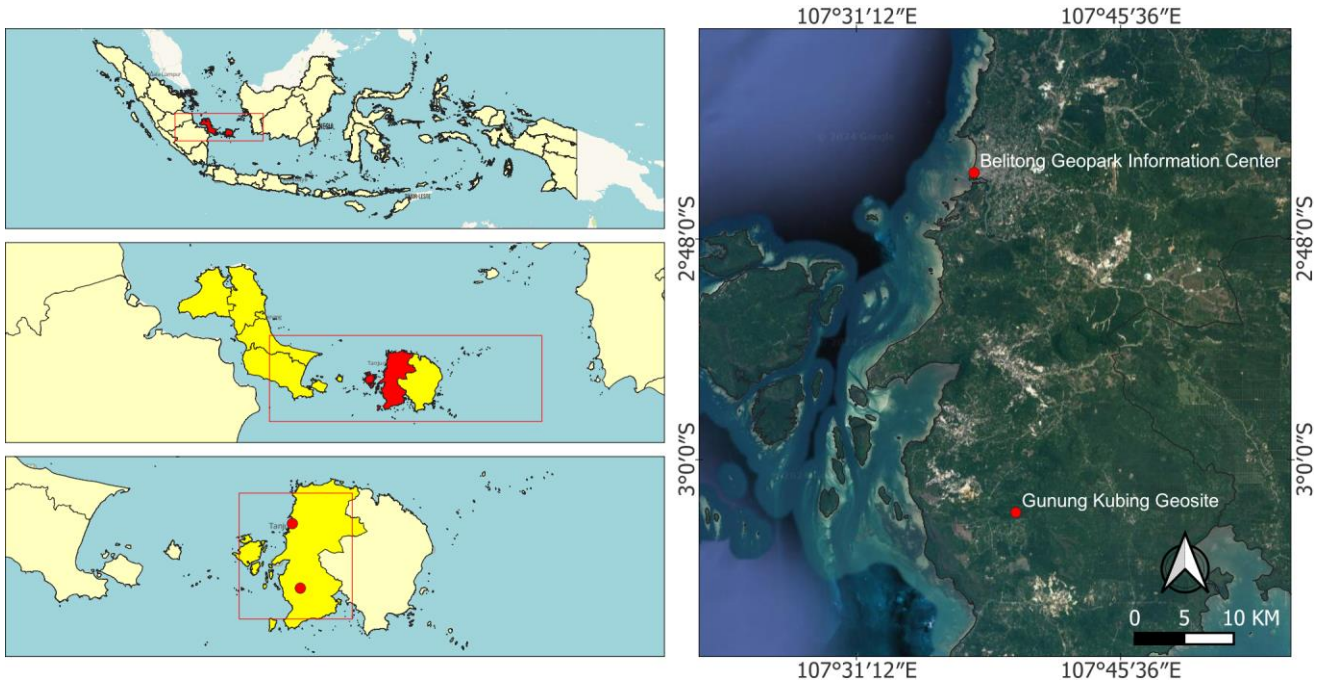

Figure 1. Location of Gunung Kubing Geosite, the Belitong UNESCO Global Geopark UGGp) in Belitung District, Bangka Belitung Islands Province, Indonesia

Data collection

This study employed a qualitative design utilizing a phenomenological approach. This study involved 65 participants, comprising 30 mud crab catchers (coded M1 to M30), 30 tourists (coded T1 to T30), and five key stakeholders: two representatives from Belitong UGGp Management (coded B1 and B2), two from the Indonesian Tourism Association (coded A1 and A2), and one from the Belitong Government's Tourism and Creative Economy Office (coded G1). The study participants were selected based on specific criteria, such as mud crab catchers living around the mangrove forest and being members of forest village community institutions, tourists visiting Gunung Kubing at least twice, the Indonesian Tourism Association regularly taking tourists to this area, and the head of the government.

The questions for participants referred to the elements of the Business Model Canvas (BMC), empathy map, and value innovation framework. The BMC comprises nine elements: value proposition, key activities, key resources, key partners, customer relationships, customer segments, channels, cost structure, and revenue streams. BMC assists in understanding how an entrepreneur generates revenue. The empathy map contained six elements of customer insight: see, hear, think and feel, say and do, gain, and pain. This map serves as a tool during the interview process to describe customer insights and is subsequently used to formulate a business model. Value innovation comprises one page with four blocks: eliminating value propositions that customers do not require, reducing value propositions that customers do not need, increasing value propositions that customers need, and creating value propositions that customers really need.

This study collected data in two phases. The first phase explores the existing mud crab business model. This involved conducting in-depth interviews with mud crab catchers and directly observing their commercial activities at the Gunung Kubing Geosite, Belitong UGGp. Observational data were captured using digital photography and detailed field notes, encompassing both descriptive and reflective elements. In addition, a focus group discussion was organized with key stakeholders. These discussions centered on the current business model and the potential for ecotourism at the Gunung Kubing Geosite, Belitong UGGp. The second phase investigated customer insights at the Gunung Kubing Geosite, Belitong UGGp. This phase entailed conducting interviews with tourists who had visited the location. Relevant documents were collected in both phases, including journals, newspapers, proceedings, and visual materials owned by informants.

Data analysis

The data analysis adopted Miles and Huberman's practical framework. The qualitative analysis procedure covered the phases of data condensation, presentation, and conclusion or verification.

Condensing the data

This phase consists of various procedures: selecting, simplifying, abstracting, and transforming the data that appear in the entire body of written field notes, interviews, transcripts, and documents. Data selection involves highlighting pertinent data pertaining to each aspect of the business model canvas. We also assigned numerical codes to each dataset, comprising interview transcripts, videos, and images. Also, data selection was actually conducted up to the focusing stage, particularly regarding the quality and sufficiency of the data pertaining to the nine components of the business model and consumer empathy map, which were both deemed satisfactory. This information was used to address the research objective. To guarantee that there were no missing or incorrect data, we repeated this abstraction process three times and carefully examined the attributes of the nine elements of the business model and empathy map. We moved on to the next stage only after confirming that this process had been completed and that there were no missing or mixed-color marks. Following the abstraction stage, the data were streamlined and refined through extensive selection, data classification, and concise descriptions.

Presenting the data

This action facilitates the comprehension of the business model canvas's nine elements, the empathy map, and value innovation, either as a whole or in specific segments.

Concluding or verification

Data verification in qualitative research was conducted continuously throughout the study. From the beginning of entering the field and during the data collection process, we tried to analyze and search for the meaning of the words collected, namely, looking for patterns, themes of relationships, things that arise, hypotheses, or so be outlined in tentative conclusions. With the addition of data through a continuous verification process, conclusions can be drawn from the figures and narratives.

Triangulation and kappa statistical tests were performed to assess the validity and reliability. The kappa coefficient obtained was 0.81, which is an excellent agreement, surpassing the threshold of 0.75. Qualitative data analysis also utilizes NVIVO software, a tool that facilitates the capture, transcription, coding, and examination of textual and graphical data.

RESULTS AND DISCUSSION

The existing mud crab business model in the mangrove ecosystems of Belitong UNESCO Global Geopark

The Belitong UGGp mangrove forest serves as a breeding ground for mud crabs to provide alternative subsistence for local communities. Torres et al. (2022) categorized mud crabs as coastal trap fisheries. During the COVID-19 pandemic, when tourists were restricted due to lockdown measures, these crabs became the main source of income for the community living in the Belitong UGGp area. Mud crab catchers found more *S. tranquebarica* (Fabricius, 1798) than other mud crab species in the Belitong UGGp mangrove forest. Figure 2 illustrates the existing mud crab business model.

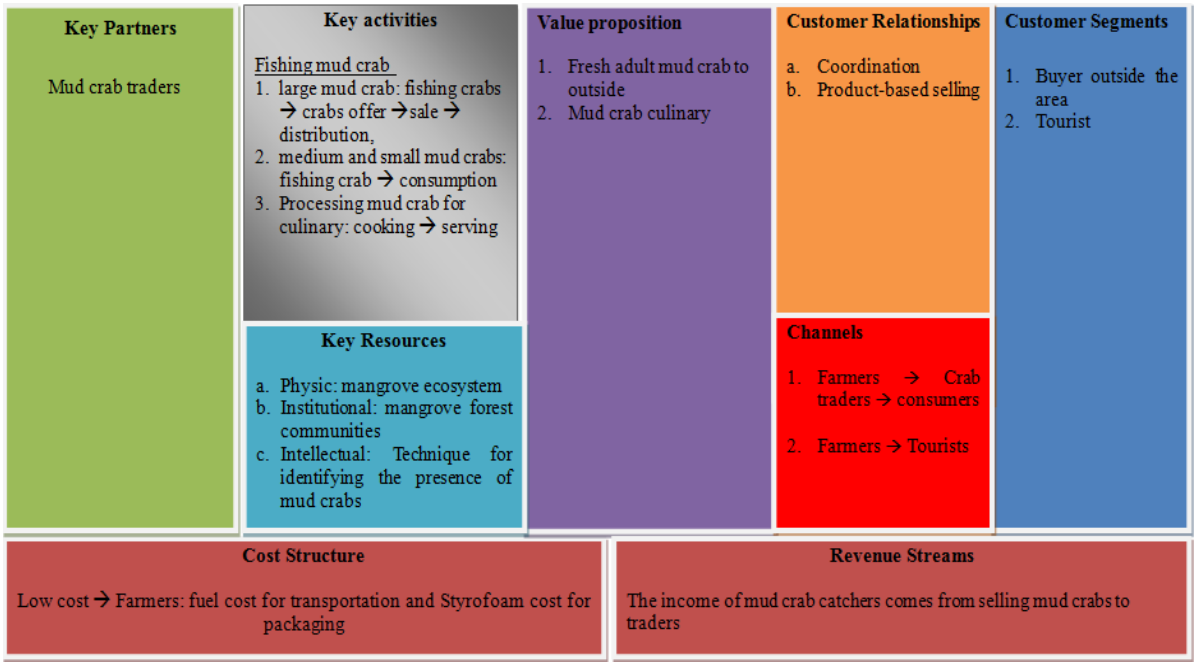

Figure 2. Existing mud crab business model in the mangrove ecosystems of Belitong UGGp, Belitung District, Indonesia

Value proposition

Mud crab catchers trade fresh adult mud crabs outside of the Belitong UGGp area. The weight of adult mud crabs sold must meet the Indonesian standard set by the Ministry of Marine Affairs and Fisheries Regulation number 7 of 2024. According to these regulations, mud crabs that can be transported must not lay eggs, have a carapace width of > 12 cm, and weigh > 150 g. The largest mud crab (1890 g) was found on the island of Sumatra, Indonesia, by Cahyadinata et al. (2021). Mud crabs are rarely traded in the Belitong UGGp tourist area, indicating that they are not widely processed into local food served by tourists, even though mangrove forests are the main destination of choice for tourists in the Belitong UGGp. As stated by Rukisah et al. (2021), this commodity is considered a delicious and healthy food.

"*I consistently sell adult mud crabs weighing in excess of 500 g per specimen to collectors, and we rarely provide mud crab culinary offerings*." (Interview with M1, M4, M6, M7, M10, M11, M15, M19, M24, M27, M28, M29, and M30).

"*Tourists must place orders in advance if they desire a mud crab specialty menu when visiting*." (FGD with A1, A2, B1, B2, and G1).

Customer segments

Mud crab customers are primarily inter-regional traders. This finding aligns with the research conducted by Yolandika et al. (2023), in which the consumer segment for fishery commodities is typically traders. This suggests that crab catchers typically sell fresh crabs to traders rather than end or household consumers. The Belitong UGGp area has the potential to process mud crabs into locally branded food that can be sold directly to visitors.

"*The primary consumers of these products are mud crab collectors from regions outside the Gunung Kubing area. Direct purchases by tourists are infrequent*." (Interviews with M2, M3, M5, M8, M9, M12, M13, and M14 as well as FGD with A1, A2, B1, B2, and G1)

Customer relationships

Griesemer and Shavit (2023) categorized interactions between groups into three types: coordination, cooperation, and collaboration. Based on this classification, the interaction between mud crab farmers and their customers is limited to coordination. Frow and Payne (2009) identified four types of customer relationship management: product-based selling, customer-based marketing, managed services and support, and individualized customer relationship management. Mud crab catchers establish relationships with customers that fall within the product-based selling category.

"*I coordinate with the crab collectors when there are quite a lot available*." (Interviews with M4, M7, M8, M12, M15, M18, M22, M23, M26, M28, and M29)

Channels

The marketing channel for mud crabs involves catchers selling to collectors, who then sell to traders in Jakarta for exportation via importers in the destination country. Ultimately, this channel provides end consumers with mud crab cuisine at various international restaurants. This channel is similar to the supply chain of mud crabs from Bangladesh to the global market, as reported by Bhuiyan et al. (2021).

"*I got information from a mud crab collector that the mud crabs were exported to ASEAN countries to become part of the favorite menu in restaurants in the destination*

countries." (Interviews with M1, M2, M3, M5, M7, M16, and M17).

Key activities

The mud crab catchers catch adult crabs weighing more than 500 g, then tie the mud crabs and put them into a Styrofoam container, offering and selling the mangrove crabs to collectors. This weight was categorized as large based on the classification by Paran et al. (2022). They classified mud crabs above 500 g as large, 400-500 g as medium, and sizes below 400 g as small. Crab catchers consume mud crabs caught in small-to-medium sizes between 200-500 g. Small mud crabs have the potential to be raised or released to maintain the sustainability of mud crabs in the Belitong UGGp area.

"*I get mud crabs by fishing in the mangrove forest area of the Gunung Kubing geosite. There are many crabs in a location based on traces or nests of mangrove crabs. We returned young crabs caught for the sustainability of mangrove crabs. we tie and pack mangrove crabs in styrofoam*." (Interviews with M2, M5, M6, M8, M10, and M11)

Key resources

The Belitong UGGp boasts extensive mangrove forests, particularly at the Gunung Kubing geosite. Water in these mangrove forests serves as the primary habitat for mud crabs (Indarjo et al. 2020). Another important resource is the Village Forest Management Institution, which includes mangrove forests members of which are also mangrove crab catchers. This institution aims to manage forest resources, including mangrove forests, sustainably, based on principles of sustainable development (Dewi et al. 2021). In addition, its members can identify the presence of mud crabs at a specific location. Overall, the local mangrove ecosystem community plays a role in maintaining and improving the ecosystem health (Elwin et al. 2024).

"*During the COVID-19 lockdown, tourist visitation to the Gunung Kubing geosite ceased. However, our residence in a mangrove forest area, which serves as a habitat for mud crabs, has proven to be advantageous. As a member of a forest community institution, I utilized this ecosystem as an alternative source of livelihood. I refined our understanding of mud crab behavior through field-based observations*." (Interviews with M1, M2, M7, M9, M12, M18, and M20)

Key partners

Individuals engaged in mud crab harvesting within the Gunung Kubing Belitong UGGp geosite region concentrated on collaborating with collector traders. They are yet to engage in discussions and consultations regarding the potential and application of mud crabs for ecotourism within the Belitong UGGp. Clarke and MacDonald (2019) posited that the establishment of sustainable local development requires cooperation among various stakeholders.

"*My main partners are mud crab traders. I have not discussed seriously with the Belitong UGGp management regarding the development of mud crab ecotourism. No party from the campus has explored the potential of mud crabs in this area*." (Interview with M3, M5, M7, M9, M11, 16, M18, M20, M22, M24, M25, M27, M29, and M30).

Cost structure

According to Goyal et al. (2018), a business model's cost structure encompasses operational expenses, transportation, and logistics. Typically, the cost structure of mud crab catching is characterized by low cost. The costs associated with this business model are primarily comprised of fuel costs for the vehicles used to travel between home and the mangrove forest waters for catching mud crabs, as well as the expense of purchasing styrofoam for packaging the crabs.

"*I catch the mud using minimal expenditure, primarily incurring costs for fuel used in transportation from residential areas to mangrove forest waters and for the purchase of styrofoam packaging materials for the mud crabs*." (Interview with M8, M10, M12, M17, M18, M20, M22, M24, M26, M27, and M28)

Revenue streams

Revenue streams refer to how business actors make money (Müller 2019). The income of mud crab catchers comes from selling mud crabs to crab traders. The income of mangrove crab catchers is contingent on the quantity and weight of the crabs they are able to catch. The greater the quantity and weight of the mangrove crabs caught, the higher the income.

"*The income generated is contingent upon the quantity and mass of crustaceans obtained through fishing activities. The market price remains relatively constant*." (Interview with M3, M5, M7, M9, M11, M12, M14, M16, M19, M21, M23, M25, M28, and M30 as well as FGD with A1, A2, B1, B2, and G1)

Customer insight of mangrove tourism of Belitong UNESCO Global Geopark

The success of business model innovation is contingent upon customer evaluation, which is based on their experience (Keiningham et al. 2019). Business model innovation requires a comprehensive understanding of the environment, routines, concerns, and aspirations of customers (Osterwalder and Pigneur 2010). They underscored the importance of viewing a business model from the customer's perspective. In addition, they recommended utilizing the empathy map created by XPLANE to delve into customer preferences. Fishing tourism managers must consider various concepts and expectations of tourists (Lankia et al. 2022), including fishery products that must meet customer desires (Zander et al. 2022). This section explores the insights of tourists who visited the mangrove ecosystem, Belitong UGGp, using the elements of the empathy map to design a mud crab ecotourism business model (Figure 3).

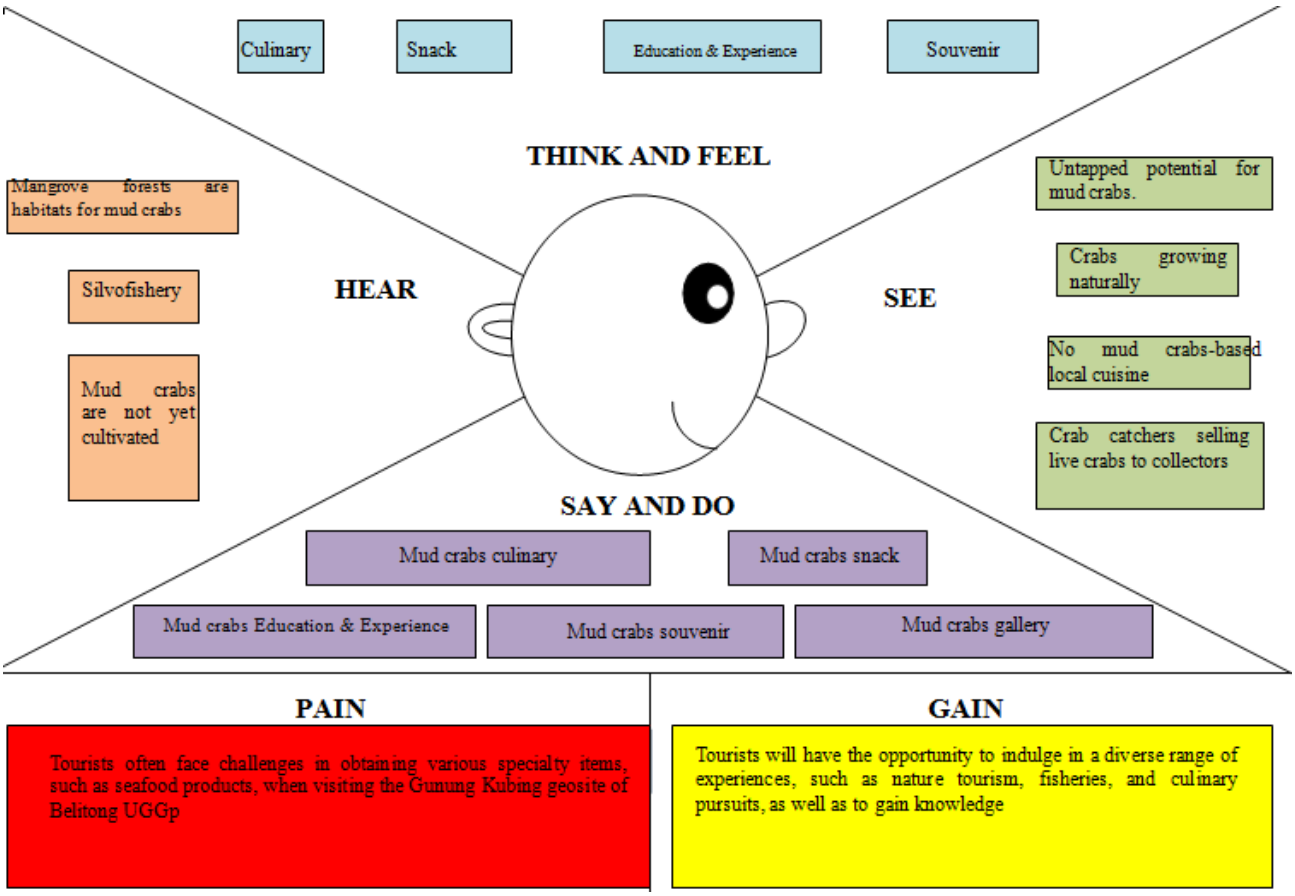

Figure 3. Customer insight into mangrove tourism of Belitong UNESCO Global Geopark, Belitung District, Indonesia

Tourists to the Gunung Kubing Geosite mangrove area in the Belitong UGGp discovered an untapped potential for mud crabs. They observed crabs growing naturally in the area as well as crab catchers selling live crabs to collectors, but none had processed them into local cuisine for visitors to consume. According to Nanda et al. (2021), crabs are highly regarded because of their delicious taste, significance as a nutritional source, and the versatility of crab waste, which can be used to produce various products, such as souvenirs. For instance, mothers in South Sulawesi successfully produced processed spicy and sour crabs (Rusydi et al. 2022).

"*I found many crabs in the mangrove forest area at the Gunung Kubing Geosite, Belitong UGGp. I met mud crab catchers who sell crabs to collectors, and I have never encountered local culinary made from local crabs consumed by tourists*." (Interview with T10, T15, T18, T21, T24, T27, T28, T29, and T30)

Tourists have heard that mangrove forests are habitats for mud crabs that can be cultivated using the silvofishery system. According to Wamnebo (2018), silvofishery is the cultivation of fishery commodities with the aim of obtaining fishery products and preserving mangrove plants. They received information that the mangrove crabs had not been cultivated in the Belitong UGGp.

"*I have heard from various mass media that mangrove forests are habitats for mud crabs. I also heard from mud crab catchers that they did not cultivate mud crabs. In fact, I have heard of silvofishery, an integrated fish farming system in the mangrove forest area*." (Interview with T2, T3, T4, T5, T7, T9, T11, T13, T16, T17, T19, T20, and T22)

Tourists perceive that the Belitong UGGp, especially the Gunung Kubing geosite area, has the potential to develop a variety of culinary items, snacks, and souvenirs using mud crabs. They also believed that this region had the potential to establish educational programs and explore mud crabs, including a mangrove crab gallery. This perspective represents future aspirations. Muñoz-Vilches et al. (2020) stated that consumer imagination can provide a new perspective on consumer insight.

"*The Gunung Kubing Geosite - Belitong UGGP exhibits potential for the development of mangrove crabs as a specialty culinary offering, source of accessories, and the subject of a dedicated gallery. Furthermore, this area demonstrates considerable merit in presenting various mangrove crab-based attractions*." (Interviews with T6, T8, T12, T14, and T25)

The visitors suggested creating culinary items, snacks, and mementos made from mud crabs, educational programs, crab exploration, and the construction of a mud crab museum. This proposal aligns with Adlan and Yusof (2024) proposal to advance crab tourism. However, their

recommendations were limited to the architectural design of a mud crab ecotourism building in Perak, Malaysia.

"*I emphasize the development of crab-based products integrated into product package offerings*." (Interview with T1, T2, T8, T9, T14, T15, T17, T18, T19, T22, T23, and T26)

Furthermore, travelers often face challenges in obtaining various specialty items, such as seafood products, when visiting the Gunung Kubing geosite of Belitong UGGp. Generally, they find traditional food options with limited variety and availability in certain locations. Local cuisine is a crucial factor that tourists consider when selecting a destination to visit (Cankül et al. 2024).

"*I have difficulty getting food, snacks, and souvenirs that are typical of the Gunung Kubing Geosite, and are not easily obtained because they are not available at public stalls around the location*." (Interview with T3, T7, T11, T12, T13, T17, T18, T21, T24, T27, T29, and T30)

Finally, tourists have the opportunity to indulge in a diverse range of experiences, such as nature tourism, fisheries, and culinary pursuits, as well as to gain knowledge. The site offers a unique opportunity to observe sustainable practices surrounding mangrove crabs and forests, which will undoubtedly prove to be an attractive feature for visitors. A study conducted by Goffi et al. (2019) revealed that tourists place a high premium on the sustainability aspects of a destination because it significantly contributes to their overall satisfaction, particularly among Large-Scale Coastal Package Tourists (LCPTs), assuring a fulfilling experience for all.

"*I will have the opportunity to enjoy mud crab-based tourism if these products are available*." (Interview with T1, T4, T8, T12, T16, T18, T19, T20, T21, T24, T25, T27, T29, and T30)

Mud crab ecotourism: the future mud crab business model in the Belitong UNESCO Global Geopark, Indonesia

Based on customer insights from previous discussions, the existing mud crab business model is evaluated using the value innovation framework (ERRC–Eliminating, Reducing, Raising, and Creating) developed by Kim and Mauborgne (2005). The design of the mud crab ecotourism business model is illustrated in Figure 4. According to Foss and Saebi (2017), there are four types of business model innovation: modular, architectural, radical, and incremental. A mud crab ecotourism business model can be classified as an architectural business model innovation that involves exploring new ways, activities, and relationships among business model components. This shift in profession from mud crab catchers to mud crab farmers has altered the business model design from a traditional mud crab trading model to a mud crab ecotourism model. In the context of customer relationships, the shift also moves from product sales-based customer relationships to customer-based marketing and managed services and support (Frow and Payne 2009).

Figure 4. Mud crab tourism: the future mud crab business model in the mangrove ecosystems of Belitong UGGp, Belitung District, Indonesia. Note: Text highlights = pink was eliminated, yellow was reduced, green was raised, and blue was created

Value proposition

The challenge for the fresh fish business is to provide quality fish throughout the year (Bertheussen et al. 2020), potentially leading to over-exploitation by fishermen. Crab farmers should take steps to limit the sale of fresh adult mud crabs outside the Belitong UGGp. In addition, these farmers process crabs into culinary and processed foods served by tourists visiting the Belitong UGGp geosite. Doucek and Zelenka (2018) revealed that farmers produce geofood in the form of local specialties that can be used as souvenirs after returning from geopark tourism. Farmers can also create mud crab souvenirs from crab shells, which would otherwise be wasted. Zilia et al. (2021) classified this effort as the implementation of a sea product circular economy. Farmers can also offer mud crab education and experience programs in the form of mud crab fishing and tracking. Liontakis and Vassilopoulou (2022) reported that fishing tourism positively affects the incomes of individual fishermen.

Customer segments

The structure of the mud crab ecotourism business model reconfigures customer segments by diminishing the sale of mangrove crabs to the trader-collector group and increasing the sale of fresh crab products to the tourist customer group, which encompasses general mangrove tourists, mud crab aficionados, and academicians. This change in the consumer segment encourages manufacturers and consumers to support the sustainability of mud crabs. In addition, consumers play a role in preserving crabs' sustainability; White et al. (2019) classified this action as sustainable consumer behavior.

Customer relationships

As indicated by Greisemer and Shavit (2023) concept of customer relationship patterns, the mud crab ecotourism business model changes its relationship pattern from coordination to collaboration. Dash and Balamurugan (2024) called for stakeholders to collaborate with local communities in an adaptive governance framework for fishery tourism development that does not harm aquatic species. Castañer and Oliveira (2020) defined collaboration as voluntarily assisting partners in achieving their goals, as exemplified by Lakshminarasimha (2017), through sharing of information and joint performance measures. Furthermore, the mud crab ecotourism business model shifts the relationship pattern from product-based selling to customer-based marketing, as identified by Frow and Payne (2009) customer relationship category. This approach focuses on customers who provide various products to meet the diverse needs of tourists, as seen in the Belitong UGGp mangrove forest area, where the mud crab ecotourism business model offers a range of processed products such as culinary items, snacks, and souvenirs.

Channels

The proposed business model advocates a distribution network that connects farmers to souvenir stores and then to tourists while also establishing a streamlined marketing channel for mud crabs that allows farmers to sell directly to tourists. Various distribution channels can enhance customer access to products (Kennedy et al. 2022). In addition, implementing an omnichannel strategy that integrates both offline and online channels is essential to provide a seamless and unified customer experience.

Key activities

The proposed business model for mud crab ecotourism recommends curtailing the trade of mud crabs beyond the Belitong UGGp area and discontinuing the consumption of small mud crabs for farming. Mud crab farming tourism avoids trampling by tourists. Park et al. (2024) stated that recreational trampling poses a serious threat to the extinction of the white-clawed fiddler crab in South Korea. The emergence of various new value propositions is expected to generate new activities, such as mud crab cultivation through silvofishery systems. The sustainability of mud crab cultivation requires capital availability, training capacity, and feed affordability (Apine et al. 2023). Financial capital is the most limited capital for mud crab farmers (Apine et al. 2019). In addition, other new activities include cooking, serving, wrapping, offering program packages, and receiving program package orders. Sjödin et al. (2020) revealed that the success of creating new value propositions hinges on the alignment of value-creation activities.

Key resources

Farmers, who are valuable human resources in mud crab ecotourism, must enhance their knowledge and skills to build positive relationships with customers and silvofishery systems. According to Khan et al. (2022), good relationships are a crucial element in attracting customers. Moreover, Herman et al. (2020) stated that Customer Relationship Management (CRM) is a useful tool for managing long-term relationships between companies and customers, resulting in customer loyalty and satisfaction. It is also important to note that Destination Management Units (DMOs) should be established to assist in the governance of ecotourism. These units will play a vital role in maintaining environmental sustainability, ensuring fair business practices, improving access to information, and enhancing tourist satisfaction (Trang et al. 2023). Arfan et al. (2021) stated that the implementation of silvofisheries supports the sustainability of mangrove forest ecosystems. Finally, the role of the mud crab gallery as a mud crab ecotourism infrastructure should not be ignored because it also contributes to these efforts.

Key partners

According to Budhi et al. (2022), collaboration with various stakeholders is essential for achieving shared innovation objectives and ensuring the long-term sustainability of a tourist destination. Local communities must be aware of this ecotourism business model development program. Azad et al. (2021) reported that the majority of local communities around the Sundarban mangrove ecosystem did not obtain information about the development program in their area. In addition, local communities need to be asked for their consent and

involvement as mud crab farmers, not catchers. Afifah et al. (2023) reported that local communities usually agree with the development of ecotourism in mangrove forests. Local community participation can help conserve mangrove forest resources (Dutta and Hossain 2020). Therefore, mud crab farmers and managers must partner with a range of institutions, including the government, particularly fisheries services, to receive assistance by implementing the silvofishery system. Tourism actors, the media, educational institutions, and the global community must be engaged in joint promotion, education, and research, as well as the certification of mud crab-based food products.

Cost structure

The cost structure of producing valuable products depends on various activities. These activities are known as cost drivers, and their magnitude depends on the time required to complete each activity. For example, there are several preparation, spread, and maintenance activities during the mud crab cultivation stage. According to Rahman et al. (2020), the spread of crab seeds is the largest source of the total cultivation costs. Another example is the stage of making food from mangrove crabs, during which there is a cooking and wrapping process. As Elshaer (2022) found, production activities that take the longest time are the largest source of cost for providing one of the food menus in a restaurant.

Revenue streams

According to Remeňová et al. (2020), revenue stream in a business model refers to the value proposition offered to customers. It is not limited to the sale of mud crabs to traders but also includes various processed crab products sold to tourists in the Belitong UGGp area, such as culinary products, snacks, and souvenirs. In addition, the income of mud crab farmers is augmented by mud crab edu tours and experience programs.

In conclusion, the mud crab trading business model in the Belitong UGGp mangrove ecosystem should evolve into a mud crab ecotourism business model that represents a significant transformation in the development of the mud crab industry. Value innovation in this business model is achieved through the creation of various products and mud crab ecotourism programs, such as culinary, snacks, souvenirs, and educational tours. New activities, including mud crab processing and new resources such as mud crab galleries, support these value propositions. The business model also benefits from new partnerships, such as collaborations with the geofood global community. Additionally, value innovation in the business model involves improving customer relations from coordination to collaboration and from product-based selling to customer-based marketing, which includes adding tourist consumer segments and channels and increasing cooperation with various stakeholders. However, there are additional costs associated with creating added value for farmers and managers of Belitong UGGp. In addition, value innovation in the business model includes reducing the trade of fresh mud crabs with collectors for consumers outside the region and eliminating the activity of harvesting small mud crabs. For future studies, we propose to explore the value chain of mud crab ecotourism, encompassing cost evaluation through activity-based costing and value-added distribution assessments. Future research is needed to design a mud crab gallery in the Belitong UGGp mangrove forest. Investigating the opportunities and challenges at each stage of the transition process from the traditional business model to the new one could provide valuable insights. Market research is also essential. Specifically capturing consumer preferences and clustering consumer segments.

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Analysis of the potential bamboo and bamboo processing industry in Sumedang District, West Java, Indonesia

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Abstract. *Al'afifah JA, Sumardi I, Darwis A. 2025. Analysis of the potential bamboo and bamboo processing industry in Sumedang District, West Java, Indonesia. Asian J For 9: 24-33.* Bamboo production in Sumedang District in 2016 reached 1,599,056 culms. This relatively high production does not align with the popularity of its bamboo processing industry. In contrast, Tasikmalaya District, which has a similar level of bamboo productivity, has become one of the centers of the bamboo industry in West Java. Therefore, this research aims to identify the current potential of bamboo, identify the potential of the bamboo industry, and determine strategies for developing the bamboo industry in Sumedang District. The identification of the potential and availability of bamboo is conducted through mixed quantitative-qualitative method analysis obtained from interviews with Forestry Department Branch IX West Java, Indonesia. In contrast, the identification of the potential of the bamboo industry is done through qualitative descriptive analysis and value added analysis using the Hayami method based on data from interviews with bamboo industry players. Industry development strategies are determined using SWOT analysis. Findings indicate Sumedang has 126,210 bamboo culms, with 3,505 available for monthly harvest. Only 73% of the harvestable bamboo, or 2,565 culms monthly, is utilized. The local bamboo industry is predominantly home-based with minimal production capacity, using basic tools to create low-priced products. The added value ranges from 0-97%, with low profit margins, and competition from substitute products hinders market competitiveness. To develop the industry, intensive strategies are needed, including product diversification and innovation, market penetration, and accessing global markets.

Keywords: Added value, bamboo industry, bamboo potential, industry development, SWOT analysis

INTRODUCTION

Bamboo is one of the most significant non-timber forest products with immense potential for economic, environmental, and social benefits. As a renewable and versatile resource, bamboo plays a crucial role in various industries and contributes substantially to rural livelihoods and international trade. Economically, the export value of bamboo has shown a consistent upward trend, reflecting its growing demand in global markets. For instance, in Indonesia, bamboo exports increased significantly from 2017 to 2019, rising by USD 1.574 million, or 8.2% per year. This growth accelerated between 2019 and 2020, with an increase of USD 1.577 million, or 14.5% per year, as noted by Simatupang and Simagunsong (2022). These numbers underscore the increasing global recognition of bamboo's utility across a diverse range of applications.

The extensive utilization of bamboo stems from its unique properties and adaptability, which make it suitable for a wide array of products. Beyond its traditional use in furniture and construction, bamboo has become an essential raw material for innovative applications such as laminated bamboo, bamboo flooring, paper production, chopsticks, and various forms of weaving (Chaudhary et al. 2024). Its versatility is not only economically advantageous but also supports sustainable development goals, as bamboo is a fast-growing, renewable resource that can help combat deforestation and climate change.

In Indonesia, bamboo production aligns with its high utilization. According to the Central Bureau of Statistics (2022), Indonesia produced a remarkable 66,921,536 bamboo culms in 2022. Java Island, known for its fertile soils and favorable climate, is a significant contributor to this production. Within Java, bamboo cultivation is particularly prominent, with 66,861,182 bamboo culms planted in 2022. Specific districts such as Ciamis, Garut, Tasikmalaya, and Sumedang are notable for their high productivity. In 2016, Ciamis District led bamboo production in West Java, yielding 4,182,150 culms, followed by Garut with 2,072,130 culms, Tasikmalaya with 1,730,792 culms, and Sumedang with 1,599,056 culms (Open Data Jabar 2016). These figures highlight the region's significant contribution to the bamboo industry and its potential for further development.

Bamboo is derived from grass-like plants characterized by pipe-shaped stems, or culms, that taper in thickness and diameter from the base to the tip (Darwis et al. 2018). This structural uniqueness allows bamboo to be used in various engineering processes to enhance its value and utility. Techniques such as coloring (Al'Afifah et al. 2024) and advanced engineering processes (Sumardi et al. 2024) have further broadened its applications, making bamboo a competitive material in the global market. In addition to its technical and economic potential, bamboo also has cultural and artisanal significance in many regions, particularly in West Java, where traditional bamboo crafts thrive.

Sumedang District in West Java, despite not being the largest producer of bamboo crafts, has a rich tradition of bamboo utilization. Industries in Sumedang produce a range of bamboo products, including bamboo matting, baskets, containers, furniture, and other forms of weaving. These crafts not only support local economies but also preserve cultural heritage. Interestingly, while districts such as Tasikmalaya, Ciamis, Garut, and Cianjur are recognized as the primary hubs for bamboo crafts in West Java, the productivity of bamboo in Sumedang District is comparable to that of Tasikmalaya District (Open Data Jabar 2016). This highlights the untapped potential of Sumedang's bamboo industry, which, with strategic planning and investment, could emerge as a significant player in the regional and national bamboo sectors.

This study seeks to explore the current potential of bamboo in Sumedang District, focusing on its production capacity, existing industries, and the challenges they face. By identifying the strengths and weaknesses of the bamboo industry in Sumedang, this research aims to propose actionable strategies for its development. Additionally, the study examines the added value of bamboo products processed in Sumedang District, offering insights into how these industries can improve their competitiveness and contribution to the local economy. By addressing these objectives, the study not only sheds light on the potential of Sumedang's bamboo industry but also contributes to the broader discourse on sustainable resource management and rural development.

MATERIALS AND METHODS

Study area

The research was conducted in Sumedang District, West Java, Indonesia (Figure 1), involving several subjects from the bamboo processing industry. The subjects were selected using a snowball sampling method by first obtaining recommendations from the Head of the Industry Division of Sumedang District, and then requesting further recommendations from the interviewed bamboo industry players.

Methods and data collection techniques

The research method combines qualitative and quantitative data collection and analysis. The data simulateneously and independently collected, followed by integrating and comparing the findings to provide a comprehensive understanding of the research problem from multiple perspectives (Adhikari and Timsina 2024). This research gathers information about the phenomenon through interviews with participants, posing broad and general questions (Muurlink and Thomsen 2024). Two types of data are required, i.e.: primary and secondary data. Primary data are obtained through interviews and observations. Interviews aim to gather information from participants to understand their feelings, perceptions, and thoughts (Cheong et al. 2023). This study uses semi-structured interviews to enrich the information regarding respondents' perceptions and thoughts while maintaining control over the questions and issues raised, resulting in a lower dross rate or less irrelevant information (Cheong et al. 2023). Interviews were conducted with 10 bamboo industry entrepreneurs in Sumedang. The data obtained from only 10 respondents is already saturated. Therefore, no additional respondents are needed. Respondents have given their consent to provide the information. Observations involve all human senses based on empirical facts (Cisielska et al. 2018). Secondary data are obtained through literature studies from related books and articles, national statistical data, and interviews with the Forestry Department Branch IX West Java, which cover Sumedang and Indramayu Sub-district, and the Department of Cooperative Small and Medium Enterprises Trade and Industry of Sumedang District.

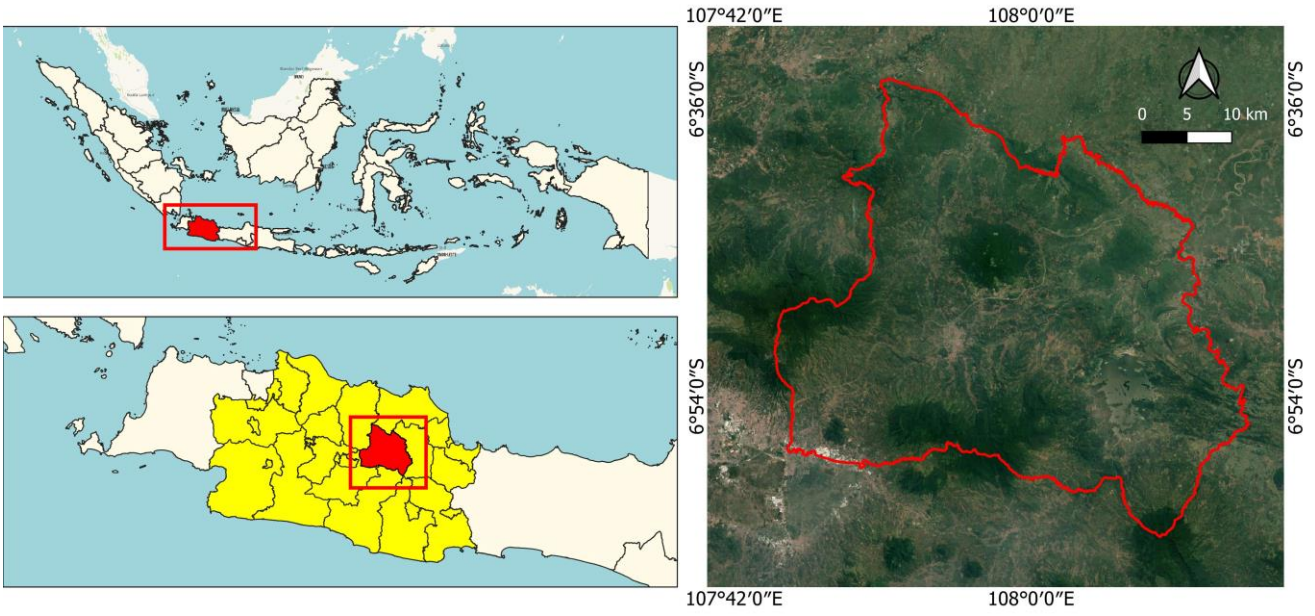

Figure 1. Research sites in Sumedang District, West Java, Indonesia

Data analysis

The data obtained was processed using Microsoft Excel. Data analysis determine the added value of bamboo for each type of product using the Hayami method. Additionally, the analysis assessed the availability of bamboo. Bamboo availability is identified by evaluating productivity, which is determined by the number of bamboo culms and their usage rates. The internal and external conditions of the bamboo industry were analyzed using SWOT analysis to understand the potential and development strategies for the bamboo industry in Sumedang District.

Added value analysis

To determine the value added by bamboo, the value added analysis using the Hayami method is used. This is widely used method for calculating the value added. Based on Hayami (1987), value added is the difference between output value and input value due to the production process. The purpose of value added analysis is to understand the remuneration of production factors and to identify employment opportunities due to increased utility. Several variables used in value added analysis include production output, raw materials, labor, raw material prices, product prices, labor wages, and other inputs. The bamboo processing industry produces products in unit product units. The calculation of bamboo value added analysis using the Hayami method is outlined in Table 1.

In calculating the value added analysis of bamboo using the Hayami method, several assumptions are necessary: (i) Value added is calculated over one month of production, (ii) The output generated represents the average production within one month, measured in units of products, (iii) The unit of input used in each bamboo culm, (iv) The prices used are based on primary data obtained from interviews.

SWOT analysis

To determine the development strategy for the bamboo industry in Sumedang, one of the methods that can be used is SWOT analysis. According to Teoli et al. (2019) and Puyt et al. (2023), SWOT analysis consists of internal factors and external factors. Internal factors encompass strengths and weaknesses within a business, including human resources, financial aspects, marketing, production capabilities, raw materials, and management. External factors affect decision-making and business success, such as government policies, socio-cultural factors, competitive landscape, and technological advancements (David et al. 2019).

Based on the data of strengths, weaknesses, opportunities, and threats identified, strengths and weaknesses (internal factors) are structured into an Internal Factor Evaluation (IFE) matrix. In contrast, opportunities and threats (external factors) are structured into an External Factor Evaluation (EFE) matrix. Each factor is rated on a scale from 1 (very poor) to 4 (very good) relative to the business conditions. The weight of each factor is calculated by dividing its rating by the total ratings as calculated in Eq (1). Scores are then computed by multiplying weights by ratings as calculated in Eq (2), and the total scores are summed up as calculated in Eq (3) (Amirshenava and Osanloo 2022):

$$Weight = \frac{Rating}{Total\ rating} \quad \ldots\ldots (1)$$

$$Score = Weight \times Rating \quad \ldots\ldots (2)$$

$$Grand\ total\ score = \sum_{j=1}^{m} (Weight \times Rating) \quad \ldots\ldots (3)$$

The next step is to plot the total scores of each IFE and EFE matrix into an IE matrix as follows (Figure 2).

The IE Matrix is used to determine the current strategic position of the bamboo industry in Sumedang. The IE Matrix plots the total scores of internal and external factors simultaneously in one matrix. Internal factors are represented on the horizontal axis, while external factors are represented on the vertical axis. Each quadrant in the IE Matrix indicates a different type of strategy, as described in Table 2.

Table 1. The Hayami method of value added analysis

Variable	Unit	Formula
Output, input, price		
Output	Unit	A
Input	Unit	B
Labor	No. of workers	C
Conversion factor		D=A/B
Labor coefficient	No. of workers	E=C/B
Output price	Rp/unit	F
Labor wages	Rp/no. of workers	G
Income		
Raw material prices	Rp/unit	H
Other input contribution	Rp/unit	I
Output value	Rp/unit	J=D x F
Value added	Rp/unit	K = J - I - H
Add value ratio	%	L = (K/J) x 100%
Direct labor income	Rp/unit	M = E x G
Share of labor	%	N = (M/K) x 100%
Advantages	Rp/unit	O = K - M
Profit rate	%	P = (O/J) x 100%

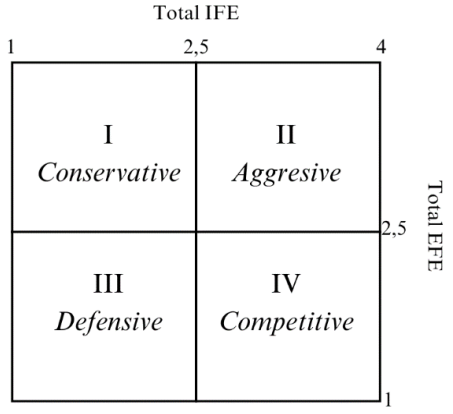

Figure 2. IE matrix (Ardeshir et al. 2016)

To formulate the strategies that can be implemented, the internal and external factors can be plotted in the following Table 3, resulting in four types of strategies: S-O (Strength-Opportunity), W-O (Weakness-Opportunity), S-T (Strength-Threat), and W-T (Weakness-Threat).

Table 2. IE matrix description

Quadrant	Strategic position	Description	Appropriate type of strategy
I	Conservative	IFE Score<2.5 and EFE score≥2.5	Conservative strategies (WO)
II	Aggressive	IFE Score≥2.5 and EFE Score≥2.5	Aggressive Strategies (SO)
III	Defensive	IFE Score<2.5 and EFE Score<2.5	Defensive Strategies (WT)
IV	Competitive	IFE Score≥2.5 and EFE Score<2.5	Competitive Strategies (ST)

Table 3. SWOT strategy analysis (Teoli et al. 2019)

Internal / External	Strength (S)	Weakness (W)
Opportunity (O)	**S-O Strategy** Use S by utilizing O	**W-O Strategy** Overcome W by utilizing O
Threat (T)	**S-T Strategy** Use S to avoid O	**W-T Strategy** Minimize W to avoid T

RESULTS AND DISCUSSION

Distribution and availability of bamboo in Sumedang

The availability of bamboo in Sumedang District is spread across 23 out of 26 subdistricts (Forestry Department Branch IX, personal communication, 2024). The subdistrict with the highest bamboo production is Rancakalong, which produces 65,100 bamboo culms, followed by North Sumedang Sub-district and Pamulihan Sub-district produces 15,000 bamboo culms each, and Jatinunggal Sub-district produces 11,399 bamboo culms. Generally, the distribution of bamboo plant potential in each sub-district is shown in Figure 3.

Bamboo distribution is evenly spread across each subdistrict, with the *tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz) variety dominating over other types. Another bamboo type found in Sumedang District is greater giant bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja), which accounts for 3.1% of the total bamboo population and is distributed only in Sukasari Sub-district, Cisitu Sub-district, Cimalaka Sub-district, Tanjungsari Sub-district, and Situraja Sub-district. Additionally, *betung bamboo* (*Dendrocalamus asper* (Schult. f.) Backer ex K.Heyne)), comprising 0.43% of the total, grows only in Buahdua Sub-district and Tomo Sub-district. The overall distribution numbers for bamboo can be seen in Table 4.

Table 4. Bamboo distribution in Sumedang District February 2024 (Forestry Department Branch IX West Jawa, 2024)

Sub-district	Bamboo types	No. of bamboo (culms)
Sukasari	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz), Greater giant bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja)	1050
Ganeas	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	2700
Pamulihan	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	15000
Buahdua	*Betung bamboo* (*Dendrocalamus asper* (Schult. f.) Backer ex K.Heyne)	500
Jatinunggal	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	11399
Rancakalong	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	65100
Cimanggung	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	1675
Conggeang	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	1350
Tomo	*Betung bamboo* (*Dendrocalamus asper* (Schult. f.) Backer ex K.Heyne)	45
Ujung Jaya	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	126
Cisitu	Greater giant bamboo (*Gigantochloa pseudoarundinacea*)	900
Paseh	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	100
Wado	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	4500
Sumedang Utara	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	15000
Cimalaka	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz), Greater giant bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja)	1100
Sumedang Selatan	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	305
Tanjungkerta	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	100
Tanjungmedar	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	2850
Tanjungsari	Greater giant bamboo (*Gigantochloa pseudoarundinacea*)	600
Cibugel	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	25
Surian	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	20
Jatigede	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz)	15
Situraja	*Tali bamboo* (*Gigantochloa apus* (J.A. & J.H. Schultes) Kurz), Greater giant bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja)	1750
Total		126,210
Total bamboo that can be harvested each month		3,505

Source: Forestry Department Branch IX West Java, Indonesia (pers. comm. 2024)

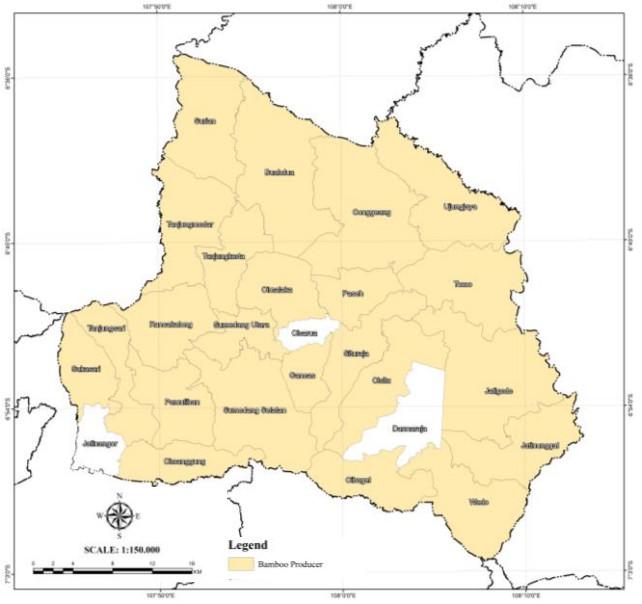

Figure 3. Distribution of bamboo producer in Sumedang District, West Java, Indonesia

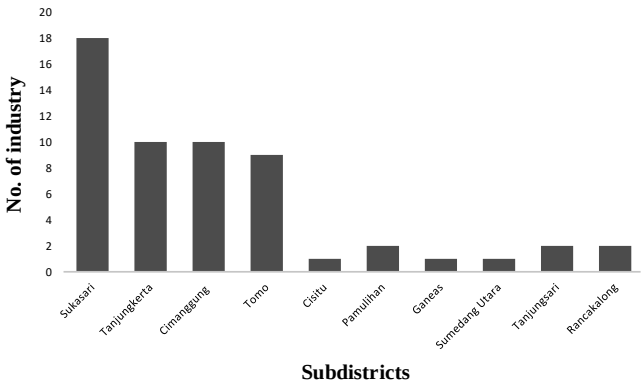

Figure 4. Number of bamboo industries in Sumedang District, West Java, Indonesia

The data in Table 4 is the result of processing potential data based on available resources. The processed involved measuring the area of bamboo groves and converting them into clump quantities. For bamboo types with large clump areas like *betung bamboo*, each clump has a wide radius of 30 meters. Meanwhile, bamboo types with smaller clump areas like *tali bamboo* and *surat bamboo* have a wide radius of 15 meters per clump. The number of clumps is then multiplied by the average number of bamboo culms per clump, which is between 90-100 culms (Forestry Department Branch IX West Jawa, personal communication, 2024)

According to this data collection method, the total number of bamboo culms in Sumedang District is 126,210, comprising a mix of young and old bamboo. According to Sutiyono and Wardani (2011), with proper clump management, one clump can have three different age generations of bamboo: 1-year-old, 2-year-old, and 3-year-old bamboo. The distribution of bamboo ages within a clump is equal, approximately 35.4, 33.8, and 30.8% for generations 1, 2, and 3 respectively. Considering that mature bamboo is typically used, based on the research mentioned above, it can be assumed that the total number of bamboo culms available can be harvested over a three years. It means that in one month, a total of 3,505 bamboo culms can be harvested.

Potential of bamboo industry in Sumedang District

Several sub-districts in Sumedang are known for bamboo processing, including Sukasari Sub-district, Tanjungkerta Sub-district, Cimanggung Sub-district, Tomo Sub-district, Cisitu Sub-district, Pamulihan Sub-district, Ganeas Sub-district, North Sumedang Sub-district, Tanjungsari Sub-district, and Rancakalong Sub-district. Each subdistrict specializes in different bamboo products. The number of industries in each subdistrict can be seen in Figure 4.

Sukasari Sub-district has the most bamboo industries in Sumedang District, followed by Tanjungkerta Sub-district and Cimanggung Sub-district. Industries in Sukasari Sub-district include *boboko*, spice racks, bamboo curtains, lampshades, coffee filters, tissue boxes, *giribig* (traditional processing rice), *bilik* (traditional wall), table and chair sets, sheepskin pads, *angklung* (traditional musical instrument), *calung* (traditional musical instrument), and various other woven products (Table 6). Tanjungkerta and Cimanggung Sub-districts also produce similar products, primarily woven items. Certain products are made exclusively in specific areas, such as *bongsang* (tofu baskets) produced only in the Ganeas and North Sumedang Sub-districts, and *giribig* (traditional processing rice) and *bilik* (traditional wall) produced in Sukasari and Tanjungsari Sub-districts.

Nearly all types of products produced in Sumedang District utilize *tali bamboo* as the raw material. According to industry players, *tali bamboo* is particularly suitable for weaving products because it is durable and less prone to breakage. Additionally, *tali bamboo* is widely used due to its abundant availability in almost every subdistrict in Sumedang District. It is because most of the bamboo products produced in Sumedang District are woven products that require highly flexibility raw materials. According to statements by Budiono (2024), *tali bamboo* is flexible and less prone to breakage, easy to shape, has long nodes, is more resistant to pests and weather, and has unique fibers that give a natural appearance. *Tali bamboo* also has better tensile strength than other bamboo species (Bahtiar et al. 2019). Meanwhile, bamboo varieties used for construction, which require high strength such as *betung bamboo*, are rarely found in Sumedang District due to their lesser usage. Regarding bamboo raw material requirements, Sumedang District requires approximately 2,567 culms of bamboo per month, as detailed in Table 5. Based on previous calculations, the monthly harvestable bamboo in Sumedang District amounts to approximately 3,505 culms. It indicates that bamboo availability in Sumedang meets the supply needs of all bamboo industries in the region, even exceeding the demand.

Value added of bamboo in Sumedang District

Value added is the difference between the output and input values resulting from the production process. The calculation in value added analysis includes calculating profits and income, and understanding the remuneration for production factors (Caruntu and Lapadusi 2012). Value added can also serve as an indicator of business sustainability. Three main criteria can be used as indicators of sustainability: value added ratio, labor share, and profitability (Tisakti et al. 2022). The value added in the industry from various products in Sumedang District ranges from 0-97%, depending on the level of difficulty, the raw materials and additional materials required, and the selling price of the products (Table 7). Furniture products such as table and chair sets, sheepskin pads, *angklung*, *calung*, and carved glasses have higher value added than woven products due to their higher selling prices and more complex manufacturing processes. Innovative products also have higher value added compared to non-innovative products. For example, sheepskin pads with name engravings have a value added of 64%, which is higher than regular sheepskin pads with a value added of 57%.

All bamboo industries in Sumedang are home-based industries operated without employees. Bamboo industry operators do not account for employees in their financial statements. Therefore, Table 7 includes the profit levels without employee wages and those with one employee. Generally, the profit levels without labor costs are high, with most of them above 50%. However, when labor costs are considered, the profit levels become smaller. The assumption used for labor cost calculation is a wage of Rp. 10,000 per product produced. In general, the profit levels with labor costs are low, with some being negative. It indicates that bamboo processing businesses generate very little profit or incur losses. Products that still have relatively high profit levels after accounting for labor costs are furniture products like table and chair sets, sheepskin pads, *angklung*, *calung*, and carved glasses. It is because furniture products typically have higher selling prices due to the more complex manufacturing process and the selection of higher-quality materials. As for the products with low or even negative profit margins, these are simple products with low selling prices that require a larger amount of raw materials.

Development strategy for the bamboo industry in Sumedang District

Developing strategies for the bamboo industry in Sumedang involves observing and evaluating the business environment. Business environment analysis is crucial as an organization is significantly influenced by its environment. This analysis is necessary to direct these influences positively, contributing to business success (Gunawan 2024). The business environment analysis is divided into two parts as shown in Table 8: internal and external analysis. Internal condition analysis provides a general overview of the organization's condition, including market availability and marketing, human resources, financial aspects, and technical operations. External condition analysis covers factors beyond the business's control that can influence decision-making, including government policies, competition levels, and socio-cultural factors.

Table 5. Raw materials needed in Sumedang District, West Java, Indonesia

Kind of bamboo industry	Raw material needed (culms/month)
Boboko (Rice basket)	256
Spice rack	16
Bamboo curtain	32
Lampshade	16
Coffee filter	8
Tissue box	7
Laundry basket	32
Fruit basket	16
Bongsang (Tofu basket)	200
Table and chair set	6
Nyiru (Winnowing basket)	80
Tolombong	256
Giribig	800
Bilik (Bamboo wall)	720
Sheepskin pads	20
Angklung	50
Calung	50
Carved glass	2
Total	2,567

Table 6. Examples of bamboo products in Sumedang District, West Java, Indonesia

Examples of bamboo products		Product uses
Boboko (Rice basket)		A container for storing rice. This product is often used in traditional households and during cultural events.
Nyiru		A bamboo tray for processing grains, mainly for rice
Bilik		A traditional wall or partition made of bamboo
Bongsang (Tofu basket)		A container for storing typical Sumedang tofu
Calung		A traditional musical instrument typical of West Java
Angklung		A traditional musical instrument typical of West Java

Table 7. Added-value and profit rate of the bamboo industry in Sumedang District, West Java, Indonesia

Products	Value added	Profit rate without calculating labor wages	Profit rate with calculating labor wages
Boboko (Rice basket)	79%	79%	69%
Spice rack	86%	86%	66%
Bamboo curtain	80%	80%	40%
Lampshade	77%	77%	43%
Coffee filter	93%	93%	83%
Tissue box	97%	97%	87%
Laundry basket	80%	80%	72%
Fruit basket	66%	66%	26%
Bongsang (Tofu basket)	78%	78%	-22%
Table and chair set	88%	88%	83%
Nyiru (Winnowing basket)	90%	90%	40%
Tolombong	63%	63%	-38%
Giribig (1.5 × 3 m^2)	50%	50%	0%
Bilik (Bamboo wall) (2 × 3 m^2)	0%	0%	-50%
Bilik batik (2 × 3 m^2)	20%	20%	7%
Sheepskin pads	57%	57%	53%
Sheepskin pads with name engraving	64%	64%	60%
Angklung	61%	61%	59%
Calung	83%	83%	80%
Carved glass	94%	94%	78%

Table 8. Added-value and profit rate of the bamboo industry in Sumedang District, West Java, Indonesia

Internal Factors	External Factors
Marketing The product sales chain involves direct sales to consumers, primarily to middlemen or traders. Prices are generally determined by middlemen, traders, or buyers, with few craftsmen setting their own prices. Sales are typically conducted directly, without using online shopping platforms, and promotions are minimal, relying mostly on word-of-mouth.	**Government Policies** There are no specific local government programs for developing the bamboo industry, as the local government prioritizes the food industry. However, general facilities like digital marketing training, partnerships with retail groups, annual exhibitions, and low-interest business loans are available but underutilized by bamboo craftsmen. The regional spatial plan includes developing cultural tourism and craft centers, presenting opportunities for bamboo industries to thrive in the cultural tourism sector.
Human Resources Bamboo industries in Sumedang are mostly small-scale home productions without employees. Craftsmen usually work alone or with family members. Their skills are inherited, without formal training. Most craftsmen are over 40 years old, and the youth rarely engage in bamboo weaving, preferring farming, especially since the government launched the Millennial Farmer program.	**Competition Levels** Competitors include other bamboo product producers from neighboring regions and substitute products like plastic baskets and modern household items. While Sumedang bamboo products are of higher quality, they lack innovation and face competition from more functional substitutes.
Financial Aspects According to calculations using the Hayami method (Table 7), the addition of bamboo product value is significant but has small profit margins. Craftsmen do not produce on a large scale, and they often need minimal initial capital from personal funds.	**Socio-cultural Factors** Bamboo crafting skills are inherited rather than formally taught, and there are no formal bamboo craft associations in Sumedang. Bamboo crafting is typically a side job, with farming or gardening as the main occupation.
Technical and Operation Aspects The production scale is small, home-based, and unstructured, with craftsmen producing bamboo products only when not farming. Production capacity is low, averaging one product per day. Simple tools are used, and production residues like bamboo dust and shavings are discarded without further processing	**Market Availability** Sumedang's bamboo products have a reasonably broad local market but haven't reached the global market. Demand remains stagnant or declining for products with substitutes.
	Raw Material Availability The primary raw material is bamboo tali, which is valued for its durability and ease of weaving. Sumedang has a sufficient supply of bamboo tali to meet local industry needs, though craftsmen sometimes source black bamboo from outside Sumedang for specific products

IFE, EFE, and IE matrices

Based on the business environment analysis, various strengths, weaknesses, opportunities, and threats are identified, as shown in Tables 9 and 10.

The IFE matrix shown in Table 8 shows that the highest strength score is attributed to the skillset inherited over generations. This indicates that this attribute is the most significant strength among the others. Meanwhile, the lowest weakness score is that bamboo products are impractical. The grand total of the IFE matrix is 2.733. According to David (2017), a score of 3 or close to 3 indicates that the bamboo industry in Sumedang has relatively small strengths.

Based on Table 10, the highest opportunity score is attributed to the availability and ease of obtaining raw materials. This indicates that this opportunity is the most significant among the others. The threats with the lowest scores are the presence of more functional substitute products and the lack of special attention from the government for the bamboo industry in Sumedang. The grand total score from the EFE matrix is 3.129, which is close to 3. According to David (2017), a score of 3 or close to 3 indicates that the bamboo industry in Sumedang has relatively small opportunities.

Based on the calculations in the IFE and EFE matrices plotted on the IE matrix (Figure 2), the bamboo industry in Sumedang occupies quadrant II, which is the aggressive strategic position. Based on this position, the suitable strategy type to apply includes intensive strategies such as market penetration, market development, product development, and diversification.

SWOT analysis

The appropriate strategy type for industries in quadrant II is the SO strategy in SWOT (Amirshenava and Osanloo 2022). Therefore, three main strategies are recommended based on the SO strategy, leveraging existing opportunities by utilizing the strengths (Benzaghta et al. 2021). The types of strategies are listed in Table 11.

The first strategy involves product diversification and innovation in existing products. This strategy leverages the strengths of the bamboo industry in Sumedang, including existing skills and opportunities such as access to soft loans and the availability and ease of bamboo raw materials. It falls under the category of related diversification strategy for bamboo processed products and product development strategy for innovating existing products. The initial step in implementing this strategy is establishing a Bamboo Craftsmen Association. This program aims to facilitate training, distribution of aid in bamboo processing, and other collective activities among bamboo craftsmen. The association serves as a platform to facilitate recommended programs.

Members of the Bamboo Craftsmen Association include a group of craftsmen along with local government representatives. Another program for implementing the diversification and innovation strategy involves training for developing new products and enhancing existing ones. Examples of new products that can be developed include plates, toothbrushes, combs, bookshelves, and other unconventional items made from bamboo. Enhancing existing products involves improving their quality through design, appearance, or functionality upgrades. An example of quality improvement is coloring *boboko* products or creating specific weaving patterns to enhance consumer appeal. These training programs can be provided through the Bamboo Craftsmen Association. Another implementation program involves providing technology assistance from the local government, which can be channeled through the Bamboo Craftsmen Association.

Table 9. IFE matrix

	Internal factors	Weight	Rating	Score
	Strength (S)			
S1	Skills are inherited and passed down through generations	0.259	3.75	0.970
S2	Non-woven products have a high profit margin	0.241	3.5	0.845
	Total	0.500		1.815
	Weakness (W)			
W1	No regular and continuous production schedule	0.138	2	0.276
W2	Most products are simple and lack innovation	0.121	1.75	0.211
W3	No organization or association of bamboo craftsmen	0.138	2	0.276
W4	Bamboo products are not practical to use	0.103	1.5	0.155
	Total	0.500		0.918
	Grand Total	1.000		2.733

Table 10. EFE matrix

	External factors	Weight	Rating	Score
	Opportunity (O)			
O1	The government provides soft loans	0.226	3.5	0.790
O2	Increasing consumer awareness of eco-friendly products	0.242	3.75	0.907
O3	Raw materials are always available and easy to obtain	0.258	4	1.032
	Total	0.726		2.730
	Threat (T)			
T1	Presence of more functional substitute products	0.081	1.25	0.101
T2	Competition from other producers making similar products	0.113	1.75	0.198
T3	No special attention from the government for the bamboo industry in Sumedang	0.081	1.25	0.101
	Total	0.212		0.399
	Grand total	1.000		3.129

Table 11. Alternative strategies

Strategy type	Strategies	Strategy implementation	PIC
Related diversification and product development	Diversification and existing product innovation	Establishing a bamboo craftsmen association	Bamboo craftsman and government
		Training for new product development and enhancement of existing products	Bamboo craftsmen association
		Providing technological assistance	Government
Market penetration	Market penetration	Educational campaigns	Bamboo craftsmen association
		Collaborating with communities or companies	Bamboo craftsmen association
		Organizing cultural exhibitions	Government
Market development	Open global market	Increasing production capacity	Bamboo craftsmen association
		Collaborating with international distributors	Bamboo craftsmen association
		Creating policies to facilitate exports	Government
		Developing an export information website and providing export consultations	Government

The second strategy involves market penetration to increase sales through various marketing methods. Some programs that can be implemented through the Bamboo Craftsmen Association include educational campaigns and collaborations with communities or businesses. Educational campaigns can include social media campaigns to raise awareness about bamboo processed products as environmentally friendly products, collaborating with influencers, creating educational videos about bamboo processed products, conducting workshops on making simple bamboo products for the general public, and more. Collaboration with communities or businesses can involve becoming a supplier to a company or organizing joint events with communities that can then increase sales or awareness of bamboo processed products. Another implementation by the government in the market penetration strategy the provision of cultural exhibitions.

The last strategy is to enter the global market, aiming to explore new markets that have not been tapped before, which falls under the category of market development strategy. Implementing this strategy involves increasing production scale to leverage existing opportunities, such as easy access to raw materials and soft loans from the local government. Production scale can be enhanced through the Bamboo Craftsmen Association acting as an aggregator to collectively market products. Furthermore, the association can collaborate with international distributors. Another implementation program by the government could include creating policies to facilitate exports and developing an export information website while providing export consultations. Facilitating exports might involve streamlining bureaucracy, offering low taxes, and subsidizing export costs, among other measures.

In conclusion, the bamboo craftsmanship industry in Sumedang District holds significant economic potential that has yet to be seriously developed. Only about 73% bamboos are utilized from the existing potential. Generally, the bamboo industry in Sumedang District is traditional and operates as home industry without employees, with very small production capacities. The production process uses simple tools and produces simple, traditional products without innovation, resulting in low-priced items. It is known that the profit margins are generally small, with some businesses even experiencing losses. Moreover, more functional substitute products make it difficult for bamboo products to compete with items that serve the same function. Intensive strategies and diversification are suitable approaches to develop the bamboo industry in Sumedang. These strategies include product diversification, product innovation, market penetration, and opening global markets.

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Species diversity of Araceae in Ninoy Aquino Parks and Wildlife Center and Arroceros Forest Park, Manila, Philippines

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Abstract. *Brillo SC, Banogon JDA, Aquila NAA, Mones JRM. 2025. Species diversity of Araceae in Ninoy Aquino Parks and Wildlife Center and Arroceros Forest Park, Manila, Philippines. Asian J For 9: 34-44.* Green spaces in urbanized areas are crucial for biodiversity conservation. However, cultivation can influence plant diversity and the ecosystem. Araceae is a plant family usually planted in these areas due to its appeal and adaptability. Despite this, exotic species are often planted without considering their potential effects on ecosystems. This study aimed to create a checklist of aroids in Ninoy Aquino Parks and Wildlife Center (NAWPC) and Arroceros Forest Park (AFP), Manila, Philippines. This study was achieved through an opportunistic, descriptive botanical inventory design. Twenty-five species across 10 genera, namely *Aglaonema, Alocasia, Caladium, Dieffenbachia, Epipremnum, Philodendron, Spathiphyllum, Syngonium, Thaumatophyllum,* and *Typhonium* were identified. Twenty-two and 10 species occur in NAPWC and AFP, respectively. Seven species are native, 12 species are introduced, and 6 species are naturalized. The species surveyed varied in morphology and habitat preference. *Epipremnum pinnatum* and *Typhonium blumei* were the most abundant. *Aglaonema commutatum, Syngonium* spp., and *Alocasia macrorrhizos* were considered site specific. Introduced species like *Dieffenbachia seguine* and *Philodendron* 'Lemon Lime' reflected human cultivation preferences. Additionally, Jaccard index of 0.4 presents a moderate similarity of Aroid species between sites. The findings highlight the underrepresentation of native aroids and prioritizing these species can promote biodiversity and sustainability in urban environments.

Keywords: Araceae, Arroceros Forest Park, inventory, Ninoy Aquino Parks and Wildlife Center, species diversity

Abbreviations: AFP: Arroceros Forest Park, IUCN: International Union for Conservation of Nature, NAPWC: Ninoy Aquino Parks and Wildlife Center, NIPAS: National Integrated Protected Areas System, RA: Republic Act

INTRODUCTION

Urban forest parks enhance well-being and reduce pollution. Arroceros Forest Park, a 2.2 ha "last lung of Manila," which was rehabilitated in 2022, supports over 3,000 trees, 8,000 ornamental plants, and ten bird species, emphasizing urban greenery's importance (PNPCSI 2019; Requejo 2022). Similarly, the 22.7 ha Ninoy Aquino Parks and Wildlife Center (NAPWC) in Quezon City, a NIPAS (National Integrated Protected Areas System)-protected area, combines conservation and education to promote Philippine wildlife preservation. These parks illustrate local and national initiatives for urban green spaces. Aroids, tropical herbs with 143 genera and 3,750 species (Boyce and Croat 2020; POWO 2024), thrive in urban forest parks due to conditions akin to forest understories, supporting terrestrial and epiphytic growth (Matthews 1995; Gerst et al. 2021; Harisin et al. 2021).

Some aroids are economically important as food sources, using their roots, leaves, and stems in the Philippines, such as *Colocasia esculenta*, *Xanthosoma sagittifolium, Alocasia macrorrhizos, Cyrtosperma merkusii*, and *Amorphophallus* sp. (Pardales Jr. 1997). Other species are used in traditional medicine, while many are cultivated as ornamental plants for their aesthetic appeals, such as *Aglaonema, Alocasia, Anthurium, Dieffenbachia, Monstera, Philodendron,* and *Pothos* (Simpson 2010; Proctor 2012; Timberlake and Martin 2012; Flores et al. 2020). In forest parks, aroids not only enrich the landscape but also contribute to the ecosystem in several ways. Their large leaves create animal habitats, while their underground structures help store nutrients and improve soil quality. Additionally, aroids can serve as food sources for humans and animals, and attract pollinators, thereby supporting broader biodiversity within the parks (Pardales Jr. 1996; Mayo et al. 1997; Chen et al. 2010).

According to Co's Digital Flora of the Philippines (2024), there are 131 native aroids, with 75 species endemic to the Philippines that belong to the following genera: *Aglaonema, Alocasia, Amorphophallus, Arisaema, Cryptocoryne, Homalomena, Pothos, Rhaphidophora,* and *Schismatoglottis*. There are 18 introduced species but now naturalized generally due to escape in cultivation, such as *Alocasia cucullata*, *Caladium bicolor*, *Epipremnum amplissimum*, *Epipremnum aureum*, *Gonatopus boivinii*, *Homalomena rubescens*, *Lemna perpusilla*, *Philodendron erubescens*, *P. hederaceum*, *Pistia stratiotes* (invasive per CABI 2017), *Spathiphyllum cannifolium*, *Syngonium podophyllum*, *Syngonium wendlandii*, *Typhonium blumei*, *T. roxburghii*, *T. trilobatum*, *Xanthosoma sagittifolium*, and

Zantedeschia aethiopica (CDFP 2024). According to Aureo et al. (2020), Araceae is a joint family with more than ten representative taxa in Rajah Sikatuna Protected Landscape in Bohol, Philippines. Po-Abit (2008) found native Araceae in Mt. Pangasugan, Leyte, namely *Homalomena philippinensis*, *Schismatoglottis calyptrata*, *Rhaphidophora*, *Amydrium medium*, *Aglaonema*, *Pothoidium lobbianum*, *Alocasia zebrina*, *Alocasia heterophylla*, *Alocasia pubera*, *Spathiphyllum commutatum*, *Rhaphidophora monticola*, *Scindapsus* spp., *S. hederaceus*, *Pothos* spp., and *Pothos ovatifolius*. Banag-Moran et al. (2022) found *Aglaonema commutatum*, *Caladium bicolor*, and *H. philippinensis* in Aklan's disturbed and undisturbed lowland forest. Despite these findings, native aroids are often underutilized in urban forest parks. These findings make aroids valuable for both conservation and landscape design. However, aroids are frequently overlooked in park planning and landscape design due to limited awareness, commercial availability, and a preference for exotic species.

This study aimed to create a checklist of native, naturalized, and introduced Araceae species in two urban forest parks in Metro Manila: Arroceros Forest Park (AFP) and Ninoy Aquino Parks and Wildlife Center (NAPWC) through an inventory survey, which provides baseline data on their occurrence and abundance and identifies species that are unique or common to both parks. This information can help in environmental planning by considering growing native aroid species and managing exotics in the area, contributing to conservation and sustainability efforts.

MATERIALS AND METHODS

Study area

A survey of aroids was conducted in two green spaces in Metro Manila, namely the Ninoy Aquino Parks and Wildlife Center (NAPWC) and Arroceros Forest Park (AFP) located in the City of Manila and Quezon City, Philippines, respectively (Figure 1). The general coordinate of NAPWC is 14° 39’ 7.56” N, 121° 2’ 43.08” E, and is relatively flat in topography, ranging from 37.7 to 44.6 m above sea level, with a man-made 4-ha lagoon located in the northwestern area. The park's soil is shallow, primarily composed of adobe rock and loam, allowing quick water recession despite flooding during heavy rains. The soil is slightly alkaline with essential nutrients, and the terrain's proximity to the lagoon indicates alluvial, silty loam soil. The park experiences a Type I climate with dry seasons from December to May and wet seasons from June to November. Hydrologically, the lagoon drains northern areas through canals and a creek in the south (NAPWC 2019).

Arroceros Forest Park (AFP) was developed in 1993 and is located on the south bank of the Pasig River near Quezon Bridge (14° 35’ 39.12” N, 120° 58’ 54.12” E) and covers an area of 2.72 ha. It consists of a secondary growth forest with 61 tree species, over 3,500 trees, and 8,000 ornamental plants, providing a habitat for 10 bird species, including the long-tailed shrike (*Lanius schach*) and Philippine pied fantail (*Rhipidura nigritorquis*). The park also features tiled pathways, concrete roads, a fish pond, a bridge, and a riverside walk. Trees such as acacia, banyan, and mahogany, along with fruit and ornamental plants, contribute to its rich biodiversity (Roces 2003, 2005).

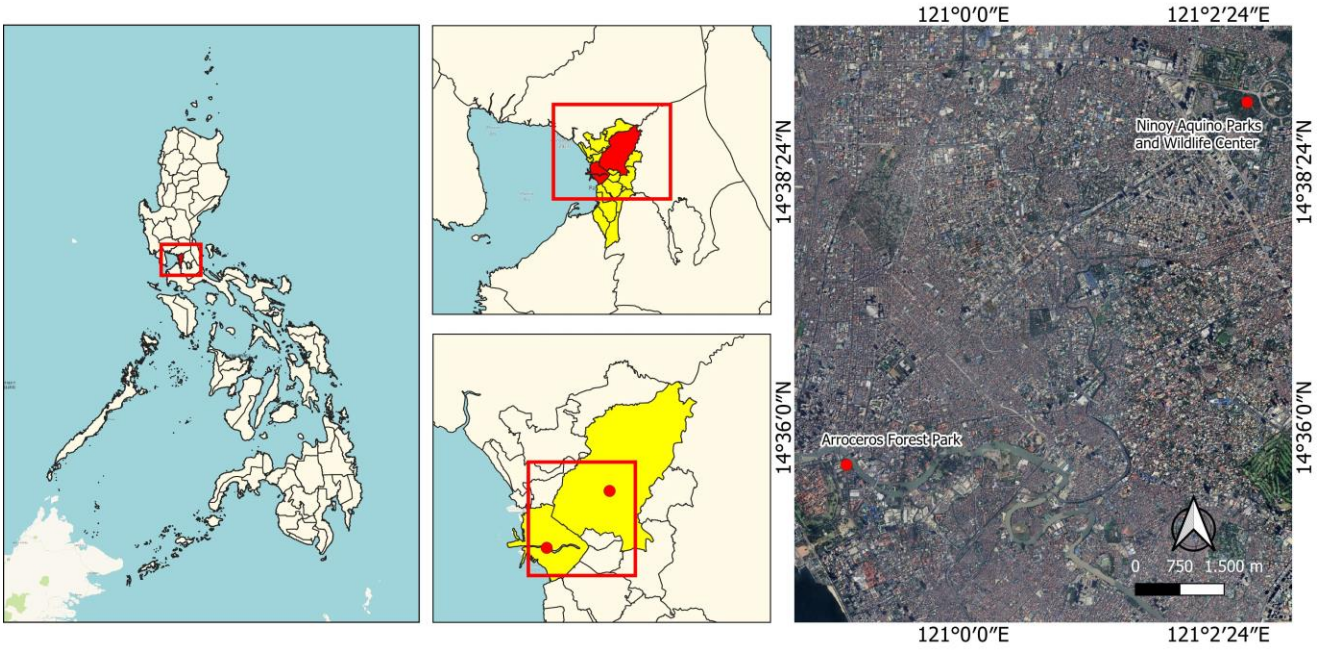

Figure 1. Study area in the Arroceros Forest Park (AFP), and Ninoy Aquino Parks and Wildlife Center (NAPWC), Philippines

These sites were selected to ensure that the aroids observed are most likely growing naturally due to their status of being a protected area. The whole area was surveyed as much as possible, except in some areas restricted to visitors with respect to the rules and regulations of the parks.

Procedures

Study design

This study follows a descriptive botanical inventory design that involves an opportunistic survey of plants in an area. This type of survey was carried out to record the plant species prior to conducting more in-depth or targeted studies. The results from this study are crucial for gaining a comprehensive understanding of the occurrence, composition, and diversity of aroids in the area.

Data collection and documentation

The study was conducted on different days between May and June 2024. Repeated walks throughout these areas were done to search for Aroid plants between 9:00 am and 12:00 pm or 1:00 pm to 4:00 pm. Equipped with a smartphone camera, all encountered Aroid species were photographed, with their abundance estimated through the direct count method, for terrestrial and epiphytic species (Hill et al. 2005). A high-definition smartphone camera and OM Systems Tough TG7 Camera were used to capture plant structures. Species included in the inventory were plants rooted in the natural substrate of the soil making up NAPWC. Plants inside pots and enclosures that were otherwise inaccessible to the researchers were excluded from the study. Furthermore, damaged plants (i.e., incomplete or torn leaves) were also not included as it would have proven challenging for identification. A measuring tape was used to measure the sizes of plant structures relevant for identification. Leaf vouchers were taken from the plant for further inspection after survey, when consulting taxonomic references.

Taxonomic identification of aroids

Identification to applicable taxonomic level below family Araceae (such as genus, species, and variety/cultivar, if necessary) was achieved using the key to the genera of Araceae of Mayo et al. (1997) and supplemented by taxonomic keys available from the International Aroid Society and online databases such as Co's Digital Flora of the Philippines (https://www.philippineplants.org/) and Plants of the World Online (https://powo.science.kew.org/), and consulting citizen science websites such as iNaturalist (https://www.inaturalist.org/). Furthermore, digitized local herbaria from the Global Biodiversity Information Facility (https://www.gbif.org/) were utilized for identification. Taxonomic names used in identifying specimens follow POWO-accepted names. Following this process, a checklist was created to document the presence, observed growth habits, general distribution, and conservation status of all Aroid species in the park.

Data analysis

Species richness was used to present the number of species identified in the area. The similarity of species richness found between NAPWC and AFP was determined using the Jaccard Similarity Index (Jaccard 1912). It was obtained using the number of common species found in both locations. It is then divided into the total number of unique species across all locations. The index value ranges from 0-1, wherein as the value approaches 1, the observed species are more similar in both locations. Thus, a value of 1 means both locations have the same species observed, and 0 means there are no common species found. To express in a formula:

$$Jaccard\ Index\ (Ji) = \frac{Number\ of\ common\ species\ (NAPWC \cap AFP)}{Total\ unique\ species\ in\ both\ sets\ (NAPWC \cup AFP)}$$

RESULTS AND DISCUSSION

Species diversity of Araceae in Ninoy Aquino Parks and Wildlife Center

Twenty-two plant species (Figure 2) along with their estimated abundance, distribution status, and conservation status. Ten Aroid genera were identified as occurring in the wildlife center, with varying estimated abundance: *Aglaonema, Alocasia, Caladium, Dieffenbachia, Epipremnum, Philodendron, Spathiphyllum, Syngonium, Thaumatophyllum,* and *Typhonium* (Table 1). Of the 22 species, eight were native, nine were introduced, and five were naturalized, according to Co's Digital Flora of the Philippines. The IUCN had not evaluated all species, except *Alocasia odora* (Figure 2.E) with their 'Least Concern' status. *Alocasia* spp. (Figures 2.C-H) were the most well represented, with six species identified, followed by *Epipremnum* spp. (Figures 2.K-M) and *Dieffenbachia* spp. (Figures 2.I-J).

The checklist of aroids in the Ninoy Aquino Parks and Wildlife Center (NAPWC) reveals a diverse collection of species with varying levels of abundance, distribution, and conservation status. Native species such as *Aglaonema commutatum* and *Epipremnum pinnatum* are well-represented, with the latter showing a high abundance of over 100 individuals. The presence of the vulnerable species *Alocasia micholitziana* (Figure 2.D) (DAO 2007) with an estimated abundance of less than 20 suggests that areas like NAPWC can serve as important refuges for threatened species, which can be a potential way in ex situ conservation. Ismail (2021) reported that urban green spaces can substantially strengthen conservation by broadening ex situ living collections and increasing genetic diversity for restoration and reintroduction programs in particular. In contrast, introduced species like *Alocasia robusta* (Figure 2.F) and *Philodendron giganteum* (Figure 2.O) are less abundant, typically with fewer than ten individuals. Several species, including *Typhonium blumei* (Figure 2.T) and *Syngonium podophyllum* (Figure 2.Q), have naturalized and thrived in the local environment, with *T. blumei* being particularly abundant with over 100 individuals. While most species are listed as "Not Evaluated" (NE) in terms of conservation status, either they have not been assessed for extinction risk or they are a

cultivar or variety of horticultural importance, *A. odora* is marked as Least Concern (LC). Overall, the table underscores the wide variety of aroids in NAPWC, with a mix of native, introduced, and naturalized species, though many lack formal conservation assessments.

Among the identified aroids, *E. pinnatum* (Figure 2.L) was the most abundant in the area with >100 estimated individuals. It was primarily found in clusters and climbing in various trees, but it can also be observed crawling on the ground in different life stages. It grows in tropical to subtropical regions, in warm temperatures, and tolerates extreme heat and drought but prefers areas receiving more significant precipitation. The species can also grow on different soil types, such as in clay, sand, and loam soils, with pH 4-6 (Rojas-Sandoval and Acevedo-Rodríguez 2022). These characteristics may be the reason for the abundant growth of *E. pinnatum* in NAPWC, as the Philippines, in general, is in a tropical region that receives very high annual precipitation. They are also widely cultivated and can be found in areas with high human activity. These characteristics also support their invasiveness outside their natural habitat. It is considered an aggressive vine that forms in dense colonies, monopolizing resources, engulfing the native species, and shading the plants growing in the understory or forest floor. In the end, this resulted in a change to the community structure of the area to which it was introduced.

Typhonium blumei (Figure 2.T) was also more abundant in the area than other aroids, with >100 estimated individuals often found in the ground. Unlike *E. pinnatum*, which is often found climbing trees or other structures, *T. blumei* tends to be more ground-dwelling. This characteristic makes it more commonly found on forest floors or in low-lying areas. In addition, *T. blumei* can be found in shaded and moist environments with well-drained soils. It thrives in forests and disturbed areas such as in gardens or on the roadside. The NAPWC provides a suitable environment for *T. blumei*, with its shaded area moist and rich soil condition. These factors create an ideal microhabitat that supports the growth and proliferation of these species. Furthermore, several research studies have shown the potential medicinal uses of these plant species. Various parts of the plant showed anti-inflammatory and pain-relieving properties (Korinek et al. 2017; Pradeepika et al. 2018; Anandhi et al. 2020).

Aglaonema commutatum 'Brilliant Beauty' (Figure 2.B), *Syngonium* spp. (Figure 2.Q-R), and *Alocasia macrorrhizos* (Figure 2.C) were also abundant, but in particular sites. *Aglaonema commutatum* 'Brilliant Beauty' was highly abundant in the area where the enclosures of birds, reptiles, and mammals were found. They were present along the walkway and on the soil surrounding the cages. Their abundance can be due to their ease of spread and the assistance of the gardeners in the area, as it is a cultivar known for its ornamental value. *Syngonium* species were mostly found climbing alongside *E. pinnatum* or growing at the sides of abandoned cages in NAPWC. The specimen for *S. angustatum* was collected near a reticulated python cage, where it dominated a circular patch of land. A possible reason why it can easily dominate is due to its inherent invasiveness. According to Chong et al. (2010), *Syngonium* species were assessed in Singapore for their invasiveness. They found out that it was only recently naturalized in the area, can spontaneously spread, and can produce viable seeds. *Syngonium* spp. was naturalized in the Philippines as well (Pelser et al. 2024). However, *S. angustatum* is not yet included in the database, indicating its exotic and "introduced" status, which is characteristic of an invasive species. Despite the potential invasiveness, *Syngonium* spp. (particularly *S. podophyllum*) can be a phytoremediator by removing toxic gasses such as benzene and formaldehyde in the air (Balan and Chandrasekaran 2022). On the other hand, *A. macrorrhizos* were abundant near the river and alongside walking roads. Unlike *Syngonium* spp., *A. macrorrhizos* is native to the Philippines. Locally, *A. macrorrhizos,* known as *gabi* is a commercially important plant for polycropping, ornamentals, and food products (Müller and Guzzon 2024). It is often planted alongside other plants, such as cassava (*Manihot esculenta*), to promote more growth and robustness of target crops. It grows in humid and sub-tropical climates and does not tolerate drought as much. This explains why most of the *A. macrorrhizos* found in NAPWC were discovered nearby rivers and water bodies.

Philodendron ×*domesticum* 'Lemon Lime' (Figure 2.N) and *Dieffenbachia seguine* (Figure 2.J) were abundant in specific sites such as nearby restrooms and signs due to their origin as ornamental plants. All the *P.* ×*domesticum* 'Lemon Lime' and *D. seguine* thriving in the area were the result of artificial introduction (gardening) as indicated by a caretaker in NAPWC. It is also because of their notorious cultivated aroids as well as their non-inclusion in Co's Digital Flora database, indicating their "Introduced" status. *P.* ×*domesticum* 'Lemon Lime' especially is a popular *Philodendron* variety and is often used for ornamentation of interior and exterior infrastructures (Phonpho et al. 2021), which can explain its abundance in the park. According to Aigbokhan and Agbontaen (2013), *D. seguine* was correlated with invasiveness in the rainforest ecosystem of Nigeria. Their findings suggested that *D. seguine* contributed to the sparse vegetation of the infested sites. One possible reason could be their deterrent mechanism against herbivory due to the abundance of oxalate crystals in their tissues (Coté 2009). It is thus essential to re-evaluate the use of *D. seguine* as an ornamental plant in natural parks such as NAPWC.

Table 1. Checklist of Aroids in NAPWC and AFP, Manila, Philippines

Species/cultivar	Location	Common or local name	Estimated abundance (NAWPC, AFP)	Distribution status	Conservation status
Aglaonema commutatum Schott	NAWPC	Philippine evergreen	<20	Native	NE
Aglaonema commutatum Schott 'Brilliant Beauty'	NAWPC, AFP	Brilliant beauty Aglaonema	>50, ~40	Native	NE
Alocasia macrorrhizos (L.) G.Don	NAWPC, AFP	giant taro (local: *badiang*)	>50, 1	Native	NE
Alocasia micholitziana Sander	NAWPC	green velvet Alocasia 'Frydek'	<20	Native	NE; VU[1]
Alocasia odora (G.Lodd.) Spach	NAWPC	night-scented lily	<20	Introduced	LC
Alocasia robusta M.Hotta	NAWPC	Borneo giant	<10	Introduced	NE
Alocasia sp. 'Amazonica'	NAWPC	Alocasia Amazonica	<20	Introduced	NE
Alocasia sp. 'Pseudosanderiana'	NAWPC	Alocasia Pseudosanderiana	<20	Possibly naturalized from cultivation	NE
Caladium bicolor (Aiton) Vent.	NAWPC, AFP	Heart of Jesus, angel wings	<10, ~10	Naturalized	NE
Dieffenbachia longispatha Engl. & K.Krause	NAWPC	Dumb cane	<10	Introduced	NE
Dieffenbachia seguine (Jacq.) Schott	NAWPC	Dumb cane	>50, ~100-200	Introduced	NE
Dieffenbachia sp. Schott	NAWPC	Dumb cane	<10	Introduced	NE
Dieffenbachia 'Tropic Marian'	AFP	Dumb cane, Tropic Marian	~50-100	Introduced	NE
Epipremnum aureum (Linden & André) G.S.Bunting	NAWPC, AFP	Golden pothos	>30, ~50-100	Naturalized	NE
Epipremnum pinnatum (L.) Engl.	NAWPC, AFP	Dragon-tail	>100, ~50-100	Native	NE
Epipremnum amplissimum (Schott) Engl.	NAWPC	Devil's ivy	<10	Naturalized	NE
Philodendron ×*domesticum* 'Lemon Lime'	NAWPC, AFP	Lemon lime Philodendron	<30, ~20	Introduced	NE
Philodendron giganteum Schott	NAWPC	Giant elephant ear Philodendron	<10	Introduced	NE
Spathiphyllum wallisii Regel	NAWPC	Peace lily	<20	Native	NE
Spathiphyllum sp. Schott	AFP	Peace lily	~50	Native	NE
Syngonium angustatum Schott	NAWPC	Five fingers	<30	Introduced	NE
Syngonium neglectum Schott	AFP	Arrowhead plant	~50-100	Introduced	NE
Syngonium podophyllum Schott	NAWPC	Arrowhead plant	>50	Naturalized	NE
Thaumatophyllum bipinnatifidum (Schott ex Endl.) Sakur., Calazans & Mayo	NAWPC, AFP	Selloum (local: *sahod-yaman*)	<10, ~30	Introduced	NE
Typhonium blumei Nicolson & Sivad.	NAWPC	Voodoo lily; (local: sometimes *gabing-nuno* for related species *T. trilobatum*)	>100	Naturalized	NE

Note: LC: Least Concern, NE: Not Evaluated, [1]Conservation status per DAO No. 2007-01

Figure 2. Species diversity of Araceae in NAPWC, Manila, Philippines: A. *Aglaonema commutatum*; B. *A. commutatum* 'Brilliant Beauty'; C. *Alocasia macrorrhizos*; D. *A. micholitziana*; E. *A. odora*; F. *A. robusta*; G. *A.* 'Pseudosanderiana'; H. *Caladium bicolor*; I. *Dieffenbachia longispatha*; J. *D. seguine*; K. *Epipremnum aureum*; L. *E. pinnatum*; M. *E. amplissimum*; N. *Philodendron* ×*domesticum* 'Lemon Lime'; O. *P. giganteum*; P. *Spathiphyllum wallisii*; Q. *Syngonium angustatum*; R. *S. podophyllum*; S. *Thaumatophyllum bipinnatifidum*; T. *Typhonium blumei*

Species diversity of Araceae in Arroceros Forest Park

Thirteen Aroid species were observed in AFP (Figure 3). Among these species, nine genera were as occurring in the park, with differences in estimated abundance. These are identified *Aglaonema*, *Alocasia*, *Caladium*, *Dieffenbachia*, *Epipremnum*, *Philodendron*, *Spathiphyllum*, *Syngonium*, and *Thaumatophyllum*. Most species are either introduced or naturalized, with only a few being native (Table 1). Most species have not been assessed for risk, as shown in the conservation status for most species, and some are cultivars or varieties, which are listed as "NE" (Not Evaluated) per IUCN. Native species include *Aglaonema commutatum* 'Brilliant Beauty' (Figure 3.F), with an estimated abundance of around 40, and *Spathiphyllum* sp. (Figure 3.H), with about 50 individuals. However, *Alocasia macrorrhizos*, an endemic species, has only one recorded individual. *Dieffenbachia seguine* (Figure 3.J) and *D.* 'Tropic Marian' (Figure 3.K) are introduced and show higher abundances, ranging from 50 to 200 individuals. Several species are naturalized or possibly naturalized, such as *Epipremnum aureum* (Figure 3.B) and *Syngonium podophyllum* (Figure 3.E), which are more abundant than most of the aroids in AFP. The differences in native, introduced, and naturalized species indicate the diversity within the collection, with varying levels of abundance and conservation considerations.

Figure 3. Species diversity of Araceae in AFP, Manila, Philippines: A. *Epipremnum pinnatum* and its host tree; B. *Epipremnum aureum* attached to the tree host *Gmelina arborea*; C. Epiphytic habit of *Syngonium neglectum*; D. Terrestrial habit of *S. angustatum*; E. *S. podophyllum* population; F. *Aglaonema* 'Brilliant Beauty'; G. *Thaumatophyllum bipinnatifidum*; H. A patch of juvenile *Spathiphyllum* sp. along with variegated *Euphorbia tithymaloides*, and a *Terminalia* seedling; I. *Caladium bicolor*; J. *Dieffenbachia seguine*; K. *Dieffenbachia* 'Tropic Marian' along with few *Syngonium* spp.

Both species of *Epipremnum* were often observed scaling trees at great heights, suggesting a strong inclination towards vertical growth. *Epipremnum pinnatum* (Figure 3.A) is a hemiepiphyte, considered native (Pelser et al. 2024), and exhibits fenestrated leaves, a characteristic adaptation for efficient light capture in its epiphytic growth. Observed individuals mostly climb on trees at elevated heights, some trailing on the ground; almost all individuals have fenestrated leaves, entirely green in color. This species appears to dominate the area by clinging to different species of trees, such as *Terminalia elliptica, Dracontomelon dao,* and *Adonidia merillii*. In contrast, *E. aureum* individuals mostly climb on trees at an elevated height, some trailing on the ground, and others occur in dense patches; two forms were observed: green and variegated "aurea." The latter is native to French Polynesia (Haigh et al. 2011), and although considered initially as an exotic species, its naturalization around cities and towns in the Philippines could be due to extensive cultivation or escaping from cultivation areas (Pelser et al. 2024), indicating that *E. aureum* has effectively acclimated to the local environment. *E. aureum* was observed attaching to some trees like *T. elliptica* and *Gmelina arborea* (Figure 3.B).

Syngonium is native to Mexico and the Tropical Americas, as documented by Haigh et al. (2011). It was later introduced in the Philippines, as reported by Stuart Jr. (2023) and Pelser et al. (2024). There is a significant number of *Syngonium* species in the park, which are primarily non-native, compared to *Epipremnum*. *Syngonium neglectum* and *S. angustatum* appear to be more prevalent than *S. podophyllum*, displaying a preference for climbing, which indicates their established presence. On the other hand, *S. podophyllum* has been observed to primarily set itself on the ground, often at the base of trees, suggesting its recent introduction to the area. This species demonstrates a notable presence with 100-200 individuals, suggesting a successful adaptation as an exotic species. The dense patches indicate that it flourishes in the terrestrial environments found within the park.

Aglaonema 'Brilliant Beauty' likely originated as a cultivar or a hybrid under *Aglaonema commutatum* complex (Nicolson 1969). Despite its potential native status, it is not as commonly found in the park, with only around 40 individuals. The distribution pattern exhibits clusters of individuals scattered randomly. *Caladium bicolor* (Figure 3.I) and *Spathiphyllum* sp. (Figure 3.H) have a relatively small number of occurrences, with *C. bicolor* having less than ten individuals and *Spathiphyllum* sp. having around 50 individuals. Their unique status and small population size indicate that they could be relatively new additions rather than being less well-suited to the park's ecosystem.

Thaumatophyllum bipinnatifidum (Figure 3.G) and *Philodendron ×domesticum'* Lemon Lime' were both found near the park's nursery area, suggesting that they are intentionally grown by gardeners for specific planting purposes. The limited locations emphasize the carefully managed introduction and potential ongoing acclimatization efforts. The diversity and distribution of Aroid species in the park indicate a combination of native and non-native species, with some being firmly established while others are still relatively scarce. The presence of naturalized and exotic species, like *E. aureum* and *D. seguine*, suggests a potential influence on the native flora and park ecology.

Similarity of species richness between NAPWC and AFP

This study emphasizes the significant ecological aspects of species that overlap between the two areas (Table 2). The Jaccard Index of 0.4 suggests a moderate level of similarity in the composition of species between the two areas (Goettsch and Hernández 2006), with 10 out of 25 species being common to both. Four species have been introduced to the Philippines, namely *D. seguine, P. domesticum'* Lemon Lime', *S. angustatum,* and *T. bipinnatifidum.* These non-indigenous species may have been deliberately introduced for decorative purposes or inadvertently introduced through various human activities. Their occurrence in both regions implies that they are either highly suited to the specific environmental conditions or deliberately controlled to sustain their numbers. The presence of introduced species in both areas indicates the existence of comparable environmental conditions or management practices.

Introduced species that have successfully established themselves in the wild are known as naturalized species. These species have adapted to the local ecosystems and are spreading autonomously. These three species, *C. bicolor, E. aureum,* and *S. podophyllum* are found in both areas of the Philippines and have become naturalized. Both regions demonstrate successful assimilation into the indigenous plant life. According to a note from CDFP (Pelser et al. 2024), *C. bicolor* is grown for its leaves with different colors, and sometimes it can be found outside of cultivation, but it is always found close to human settlements. In addition, *S. podophyllum* is found in secondary forests adjacent to bodies of water, whereas *E. aureum* is naturalized in urban areas and cultivated regions (Suarez 2021, pers.com.). These signs indicate their adaptability but also raise concerns regarding their potential impact on native species and ecosystems, particularly if they become invasive.

The occurrence of native species in both regions (*A. commutatum, A. macrorrhizos,* and *E. pinnatum*) serves as a favorable indication of the conservation of local biodiversity. However, the results of the inventory study show that these native aroids are still underrepresented, with only three being common in both areas. *A. commutatum* is native to the Philippines, and the cultivar 'Brilliant Beauty' may have been primarily produced in cultivation locally. The precise geographic range of *A. macrorrhizos* is uncertain. However, it has been observed in its natural state in India, Sri Lanka, and Peninsular Malaysia (Pelser et al. 2024). It has a broad distribution as both a cultivated crop and an ornamental plant. Several cultivars have been identified, often initially classified as species, with or without specific examples being mentioned. *E. pinnatum* is a prevalent epiphytic Aroid that typically inhabits dense vegetation and forests at various

altitudes, ranging from sea level to moderate heights (Pelser et al. 2024). These species play a vital role in the local ecosystem, enhancing its stability and ability to recover from disturbances. The presence of overlap between the two areas suggests that both habitats possess comparable ecological characteristics, which in turn promote the growth of native flora.

Opportunities for cultivating native Aroid species

The utilization of empty spaces is an excellent opportunity to promote the conservation of plant species, particularly Aroid species native to the Philippines. Aroids of various life habits can be cultivated in the park, whether terrestrial or epiphytic. Aquatic aroids, such as *Lemna aequinoctialis, L. minor, L. trisulca, Spirodela oligorrhiza, S. polyrhiza,* and *Wolffia globosa,* can also be grown in artificial aquatic ecosystems within the park. The typical habitat features of AFP and NAPWC for native terrestrial aroids consist of elevated humidity levels, damp to saturated soil conditions, and a preference for organic-rich soils. Such native terrestrial aroids include *Aglaonema* (*A. commutatum, A. cordifolium, A. densinervium, A. nitidum, A. philippinense, A. robeleynii, A. simplex, A. tricolor*), *Alocasia* (*A. atropurpurea, A. boyceana, A. clypeolata, A. culionensis, A. heterophylla, A. macrorrhizos, A. maquilingensis, A. micholitziana, A. portei, A. ramosii, A. sanderiana, A. scalprum, A. sinuata, A. zebrina*), *Arisaema* (*A. filiforme, A. laminatum, A. polyphyllum*), *Colocasia* (*C. esculenta, C. formosana*), *Cyrtosperma merkusii, Homalomena* (*H. humilis, H. palawanensis, H. philippinensis*), *Leucocasia gigantea, Schismatoglottis* (*S. bogneri, S. calyptrata*), and *Spathiphyllum commutatum* (Nicolson 1968b, 1969; Hay 1988, 1999; Yeng et al. 2013; Boyce et al. 2015; Matthews et al. 2015, 2017; Pelser et al. 2024).

Aglaonema species, native to South Asia, Southeast Asia, and New Guinea, are ideal aroids to be planted in urban parks due to their ability to thrive in low-light environments and their contribution to enhancing urban biodiversity plus their low-maintenance nature makes them suitable for sustainable urban greening initiatives (Lestari and Asih 2017). On the other hand, *Alocasia* species which are commonly found in Asia and eastern Australia, thrive in soil that drains well and has a high level of humidity and tend to grow in areas with partial shade, such as near streams or consistently moist environments (Hay and Wise 1991; Hay 1999). However, *Colocasia* (taro) and their close relatives *Leucocasia*, *Homalomena*, and *Cyrtosperma*, are well-suited for wetland environments, such as riverbanks and marshy areas (Matthews et al. 2015, 2017; Pelser et al. 2024). They flourish in nutrient-rich, loamy soils and prefer areas with ample sunlight. These plants typically thrive in stagnant water and thrive in consistently damp to saturated environments. Although numerous plants are well-suited for shaded or partially shaded environments as understory plants, a few, such as *Colocasia* and *Leucocasia*, can thrive in full sun (Mahr 2024).

Table 2. Similarity of species richness between NAPWC and AFP, Manila, Philippines using Jaccard Index

Species	NAPWC	AFP	NAPWC ∩ AFP
Aglaonema commutatum Schott	+		
Aglaonema commutatum Schott 'Brilliant Beauty'	+	+	++
Alocasia macrorrhizos (L.) G.Don	+	+	++
Alocasia micholitziana Sander	+		
Alocasia odora (G.Lodd.) Spach	+		
Alocasia robusta M.Hotta	+		
Alocasia sp. 'Amazonica'	+		
Alocasia sp. 'Pseudosanderiana'	+		
Caladium bicolor (Aiton) Vent.	+	+	++
Dieffenbachia longispatha Engl. & K.Krause	+		
Dieffenbachia seguine (Jacq.) Schott	+	+	++
Dieffenbachia sp. Schott		+	
Dieffenbachia 'Tropic Marian'	+		
Epipremnum aureum (Linden & André) G.S.Bunting	+	+	++
Epipremnum pinnatum (L.) Engl.	+	+	++
Epipremnum amplissimum (Schott) Engl.	+		
Philodendron ×domesticum 'Lemon Lime'	+	+	++
Philodendron giganteum Schott	+		
Spathiphyllum wallisii Regel	+		
Spathiphyllum sp. Schott		+	
Syngonium angustatum Schott	+	+	++
Syngonium neglectum Schott		+	
Syngonium podophyllum Schott	+	+	++
Thaumatophyllum bipinnatifidum (Schott ex Endl.) Sakur., Calazans & Mayo	+	+	++
Typhonium blumei Nicolson & Sivad.	+		

Note: (+) indicates a species is present, (++) indicates a species is present in both areas

The abundance of tree species in AFP and NAPWC can host native epiphytic aroids, such as *Amydrium* (*A. medium, A. zippelianum*), *Anadendrum* (*A. latifolium, A. microstachyum, A. montanum*), *Pothoidium lobbianum*, *Pothos* (*P. cylindricus, P. dolichophyllus, P. inaequilaterus, P. insignis, P. luzonensis, P. ovatifolius, P. philippinensis, P. scandens*), *Rhaphidophora* (*R. acuminata, R. banosensis, R. conocephala, R. cretosa, R. elmeri, R. korthalsii, R. minor, R. monticola, R. perkinsiae, R. philippinensis, R. todayensis*), and *Scindapsus* (*S. curranii, S. falcifolius, S. hederaceus, S. longistipitatus, S. pictus, S. treubii*) (Nicolson 1968a; Boyce 2000; Othman et al. 2010; Pelser et al. 2024). These aroids have evolved to thrive in the distinct environment of tropical rainforests, where they can be found flourishing on the trunks and branches of trees. The microclimate that the forest park provides is suitable for these aroids to thrive.

While there are native aroids in the genera *Amorphophallus*, *Cryptocoryne*, and *Schismatoglottis*, introducing them into a forest park necessitates careful deliberation because of their distinct habitat requirements, strict environmental requirements, biology, and conservation statuses (Pelser et al. 2024). The genus *Amorphophallus* is commonly found in tropical and subtropical regions, thrive in well-drained, fertile soils with dappled light, which the forest park can simulate. It is worth noting that many of these species are currently classified as vulnerable, threatened, or critically endangered (Pelser et al. 2024), so ethical acquisition of these species from the wild and to be introduced in the park may be a challenge. *Cryptocoryne* is commonly found along streams and riverbanks in the Philippines, thrive in stable aquatic environments with clean, nutrient-rich water and optimal pH levels and are pretty elusive and consist of species that are vulnerable or critically endangered (Lansdown et al. 2023). Species of *Schismatoglottis* flourish in environments with high humidity and shaded rainforest understories and usually are found near bodies of water, like *Cryptocoryne* (Delos Angeles et al. 2023). While these species show promise for enriching Aroid diversity, their habitat types may not be replicable in AFP or NAPWC. Therefore, a thorough study of their habitat preferences and growth requirements is essential before planting them.

In order to effectively incorporate these plants, the forest parks or wildlife centers must create environments that closely resemble their native habitats. This involves carefully matching climate conditions, adjusting soil and water conditions, and taking into account the ecological impact to maintain the existing balance of the ecosystem. Continual monitoring and maintenance are crucial to maintain their growth, development, and preservation.

In conclusion, this study identified 25 Aroid species across 10 genera in NAPWC and AFP sites. A checklist was created to provide valuable baseline data for understanding their composition and distribution in urban forest parks in Metro Manila. The findings reveal that aroids in these areas are predominantly introduced and naturalized, with native species significantly underrepresented. This highlights the anthropogenic influences shaping green spaces, often through accidental or intentional cultivation without considering the ecological identity and impacts of plant species. Despite differences in park size, a Jaccard index value of 0.4 shows a moderate overlap in species composition, with introduced and naturalized species remaining dominant, reflecting the shared ecological characteristics of these areas. To optimize park spaces for conservation, prioritizing the introduction and propagation of Philippine native Aroid species is essential. It is strongly recommended that park authorities focus on planting native aroids to enhance biodiversity, support ecosystems dependent on these plants, promote ecological sustainability, and contribute to the conservation of native species in urban environments.

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Traditional medicinal plants used by To Bungku Ethnic in Morowali District, Central Sulawesi, Indonesia

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Abstract. *Pitopang R, Asrun, Banilai PAS, Sangadji MN, Mertosono S. 2025. Traditional medicinal plants used by To Bungku Ethnic in Morowali District, Central Sulawesi, Indonesia. Asian J For 9: 45-52.* Plants play an imperative role in the well-being of human being as they deliver the fundamental needs of mankind, that is, food, shelter, clothing, and medicines. They also provide the basis for centuries-old traditional medicinal systems. The objective was to explore species of medicinal plants used in Sakita Village, Bungku Tengah, Central Sulawesi including information about the parts used, method of use, and habitus. Data were collected through direct observation, participatory observation, interview, and literature review. A snowball method was used to obtain appropriate respondents, including village, custom (*adat*), traditional (*sando*), and religious leaders, rattan and dammar collectors, as well as farmers. The collection and photography of all samples of medicinal plants were conducted, followed by their identification at the Laboratory of Plant Biosystematics, Department of Biology, Faculty of Mathematics and Natural Sciences, and the Herbarium Celebense (CEB), Tadulako University. The results showed that there were 37 species of plants, consisting of 26 families used as traditional medicine by To Bungku ethnic. The family widely used is Zingiberaceae (4 species) then followed by Euphorbiaceae (3 species), Fabaceae, Arecaceae, Asteraceae, and Myrtaceae with 2 species. Furthermore, methods of use included boiling, pounding, consuming directly, squeezing, spreading, and chewing. The organs mostly used were leaves, stems, bark, fruit, and rhizomes, with the highest percentage being leaves at 51%. The percentage of plants with the highest use was *tofu-tofu* (*Cheilocostus speciosus* (J.Koenig) C.D. Specht) at 100% and the lowest was *benalu* (*Macrosolen cochinchinensis* (Lour) Van Tieng) at only 16%.

Keywords: *Cheilocostus speciosus*, ethnobotany, medicinal plants, Morowali

INTRODUCTION

Plants are important resources of conventional medicines used against different diseases (Tariq et al. 2015). Amongst the 374,000 plant species on the earth (Christenhusz and Byng 2016), about 28,187 species are currently used for medicinal purposes (Alkin 2017). Furthermore, over 70% of the developing world population still depends on complementary or alternative systems known as traditional medicine, including about 80% of the population in Africa, 71% in Chile, 40% in Colombia (Syaikh and Hatcher 2005), and in Indonesia about 44.2% of households utilize traditional healthcare (Rahayu et al. 2020)

Medicinal plants are widely used on every continent, for example, in Asia, the practice is well-established and documented (Ali et al. 2020). Consequently, most of the medicinal plants that have international recognition originate from this area, particularly China (Liu 2021; Liu et al. 2023), India (Shi et al. 2021), Indonesia (Elfahmi et al. 2014; Sholikhah 2016; Rahayu et al. 2020; Cahyaningsih et al. 2021) and other developing countries (Magersa et al. 2019; Khesht et al. 2021; Nafeeza et al. 2022). In Europe, there are more than 30,000 vascular plant taxa, however, only a small proportion of these have an identified medicinal use, however the use of herbal medicine is increasing rapidly, specifically to correct metabolic disorders caused by modern diets and lifestyles (Allen et al. 2014).

Indigenous knowledge systems of medicinal plants are beneficial not only for the conservation of cultural traditions and biodiversity but also for the development of health care and treatment for the poor community (Gijan and Dalle 2019). It has been the only option available for health care before the induction of modern medicine for the prevention, diagnosis, treatment of social, mental, and physical illness (Salmeron-Manzano et al. 2020).

In Indonesia, the practice of traditional medicinal plants is an important component of the healing process (Purwanto 2021). As a large archipelago country in the world (Cleary and De Vantier 2011), Indonesia is a populous country with abundant medicinal plant resources (Liu 2021). It is also occupied by 1,340 ethnic groups with varied cultures, languages, and local wisdom in using

biological resources such as plants to meet primary healthcare needs (Elfahmi et al. 2014; Sumarni et al. 2019).

The people of Central Sulawesi constitute the plural society in Indonesia. This is reflected in the socio-cultural condition of this area inhabited by different indigenous ethnics (Andriansyah and Wekke 2018). The ethnic groups occupy different areas, and each of whom has individual culture and traditions in utilizing plants for daily purposes such as for household appliances, pharmaceuticals, and medicine (Fathurrahman et al. 2016; Pitopang and Ramawangsa 2016).

Many studies on ethnopharmaceuticals, especially concerning local wisdom in using natural plant resources as traditional medicines, have been conducted in Central Sulawesi. Some of them include the indigenous people of the Kaili Ledo (Pitopang et al. 2024), Kaili Rai ethnic group (Bana et al. 2016; Agung et al. 2018), Kaili Tara (Zubair et al. 2019), Seko (Tapundu et al. 2015), Taa Wana (Akhsa et al. 2015; Pitopang et al. 2021), Tajio (Yuliarsih et al. 2013), Tialo (Anggareni et al. 2016) Toli-toli (Nulfitriani et al. 2013), and Topo Uma Kulawi (Yulia et al. 2017).

To Bungku Ethnic is one of the indigenous people who settled in Morowali District, Central Sulawesi. This particular community has used various plant species as medicine for healing several diseases although the knowledge system is not documented. As one of the indigenous communities living in an area with very high Nickel mining activities in Central Sulawesi, it is feared that it will be able to reduce their local knowledge system and the diversity of plant species around them, it is therefore necessary to conduct research on traditional medicinal plant that aim to identify the species of medicinal plants and the part used, the preparation methods, life forms, and the types of diseases.

MATERIALS AND METHODS

Study area

The study was conducted at Sakita Village (formerly known as *pekampua*), with an area of 1.835 square kilometers, in Central Bungku Sub-district, Morowali, Central Sulawesi, Indonesia (Figure 1). It is inhabited by 1,676 residents consisting of 482 households (833 male, 843 female). The indigenous people are referred to as To Bungku Ethnic, with strong customary characteristics, specifically in maintaining cultural values and kinship relations. The people use To Bungku language in daily life but use Indonesian (Bahasa Indonesia) outside of the community. The main livelihood of the community is working in the agricultural services, and craftsmen. The demographic structure of To Bungku Ethnic is presented in Table 1.

This study was conducted at one of the areas with high development dynamics in Central Sulawesi (Zuada et al. 2023). The area is among the main sources of nickel in Indonesia (26%) together with Southeast Sulawesi (32%) and North Maluku (27%) (Arif 2018; Rushdi et al. 2020). Nickel content in Central Sulawesi makes it one of the development areas for mining Special Economic Zones and industrialization centers. This is a derivative policy from the Master Plan for Acceleration and Expansion of Indonesia Economic Development (MP3EI) launched in 2011. Massive mining activities in the study area can reduce biodiversity and eliminate local knowledge systems related to the use of medicinal plants.

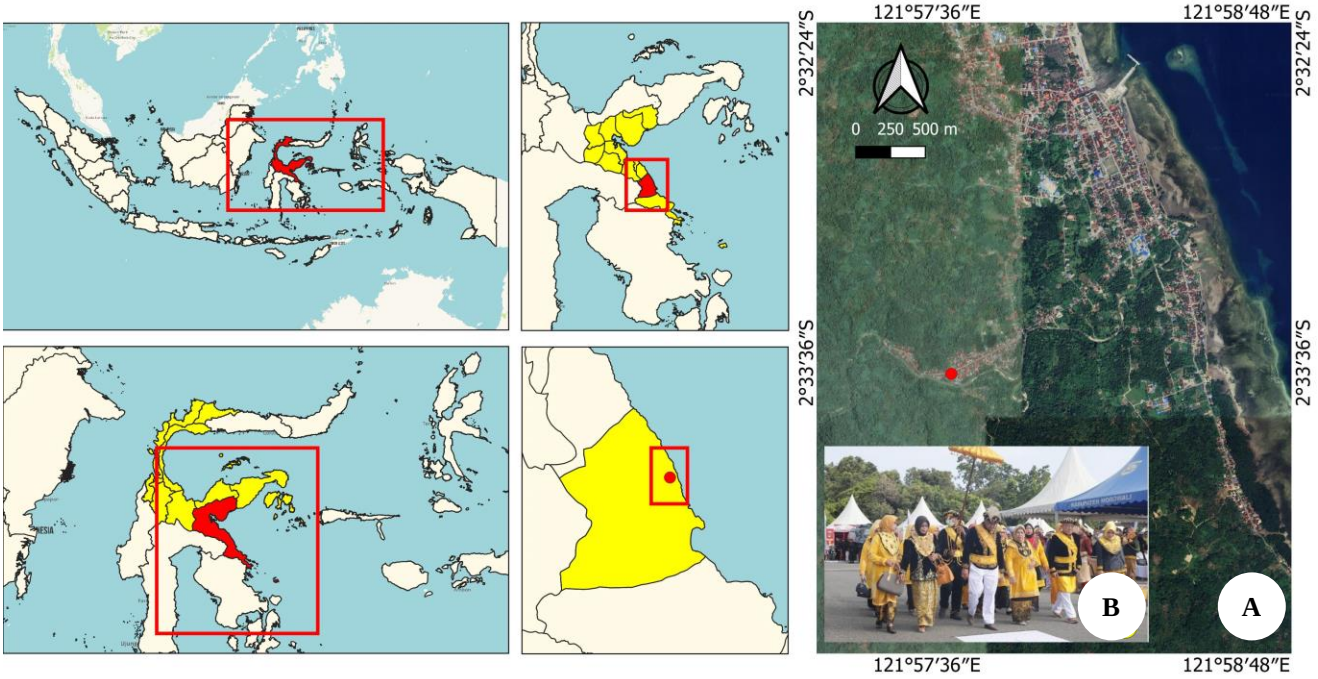

Figure 1. A. Study area Sakita Village, Bungku Sub-district, Morowali District, Central Sulawesi Indonesia; B. *Adat* leaders with traditional custom of To Bungku Ethnic (kindly provided by Zakia Sukma Ranti)

Table 1. Demographics structure, age composition, educational background, and religion of To Bungku Ethnic in Sakita Village, Morowali, Indonesia

Demographics structure	Individual number	Percentage (%)
Age groups (years)		
0-5	320	19.09
15-60	1288	76.85
>60	68	4.06
Total	1676	100
Education background		
Not yet attended education	57	9.38
Elementary school	17	2.80
Junior high school	77	12.66
Senior high school	340	55.92
Diploma	35	5.76
Graduate (Bachelor)	76	12.50
Magister (Program)	6	0.99
Total	608	100
Livelihood		
Farmer	832	74.82
Animal husbandry	106	9.53
Fisherman	8	0.72
Handicraft	10	0.89
Civil servant	71	6.38
Local government employee	10	0.89
Police and military	3	0.27
Teachers	38	3.42
Nurses	17	1.53
Medical doctor	2	0.18
Private employee	12	1.08
Financial institution service	3	0.27
Total	1112	100

Source: Local Government of Sakita Village (2022)

Data collection

The field study was conducted with a purposive sampling method (Tongco 2007). Data were obtained through direct observation, participatory observation, interview, and literature review (Cotton 1996; Martin 2007). A snowball method was used to obtain appropriate respondents (Bernard 2002) including village, custom (*adat*), traditional (*sando*), and religious leaders, rattan and dammar collectors, as well as farmers. The interviews were performed using semi-structured and open-ended methods related to the perceptions of the traditional use of medicinal plants. These interviews were recorded using audio recorders and notebooks. Photographs were also taken to record information (Turner 1988).

All medicinal plants used by local people were collected for herbarium collection and then identified at Herbarium Celebense (CEB), Tadulako University, Palu. The identification process involved comparing the sample with reference specimens and utilizing relevant literature (http://floramalesiana.org/) with the assistance of experts. Supplementary information, such as the local name, botanical name, family, and plant habitus (life form), were documented. The species were named according to the International Plant Names Index (IPNI) and their distribution was determined using the Plants of the World Online (POWO) database from the Royal Botanic Gardens, Kew. Ornamental plants that are considered invasive alien species are evaluated using the criteria outlined in Setyawati et al. (2015). The initial assessment of the conservation status was conducted following the guidelines of the IUCN Red List, available at the website https://www.iucnredlist.org/en, while specimens with labels were deposited at CEB, Tadulako University, Palu, Indonesia.

Data analysis

A descriptive statistical method was used to analyze and summarize the ethnobotanical data on the reported medicinal plants and associated knowledge that focus on knowledge documentation to facilitate its circulation in the communities form of databases (Łuczaj 2023).

RESULTS AND DISCUSSION

Traditional healers in Bungku use the plant resources available in nature for various disease treatments. This study found that there were 37 species of medicinal plants belonging to 26 families used by To Bungku Ethnic (Table 2). The family widely used by the people of Sakita Village is Zingiberaceae (4 species) then followed by Euphorbiaceae (3 species), Fabaceae, Arecaceae, Asteraceae, and Myrtaceae with 2 species, respectively. The families less used are Anacardiaceae, Annonaceae, Apocynaceae, Caricaceae, Costaceae, Lamiaceae, Leguminosae, Loranthaceae, Lythraceae, Malvaceae, Manispermaceae, Meliaceae, Menispermaceae, Moraceae, Muntingiacea, Oxalidaceae, Phyllanthaceae, Rubiaceae, Rutaceae, Solanaceae, and Verbenaceae (1 species each). Medicinal plants are obtained by the community from different habitats that grow naturally around the environment of the village, including forests or agroforests, gardens, as well as cultivation. To Bungku people use various plant species as medicine based on organ parts such as bark, sap, rhizome, fruit, leave, root, and stem. The percentage of organ parts used is presented in Figure 2.

Leaves are the most preferred plant part used in herbal formulation (48%), followed by fruits (16.22%), stem (13.51%), rhizome (8.11%), roots (2.7%), seeds (0%), sap (2.7%) as well as bark and mix with percentage of 5%. A total of 18 plant leaves are used as medicine by the local community in the studied area. Based on the information gathered from respondents, there are five types of life forms in the studied area including trees (18 species), herbs (10 species), shrubs (5 species), climbers (3 species), and epiphytes (1 species). The life form of each medicinal plant species is provided in Figure 3.

Based on the interview results, there were seven methods of concocting medicinal plants practiced by local people in the studied area namely, boiling, pounding, burning, consuming directly, squeezing, spreading, and chewing. The number of traditional medicinal plants used for each method is presented in Figure 4.

Table 2. Medicinal plants used by To Bungku Ethnic in the Morowali District, Central Sulawesi, Indonesia

Family	Botanical name	Local name (To Bungku Language)	Habitus	Part of Organ	Disease	Mode of preparation	Conserv. status
Anacardiaceae	*Mangifera indica* L.	*La'a Moolo*	Tree	Bark	Dental care/toothache	The bark is boiled and the water is gargled	DD
Annonaceae	*Annona muricata* L.	*Nangka falanda*	Tree	Leaves	High blood pressure/ hypertension	The leaves are boiled and then the water is drunk	LC
Apocynaceae	*Alstonia scholaris* (L.) R.Br	*Kompanga*	Tree	Bark of stem	Dental care/toothache	Boil the bark and drink the water	LC
Arecaceae	*Areca catechu* Burm.f	*Fua*	Tree	Nut	Dental care	The nut is chewed	LC
Arecaceae	*Cocos nucifera* L.	*Nimokohoni*	Tree	Fruit	Food poisoning	The water is drunk	NE
Asteraceae	*Blumea balsamifera* (L.) DC.	*Lefe ombu*	Shrub	Leaves	Gout urinary stones, kidney failure	The leaves are boiled and the water is drunk	LC
Asteraceae	*Elephantopus scaber* L.	*Patua Bumbu*	Herb	Leaves	Headache	The leaves are soaked in hot water, then the water is drunk	NE
Caricaceae	*Carica papaya* L.	*Pepaea*	Tree	Leaves	Indigestion	The leaves are boiled and then the water is drunk	DD
Costaceae	*Cheilocostus speciosus* (J.Koenig) C.D.Specht	*Tofu-Tofu*	Herb	Stem	Fever	The stem is grated, filtered, then drunk and applied all over the body	LC
Euphorbiaceae	*Aleurites moluccanus* (L.) Wild	*Beau*	Tree	Fruit	Tumor	Fruit endosperm is crushed and pasted over the tumor	LC
Euphorbiaceae	*Euphorbia hirta* L.	*Panga Bali*	Herb	Stem and leaves	Appendicitis	The stem and leaves are boiled and then the water is drunk	NE
Euphorbiaceae	*Jatropha curcas* L.	*Kalikaliki*	Shrub	Leaves	Rheumatism	The leaves are boiled and then the water is drunk	LC
Fabaceae	*Crotalaria spectabilis* Rotb.	*Kofi-kofi*	Shrub	Leaves	Eye care	The leaves are boiled and the water is drunk	NE
Fabaceae	*Senna alata* (L.) Roxb.	*Panda Kori*	Tree	Leaves	Dermato disease (ringworm)	The leaves are crushed until smooth and, rubbed on the skin	LC
Fabaceae	*Sesbania grandiflora* (L) Poiret.	*Kandadafa*	Tree	Leaves	Indigestion	The leaves are boiled and the water is drunk	DD
Fabaceae	*Spatholobus littoralis* Hassk.	*Bajaka*	Climber	Root	Cancer/tumor	The roots are cut into small pieces and swallowed	NE
Lamiaceae	*Orthosiphon aristatus* (Blume) Miq.	*Kumis Kucing*	Herb	Leaves	Appendix kidney stones	The leaves are boiled and the water is drunk	NE
Loranthaceae	*Macrosolen cochinchinensis* (Lour.) Tiegh	*Benalu*	Epiphyte	Leaves	Cancer/tumor	The leaves are boiled and the water is drunk	NE
Lythraceae	*Lawsonia inermis* L.	*Petaha keu*	Shrub	Leaves	Indigestion	The leaves are boiled and the water is drunk	LC
Malvaceae	*Theobroma cacao* L	*Fuano Sakulati*	Tree	Fruit	Tumor	The fruit is mashed until smooth and then pasted	NE
Meliaceae	*Lansium domesticum* Correa	*La Bubuno*	Tree	Stem bark	Vomiting blood	Boil the bark and drink the water	NE
Menispermaceae	*Arcangelisia flava* (L.) Merr.	*Akar kuning*	Climber	Stem	Hepatitis/Jaundice and diabetes	The roots are cut into small pieces and then boiled, the water is drunk	NE
Menispermaceae	*Tinospora crispa (*L.) Hook.f.& Thomson	*Oweo mpai*	Climber	Stem	Hepatitis, diabetes	The roots are cut into small pieces and boiled, the water is drunk	NE
Moraceae	*Artocarpus altilis* (Parkinson) Fosberg	*Lefe Bokulu*	Tree	Leaves	Hepatitis, jaundice	The leaves are boiled and the water is drunk	NE
Muntingiaceae	*Muntingia calabura* L.	*Gersen*	Tree	Leaves	Gout	The leaves are boiled and the water is drunk	LC
Myrtaceae	*Psidium guajava* L.	*Jampu*	Tree	Leaves	Diarrhea/digestive disorders	The leaves are boiled and the water is drunk	LC

Myrtaceae	*Syzygium malaccense* (L). Merr. & L. M. Perry	*Oa*	Tree	Leaves	Appendix disease	The leaves are boiled and then the water is drunk	LC
Oxalidaceae	*Averrhoa bilimbi* L.	*Lefe Takule*	Tree	Leaves	Hepatitis	The leaves are boiled and the water is drunk	LC
Phyllanthaceae	*Phyllanthus urinaria* L.	*Ido-ido*	Herb	Whole plant	Appendix	Boil all parts of plant and then drink the water	NE
Rubiaceae	*Morinda citrifolia* L	*Bangkudu*	Tree	Fruit	Diarrhea/digestive disorders	The fruit is cut into pieces roasted and pounded, brewed with hot water, and drunk	LC
Rutaceae	*Citrus aurantiifolia* (Christm.) Swingle	*Lemo bio*	Tree	Fruit	Tetanus, infection wound	The fruit is burned and squeezed	NE
Solanaceae	*Physalis angulata* L.	*Botu-Botu*	Herb	Leaves	Indigestion	The leaves are boiled and the water is drunk	LC
Verbenaceae	*Clerodendrum paniculatum* L.	*Langara*	Shrub	Leaves	Diarrhea/digestive disorders	The leaves are boiled and the water is drunk	NE
Zingiberaceae	*Curcuma longa* L.	*Kuni Pae*	Herb	Rhizome	Stomach ulcers	Rhizome is ground until smooth then filtered and drunk	DD
Zingiberaceae	*Etlingera calophrys* (K.Schum) A.D. Poulsen	*La mpana*	Herb	Stem	Wound	The stems are burned, squeezed and then dropped on the wound	LC
Zingiberaceae	*Etlingera tubilabrum* A.D. Poulsen	*Panasimpo*	Herb	Rhizome	Internal wounds, bloody stools	Rhizome is ground until smooth, filtered, and drunk	VU
Zingiberaceae	*Zingiber officinale* Roscoe	*Loiya*	Herb	Rhizome	Diarrhea/digestive disorders	Rhizome is ground until smooth, filtered, and drunk	DD

Note: NE: Not evaluated, DD: Data deficient, LC: Least concern, NT: Near threatened, VU: Vulnerable, EN: Endangered, CR: Critically endangered, EW: Extinct in the wild, EX: Extinct

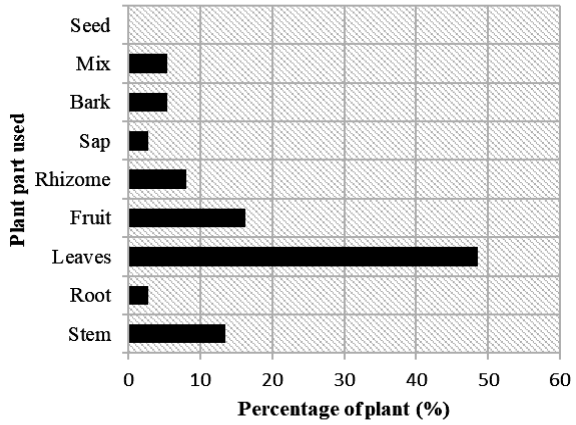

Figure 2. Plant parts used for medicine by To Bungku Ethnic in the study area

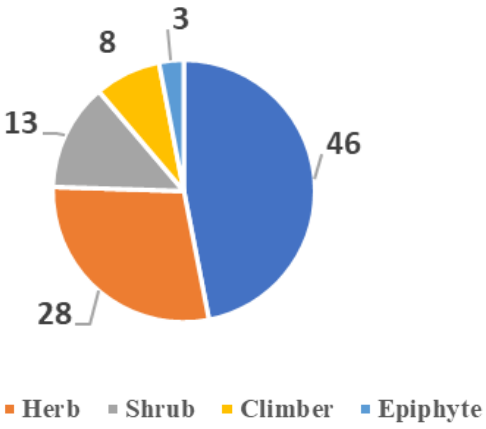

Figure 3. Percentage (%) of life forms of medicinal plants used by To Bungku Ethnic in the study area

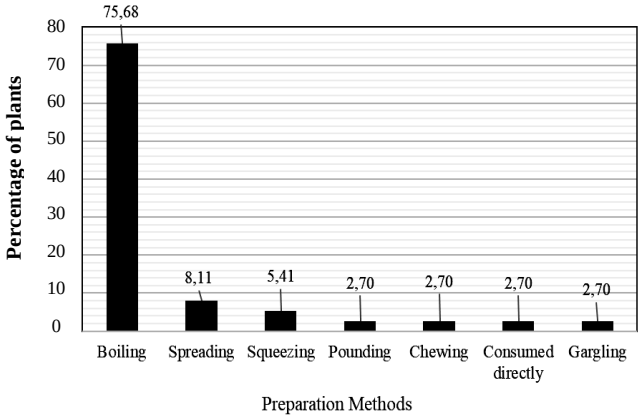

Figure 4. Preparation method of medicinal plants

Discussion

To Bungku Ethnic at Sakita Village uses medicinal plants for several purposes. Some species can be used for treatment of both single and different kinds of diseases including appendicitis, cancer, diabetes, diarrhea, gout, high blood pressure, jaundices, and urinary stones. Based on a field guide for local knowledge of ethnomedicine and medicinal plant studies in Indonesia published by the Ministry of Health of Republic Indonesia (2017), there are 74 common terms for local public health, some of which are tonsils, anti-mosquito, cough, swelling, diarrhea, overweight, chicken pox and measles.

In daily life, To Bungku Ethnic still relies on using traditional medicinal plants to maintain and care for health. Treatment using plants from the village leader is carried out by shamans or people considered to have more knowledge such as customary leaders, and village midwives. This tribe believes in the use of traditional medicinal plants that have been passed down from one generation to another from the parents. According to Zaki et al. (2019), the indigenous knowledge of preparing medicine was passed down to indigenous from the older generation by orally without any documentation. Most of the respondents claim they only identify the type of medicinal plants used when they are involved with old people or traditional healers during the preparation of the plants and remedies. They also have poor knowledge of dosage while preparing the remedies for their patients.

A total of 37 medicinal plant species belonging to 26 families are used. The most widely used family is Zingiberaceae (4 species) followed by Euphorbiaceae (3 species), Fabaceae, Arecaceae, Asteraceae, and Myrtaceae with 2 species respectively. The Zingiberaceae species, including *kuni pae* (*Curcuma longa*), *loiya* (*Zingiber officinale*), *panasimpo* (*Etlingera tubilabrum*), and *la mpana* (*Etlingera calophrys*) are used as herbal medicine against various diseases including bloody stools, diarrhea/ digestive disorders, internal wounds, and maag. *Etlingera tubilabrum* (Zingiberaceae) is among the 37 species recorded as being in the category of vulnerable to extinction based on the IUCN Red List of Threatened Species (https://www.iucnredlist.org/species/126984481/126984759).

Zingiberaceae (ginger group) is the largest family of the order Zingiberales, containing more than 52 genera and 1600 species (Kress et al. 2005). These aromatic herbs with horizontally creeping or tuberous rhizomes are widely used by humans, specifically as condiments, cut flowers, dyes, parfumes, spices, and traditional medicine (Pitopang et al. 2019, 2020). The rhizomes can be consumed raw or cooked as vegetables and used to make food flavoring ingredients (Larsen et al. 1999). Furthermore, Zingiberaceae contains essential oils and resins (Pitopang et al. 2022). Pitopang et al. (2019) reported 24 species, some of which are endemic to Sulawesi, and used traditionally by three different local ethnics in Lore Lindu National Park.

To Bungku ethnic uses various plant species as herbal medicine including bark, fruit, leave, rhizome, root, and stem, with the most commonly used being leaves. Knowledge about the uses of part of the plant as traditional medicine varies among local communities. Suharjito et al. (2014) reported that plant parts most frequently used were roots and leaves among the local people of Long Nah Village, East Kalimantan, while the native people of Donglai Baru, Hulu Langat, Malaysia predominantly used leaves (Ramli et al. 2021).

The life form of medicinal plants consists of trees, shrubs, herbs, lianas, epiphytes, and parasites. In this study, tree was found to be more widely used by To Bungku people as traditional medicine compared to other life forms of plants. Oktavia et al. (2022) showed that the life form of medicinal plants was dominated by trees (45%), woody lianas (21%), small trees (13%), herbs (13%), and lianas (8%) in Kelubi Village, Belitung Island, Indonesia.

According to Moges and Moges (2019), there are different types of medicinal plant species with parts, life forms, and disease types in the world. In Ethiopia, for example, approximately 800 species of medicinal plants are used to treat about 300 medical conditions. The life forms of medicinal plants include climbers, herbs, shrubs, and trees. Among all these life forms, herbs are majorly used by the community for human treatment followed by shrubs and trees.

Medicinal plants have been discovered and used in traditional medicine practices since prehistoric times. The use is due to phytochemical constituents (Awuchi 2019) synthesized in specific parts (Jantan et al. 2019). Plants synthesize hundreds of chemical and biochemical compounds for varied functions including defense against insects, herbivorous mammals, fungi, and diseases (Ahn 2017). Numerous phytochemicals with potential biological activity have been identified. Additionally, about 4000 phytochemicals have been identified (Jantan et al. 2019).

In conclusion, there are 37 species of medicinal plants used by To Bungku Ethnic. The predominant methods of use include boiling, chewing, consuming directly, pounding, spreading and squeezing, the parts commonly used are leaves, stems, bark, fruit, and rhizomes, with leaves having the highest percentage. The most common medicinal plant used by To Bungku Ethnic is *tofu-tofu* (*Cheilocostus speciosus* (J.Koenig) C.D. Specht) and the least is *benalu* (*Macrosolen cochinchinensis* (Lour) Van Tieng).

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Land use direction based on landslide susceptibility levels in the Rongkong Watershed, South Sulawesi, Indonesia

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Abstract. *Tirsyayu T, Soma AS, Paembonan SA. 2025. Land use direction based on landslide susceptibility levels in the Rongkong Watershed, South Sulawesi, Indonesia. Asian J For 9: 53-66.* Landslides, a common natural disaster in Indonesia, cause significant material and non-material losses. Mitigation efforts, including the provision of accurate information about landslide-prone areas and appropriate land-use recommendations, are crucial for minimizing their impact. This study, which analyzed landslide susceptibility using the frequency ratio method integrated with GIS technology, provides confidence in its methodology. The research, which began with data collection on landslide occurrences through imagery, identified 388 landslide points. These data were divided into two groups: validation data (20%) and training data (80%). The validation process, using the ROC curve, yielded an AUC value of 0.81, indicating the effectiveness of the frequency ratio method in predicting landslide occurrences in the Rongkong Watershed, South Sulawesi, Indonesia. The study revealed that parameters such as rainfall, slope gradient, land cover, elevation, lithology, curvature, and slope aspect significantly influence landslides in the Rongkong Watershed. In contrast, parameters such as distance from rivers, distance from roads, and NDVI had less influence. The study's findings, which classified landslide susceptibility levels as very high (1.32%), high (29.05%), and moderate (25.70%) based on the total area of the Rongkong Watershed, are of significant importance. They suggest that land use in areas with very high and high susceptibility should be designated for conservation or protected zones. In comparison, areas with moderate susceptibility can be utilized for limited and controlled cultivation, such as implementing agroforestry systems.

Keywords: Frequency ratio, landslide susceptibility, land use guidance, Rongkong Watershed

Abbreviations: AUC: Area Under the Curve, DEM: Digital Elevation Model, FR: Frequency Ratio, GIS: Geographic Information System, LSI: Landslide Susceptibility Index, NDVI: Normalized Difference Vegetation Index, ROC: Receiver Operating Characteristics, SPSS: Statistical Product and Service Solutions

INTRODUCTION

The incidence of landslides in Indonesia has shown a worrying increase due to climate change, urbanization, and environmental degradation. According to the National Disaster Management Agency (BNPB 2022), there were 17,296 natural disasters in Indonesia over the last five years (2017-2021), with landslides ranking as the third most frequent disaster, totaling 3,811 cases. The highest number of landslide incidents occurred in 2020, with 1,152 cases resulting in 128 fatalities and causing other significant damages. Proactive mitigation efforts are crucial to reduce these impacts. Providing information about landslide-prone areas is one of the strategies to minimize landslide consequences. Landslide susceptibility levels can be calculated using the Frequency Ratio (FR) method (Cantarino et al. 2023; He et al. 2023; Khan et al. 2024), which evaluates the relationship between landslide-causing factors and landslide occurrences. The larger the ratio, the stronger the relationship between the landslide events and contributing factors (Soma and Kubota 2017). The factors analyzed using the frequency ratio method depend on the availability of field data, such as slope gradient, slope aspect, elevation, curvature, lithology, land cover, distance from rivers, distance from roads, rainfall intensity, and vegetation density.

The Rongkong Watershed, spanning approximately 107.10 km in length and covering an area of 172,878.68 hectares, is one of the regions frequently experiencing landslides. According to Al-Ghifary et al. (2016), the Rongkong Watershed is categorized as highly critical and prone to landslides due to its mountainous topography and high rainfall. Their study employed a scoring method focusing on the upstream area of the watershed. Kurniawan (2019) suggested increasing accuracy and adding parameters to improve landslide susceptibility assessments. Research by Gholami et al. (2019) found that the FR method has higher predictive accuracy than other methods. This method is also widely used for landslide susceptibility mapping (Jaafari et al. 2014; Meten et al. 2015; Efiong et al. 2021; KC et al. 2022; Keshri et al. 2023) and can be easily integrated with GIS technology. Geographic Information System is a computer-based system used to process spatial data or data that has geographic references. This technology is widely used in spatial analysis because it improves time efficiency and accuracy. Therefore, the application of the FR method is crucial to reducing researcher subjectivity, improving accuracy, incorporating additional parameters, and covering broader areas. This approach aims to assess entire watershed ecosystems, supporting safe and sustainable management while mitigating disaster risks exacerbated by increasing rainfall

intensity due to climate change. Furthermore, using watersheds as the unit of analysis, the causal relationships between upstream and downstream impacts can be clearly demonstrated (Narendra et al. 2021).

In addition to providing information on landslide-prone areas, offering proper land-use guidance is also an important effort to reduce the risk of landslide disasters. According to Arjomandi et al. (2021), one of the main contributors to environmental degradation is improper land-use allocation. Comprehensive watershed management within a unified ecosystem is essential for maintaining ecological balance, controlling floods and erosion, ensuring water quality, and supporting the sustainability of natural resources. A key approach to sustainable watershed management and development is the proper allocation of land use within the watershed. Land-use planning guidelines serve as a framework or policy designed to regulate and optimize land utilization in a given area to align with its function, capacity, and environmental conditions. In the context of disaster vulnerability, such as landslides, land-use planning plays a crucial role in minimizing risks by identifying safe areas for development and areas that should be preserved or left in their natural state. Improper land use, such as construction on steep slopes or deforestation, can significantly increase the risk of landslides and other natural disasters. Therefore, by incorporating landslide susceptibility into land-use planning, a balance can be achieved between development needs, environmental protection, and disaster risk reduction.

MATERIALS AND METHODS

Study area

This research was conducted from March to August 2024 in the Rongkong Watershed (2° 21' 35"-2° 56' 15" S and 119° 51' 45"-120° 23' 15" E), which encompasses the regions of North Luwu and Luwu Districts in South Sulawesi Province, Indonesia. Data processing was carried out at the Watershed Management Laboratory, Faculty of Forestry, Hasanuddin University, Makassar, Indonesia (Figure 1).

Procedures

Tools and materials

The tools used include a laptop equipped with ArcGIS 10.8 and SPSS (Statistical Product and Service Solutions) applications, writing instruments, a camera, and a smartphone with mapping applications (SW Maps and Avenza Maps). The materials used include the Rongkong Watershed boundary map, administrative maps of Luwu and North Luwu Districts, Google Earth Pro imagery for landslide inventory from 2013-2023, Sentinel-2 imagery, the 2023 National DEM, rainfall data from 2013-2023, and the geological map of South Sulawesi.

Landslide Inventory

The landslide data for the Rongkong Watershed was obtained through the interpretation of Google Earth Pro imagery from 2013 to 2023. A total of 388 landslide points were identified, and a ground check was conducted to ensure the accuracy of the interpretation at several landslide points using a non-probability sampling technique. This technique does not provide equal opportunities for all population members to be selected. The type of sampling used was purposive sampling, where samples are chosen based on specific criteria such as accessibility to the location. This technique is among the most commonly used sampling methods (Palinkas et al. 2015). A total of 30 landslide points and 15 non-landslide points were used as research samples. The results of the ground check are shown in Figure 2.

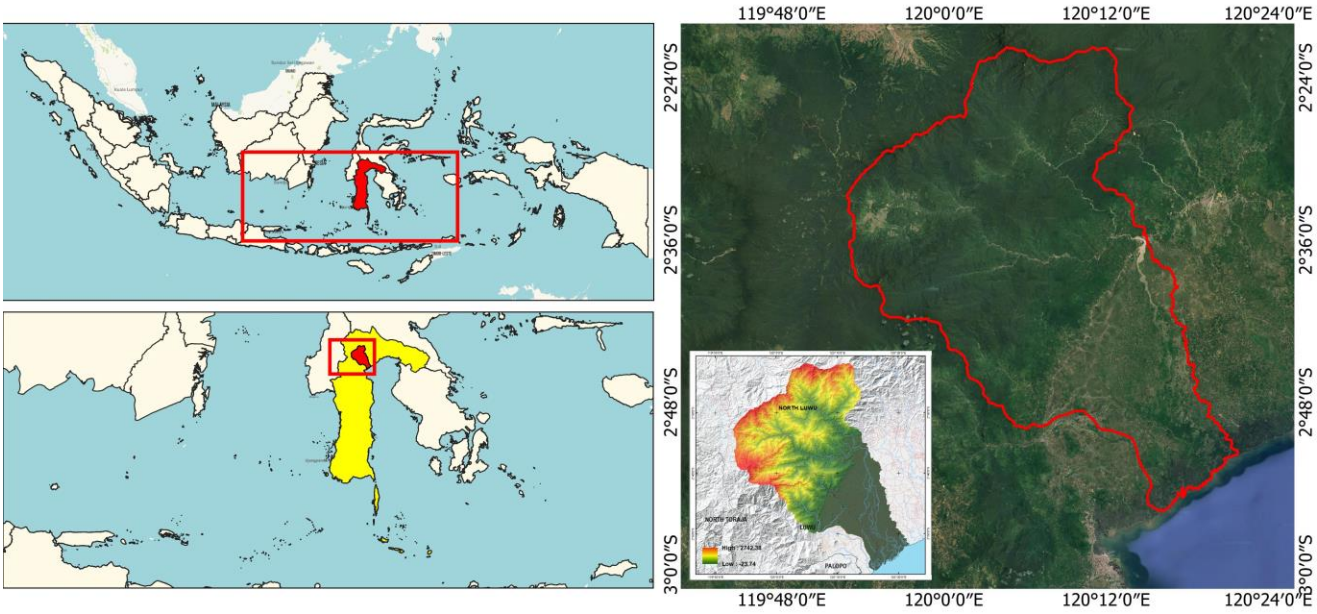


Figure 1. Map of the research area in the Rongkong Watershed, South Sulawesi Province, Indonesia

Figure 2. Landslides in the Rongkong Watershed. A. Interpretation results from Google Earth Pro; B-E. Ground check results

The validation of landslide occurrence data using the confusion matrix method and accuracy testing with overall accuracy showed that 91.11% of the data is accurate and acceptable, as it exceeds the 85% threshold set by Lillesand and Kiefer (2015). Landslide occurrence data were assigned a value of 1, and non-landslide data were assigned a value of 0, then converted into raster data with a pixel size of 10 × 10 m. The total number of landslide pixels is 24,712 out of the total area of the Rongkong Watershed, which contains 17,287,886 pixels. This data was divided into two parts: 20% (4,943 pixels) for validation and 80% (19,769 pixels) for training.

Data on the factors contributing to landslides

This study analyzes the factors contributing to landslides, including rainfall, slope gradient, land cover, elevation, lithology, distance from rivers and roads, surface curvature, slope aspect, and vegetation density. Rainfall data from 2013 to 2023 was downloaded from NASA's website after identifying representative rainfall station points and stored in CSV format. The average annual rainfall was processed in ArcGIS using the Isohyet method and classified according to the Meteorology, Climatology, and Geophysics Agency (BMKG 2021) into four rainfall categories: low rainfall (0-1,500 mm), medium rainfall (1,500-3,000 mm), high rainfall (3,000-4,500 mm), and very high rainfall (>4,500 mm).

Land cover data was generated through the interpretation of Sentinel-2A imagery. The interpretation was performed by analyzing patterns, tones, colors, and textures in the imagery and classifying them based on the 2010 National Standardization Agency guidelines. Field observations were conducted by selecting sample locations using the purposive sampling method, ensuring accessibility of the locations. Data validation was carried out using the confusion matrix method, and accuracy testing with Overall Accuracy indicated a data accuracy of 92.5%. There are 12 types of land cover in the Rongkong Watershed: shrubs, primary dryland forest, secondary dryland forest, secondary mangrove forest, grassland, plantations, settlements, dryland agriculture, mixed dryland agriculture and shrubs, rice fields, rivers, and fishponds.

Elevation, slope gradient, distance from rivers, curvature, and slope aspect data were obtained from processing National DEM (Digital Elevation Model) data. Elevation data was classified based on the Minister of Public Works Regulation No. 20 of 2007 into the following classes: <500 meters above sea level (masl), 500-1,500 masl, 1,500-2,500 masl, and >2,500 masl. Slope gradient data was classified according to the Perdirjen BPDASPS No. P.4/V-SET/2013: flat (<8%), gentle (8-15%), moderately steep (16-25%), steep (26-40%), and very steep (>40%). Distance from rivers was categorized into four classes: 0-100 m, 100-200 m, 200-300 m, and >300 m. Lithology data was derived from the geological map of South Sulawesi. Distance from roads was obtained by processing road data from the Geospatial Information Agency and classified into five classes: <500 m, 500-1,000 m, 1,000-1,500 m, 1,500-2,000 m, and >2,000 m.

Vegetation density was derived from Sentinel-2 imagery and assessed using the Normalized Difference Vegetation Index (NDVI) with the following formula (Jacquemart and Tiampo 2021; Niraj et al. 2023):

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

Where: NIR refers to the band with a near-infrared wavelength (band 8), while RED refers to the band with a red wavelength (band 4). NDVI values are classified into five categories: non-vegetated (-1 to 0.25), sparse

vegetation (0.25 to 0.35), moderately dense vegetation (0.35 to 0.45), dense vegetation (0.45 to 0.50), and very dense vegetation (0.50 to 1). NDVI values range from -1 to 1 (Yengoh et al. 2015; Marsujitullah et al. 2023; Martinez and Labib 2023; Rashid et al. 2023). A value of -1 indicates a non-vegetated classification, whereas a value of 1 represents a very dense vegetation classification.

Data limitations and bias control strategies

The historical landslide event database is often incomplete or poorly documented, and there are data gaps in certain years, making it difficult to analyze trends consistently and comprehensively. This study introduces an innovative combined approach and integrates existing historical data with remote sensing data, such as satellite imagery and more recent field information, to address this limitation. This novel approach significantly improves the accuracy of the landslide susceptibility analysis, reflecting a more comprehensive condition.

Landslide susceptibility level analysis

The landslide susceptibility level is calculated based on the influence of rainfall, slope gradient, land cover, elevation, rock type/lithology, distance from rivers, distance from roads, surface curvature, slope aspect, and vegetation density on landslide occurrences, analyzed using the frequency ratio method with the following formula (Soma and Kubota 2017):

$$FR = \frac{PxcL(nm)/\sum PnxL}{Pixel(nm)/\sum Pnx}$$

Where: FR stands for Frequency Ratio; PxcL refers to the number of landslide pixels in class n of parameter m (nm); Pixel represents the number of pixels in class n of parameter m (nm); ∑PnxL is the total pixels of parameter m; and ∑Pnx is the total pixels of the area. The larger the ratio exceeds 1, the stronger the relationship between landslide occurrences and the causal factor. Conversely, if the ratio is less than 1, the relationship between landslide occurrences and that factor is weak (Pradhan and Lee 2010). The Landslide Susceptibility Index (LSI) is created by mapping all factors into raster maps based on their FR values, which are then summed using the formula (Abbasa et al. 2024; Gulbet and Getahun 2024):

$$LSI = \sum FR$$

Data validation

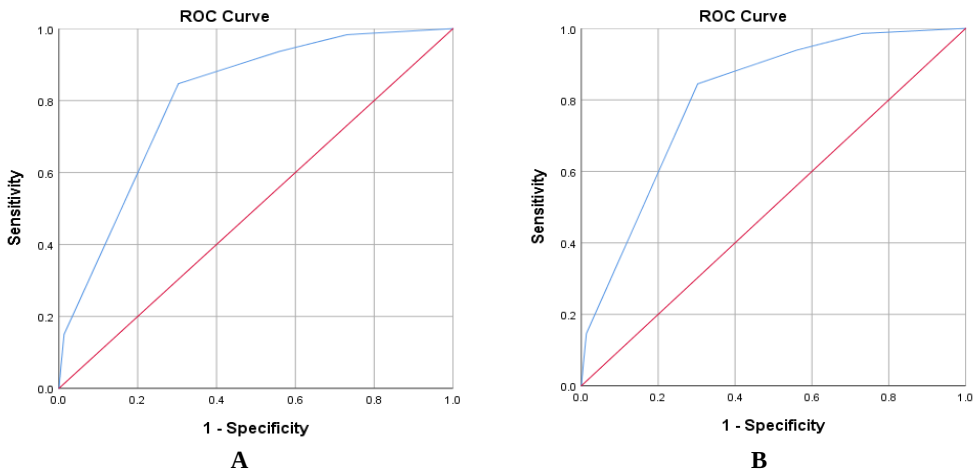
Data validation is intended to evaluate a classification model. The validation process uses the ROC (Receiver Operating Characteristics) curve, calculated using SPSS software. The ROC curve displays the AUC (Area Under Curve) value. AUC evaluation results are classified according to Rasyid et al. (2016) as follows: fail (0.50-0.60), poor (0.60-0.70), fair (0.70-0.80), good (0.80-0.90), and excellent (0.90-1.00). The data used include landslide events divided into two sets: 20% for assessing the model's predictive capability and 80% for evaluating the model's success. The validation results (Figure 3) show identical AUC values for both the model prediction rate (20%) and the model success rate (80%), at 0.806 or 0.81.

According to Rasyid et al. (2016), an AUC value within the range of 0.80-0.90 indicates that a model performs well. In this case, the frequency ratio method is considered effective in predicting landslide occurrences in the Rongkong Watershed.

RESULTS AND DISCUSSION

Results of the frequency ratio analysis of landslide contributing factors in the Rongkong Watershed

The factors causing landslides are extracted into landslide data points, and their ratio to landslide occurrences is calculated. The FR value indicates the extent of a factor's influence on landslide occurrences. An FR value of 1 represents the average FR value; if FR >1, it means the factor is correlated with landslide occurrences. Conversely, if FR <1, the factor has minimal influence. The higher the FR value, the greater its impact on landslide occurrences (Huang et al. 2021; Sahrane et al. 2023). The FR value for each factor can be found in Table 1.



A B

Figure 3. The ROC curve. A. Model Prediction Rate (20%) and B. Model Success Rate (80%)

Table 1. The FR values of the factors contributing to landslides in the Rongkong Watershed, South Sulawesi, Indonesia

Parameter	Class	PxcL	% PxcL	PnXL	% PnXL	FR
Rainfall (mm/year)	3,370.36	19,523	98.76	13,008,802	75.25	1.31
	3,389.49	85	0.43	610,461	3.53	0.12
	3,413.81	77	0.39	415,767	2.41	0.16
	3,433.59	0	0.00	2,617,272	15.14	0.00
	3,441.69	84	0.42	634,761	3.67	0.12
	Total	19,769	100	17,287,063	100	
Slope (%)	0-8	235	1.19	4,339,796	25.10	0.05
	8-15	347	1.76	933,749	5.40	0.32
	16-25	873	4.42	1,448,739	8.38	0.53
	26-40	4,395	22.23	4,556,209	26.36	0.84
	>40	13,919	70.41	6,008,570	34.76	2.03
	Total	19,769	100	17,287,063	100	
Land Cover	Shrubland	2,853	14.43	230,694	1.33	10.81
	Primary Dryland Forest	1,671	8.45	814,697	4.71	1.79
	Secondary Dryland Forest	13,761	69.61	9,267,173	53.61	1.30
	Secondary Mangrove Forest	0	0.00	27,678	0.16	0.00
	Grassland	51	0.26	1,557	0.01	28.64
	Plantation	366	1.85	1,748,136	10.11	0.18
	Settlement	0	0.00	398,278	2.30	0.00
	Dryland Farming	5	0.03	1,615,109	9.34	0.00
	Dryland Farming Mixed with Shrubs	680	3.44	933,678	5.40	0.64
	Rice Field	261	1.32	1,478,531	8.55	0.15
	River	121	0.61	301,517	1.74	0.35
	Ponds	0	0.00	470,015	2.72	0.00
	Total	19,769	100	17,287,063	100	
Elevation (masl)	<500	1,159	5.86	7,207,798	41.69	0.14
	500-1500	15,352	77.66	7,207,675	41.69	1.86
	1500-2500	3,252	16.45	2,852,047	16.50	1.00
	>2500	6	0.03	19,543	0.11	0.27
	Total	19,769	100	17,287,063	100	
Lithology	Latimojong Formation	174	0.88	797,799	4.62	0.19
	Matano Formation	0	0.00	9,478	0.05	0.00
	Ultramafic Complex	0	0.00	128,385	0.74	0.00
	Alluvium	0	0.00	4,292,413	24.83	0.00
	Barufu Tufa	78	0.39	543,098	3.14	0.13
	Toraja Formation	214	1.08	512,469	2.96	0.37
	Intrusive Rocks	0	0.00	1,296	0.01	0.00
	Dondo Suit	16,834	85.15	7,626,040	44.11	1.93
	Lamasi Volcano Rocks	2,469	12.49	3,376,085	19.53	0.64
	Total	19,769	100	17,287,063	100	
Distance from the river (m)	0-100	410	2.07	1,012,573	5.86	0.35
	100-200	628	3.18	928,857	5.37	0.59
	200-300	850	4.30	883,972	5.11	0.84
	>300	17,881	90.45	14,461,661	83.66	1.08
	Total	19,769	100	17,287,063	100	
Distance from the road (m)	<500	1,443	7.30	4,525,896	26.18	0.28
	500-1000	885	4.48	2,029,977	11.74	0.38
	1000-1500	822	4.16	1,449,588	8.39	0.50
	1500-2000	57	0.29	1,402,114	8.11	0.04
	>2000	16,562	83.78	7,879,488	45.58	1.84
	Total	19,769	100	17,287,063	100	
Curvature	Concave	1187	6.00	676,138	3.91	1.54
	Flat	10,361	52.41	8,251,754	47.73	1.10
	Convex	8221	41.59	8,359,171	48.36	0.86
	Total	19,769	100	17,287,063	100	
Slope aspect	Flat	26	0.13	30,950	0.18	0.73
	North	1,791	9.06	2,088,612	12.08	0.75
	Northeast	2,746	13.89	2,135,194	12.35	1.12
	East	3,224	16.31	2,396,859	13.87	1.18
	Southeast	3,749	18.96	2,728,425	15.78	1.20
	South	3,258	16.48	2,443,406	14.13	1.17
	Southwest	2,306	11.66	1,998,299	11.56	1.01
	West	1,272	6.43	1,724,967	9.98	0.64
	Northwest	1,397	7.07	1,740,351	10.07	0.70
	Total	19,769	100	17,287,063	100	
Vegetation density	Non-Vegetated	744	3.76	701,002	4.06	0.93
	Sparse Vegetation	450	2.28	313,993	1.82	1.25
	Moderately Dense Vegetation	467	2.36	380,781	2.20	1.07
	Dense Vegetation	294	1.49	188,867	1.09	1.36
	Very Dense Vegetation	17,814	90.11	15,702,420	90.83	0.99
	Total	19,769	100	17,287,063	100	

Based on Table 1, it is evident that each factor has a different FR value, indicating that not all factors have the same level of correlation with landslide occurrences in the Rongkong watershed. The map of landslide-causing factors in the Rongkong Watershed can be seen in Figure 4. The FR value for each landslide-causing factor is presented in the graph below (Figure 5).

According to Hontus (2016), rainfall is a natural factor that plays an important role in landslide events. Rainfall is the dominant factor controlling slope stability (Zhang et al. 2019; Alsubal et al. 2019; Farooq and Akram 2021; Chellamuthu and Ganapathy 2024). High rainfall can increase the water pressure in the soil. Water that permeates the soil saturates it, reducing the soil's bearing capacity and increasing the risk of landslides (Gallage et al. 2021; Poddar and Roy 2024). High rainfall can also expand the soil's porosity. Water that seeps into the soil fills the pores, weakening the soil structure and making it more susceptible to mass movement. An increase in precipitation in a region will lead to more frequent landslide occurrences.

Based on the rainfall data processing from the last 10 years (2013-2022), the rainfall data for the Rongkong Watershed ranges between 3,370.36 and 3,441.69 mm/year, which falls into the high rainfall category (3,000-4,500 mm/year). The corresponding FR value, which indicates the potential for landslide events, is shown in Figure 5.A. Figure 5.A also presents a surprising finding: while still categorized as high, a rainfall of 3,370.36 mm/year has an FR value of 1.31, the highest in the lowest class. This unexpected result underscores the strong relationship between landslide occurrences and rainfall. It suggests the influence of other factors, such as the predominantly very steep slope steepness and the land cover, including grasslands and shrubs.

Slope steepness has a significant influence on the potential for landslides (Guo et al. 2021; Tesfa and Woldearegay 2021). Steeper slopes exert greater pressure on the soil material, increasing the likelihood of mass movement downwards. According to the study by Roback et al. (2018), the highest landslides occur at the junction of steep slopes. The steeper the slope, the more likely a landslide will occur (Diara et al. 2022; Ma et al. 2022; Arumugam et al. 2023; Xie et al. 2023). The FR value of slope steepness in the Rongkong Watershed can be seen in Figure 5.B.

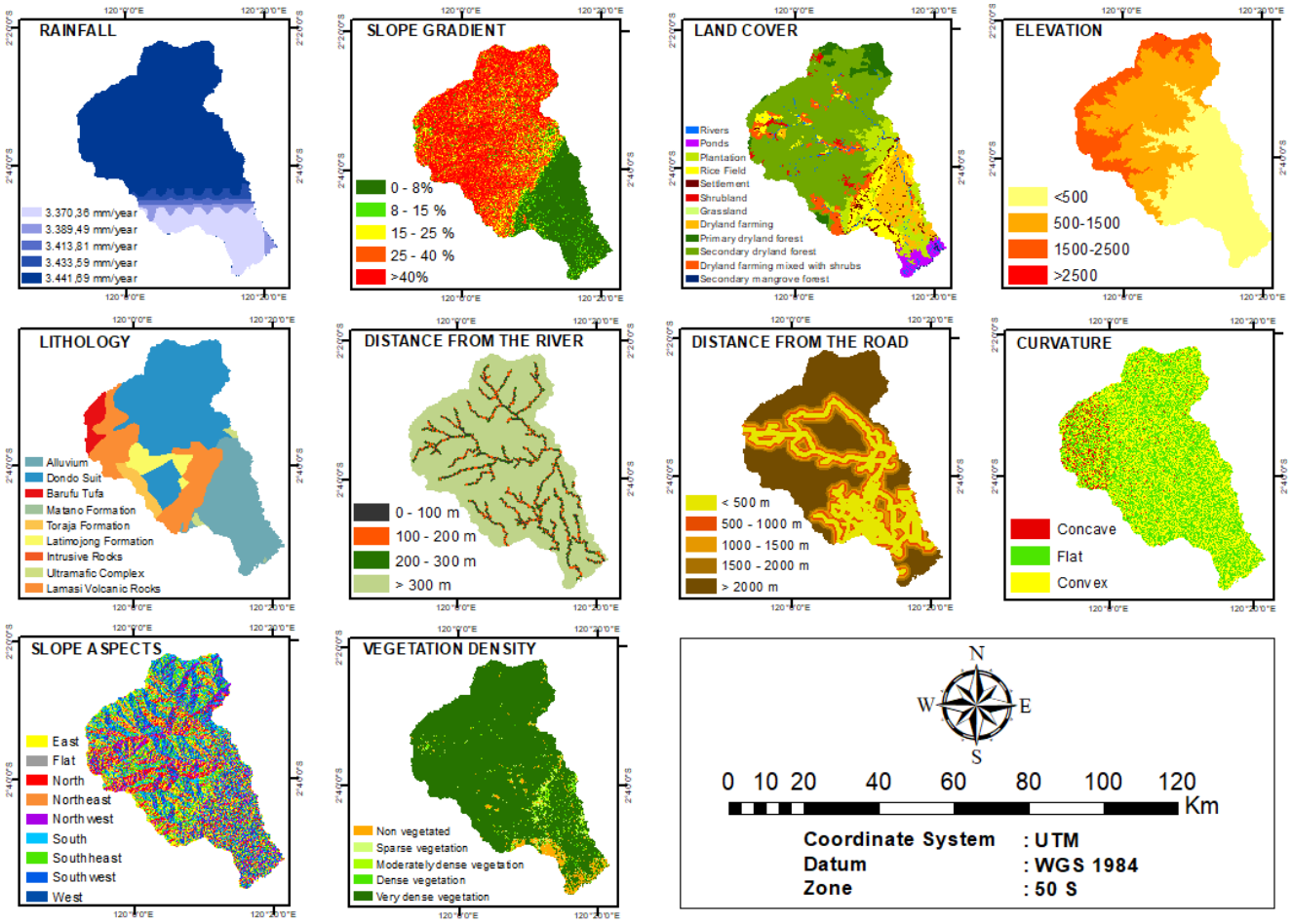


Figure 4. Map of landslide triggering factors in the Rongkong Watershed, South Sulawesi, Indonesia

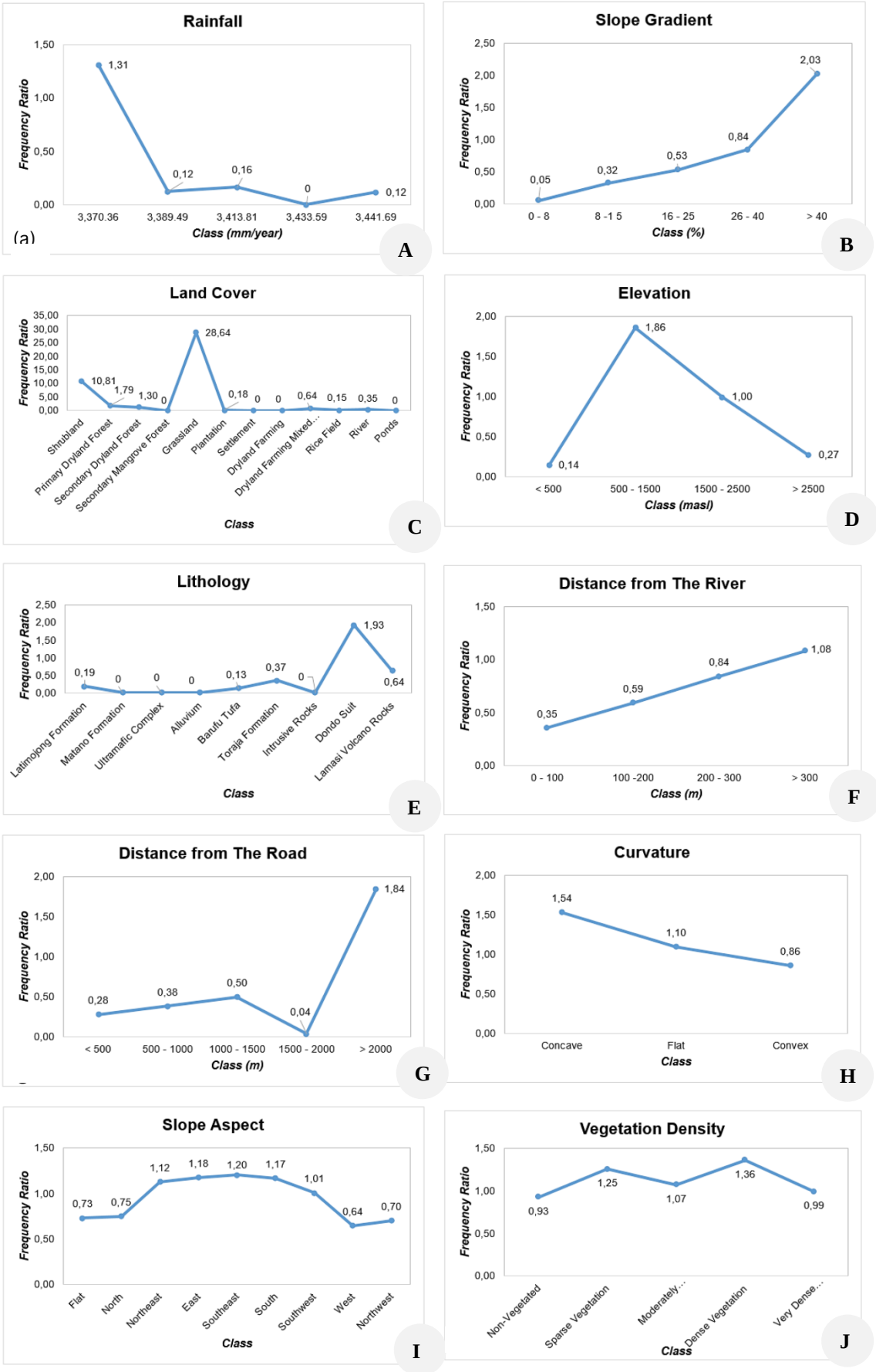


Figure 5. Graph of FR values for landslide-causing factors

At slopes >40% (very steep), the FR value is >1, specifically 2.03, indicating a strong relationship with landslide occurrences. Meanwhile, the slope classes of steep, moderately steep, gentle, and flat have FR values <1, indicating a low correlation. This aligns with the study by Tang et al. (2015), which found that landslide concentration increases with steeper slope angles. Slopes steeper than 20° are highly prone to landslides (Acosta-Quesada and Quesada-Román 2024). Additionally, other factors, such as high rainfall and land cover (grasslands and shrubs), have a significant impact on landslide occurrences on very steep slopes.

Land covered with dense vegetation and strong roots tends to have a lower risk of landslides because it can absorb rainwater and prevent material saturation on slopes, especially on steep slopes (Jeong et al. 2017). Forests with strong root systems can stabilize the soil and help maintain slope stability (Soma and Kubota 2017; Sujatha et al. 2023). The roots of vegetation can help maintain soil stability by reinforcing the soil structure and preventing erosion (Dorairaj and Osman 2021; Jafari et al. 2022; Gong et al. 2024; Lann et al. 2024).

Based on Figure 5.C, land cover types with an FR value >1 include grasslands, shrubs, primary dryland forests, and secondary dryland forests. Grasslands, covering an area of 15.57 ha, have an FR value of 28.64; shrubs, with an area of 2,306.94 ha, have an FR value of 10.81; followed by primary dryland forests, covering 814,697 ha with an FR value of 1.79, and secondary dryland forests, covering 9,267,173 ha, with an FR value of 1.30.

Landslides can occur in areas with land cover types such as bare land, fields, shrubs, and grasslands. According to Hurlimann et al. (2022), root strength is higher in forests than in grasslands and shrubs. In a previous study by Abedin (2020), most landslide events occurred in areas with shrub and grassland cover. Shrubs and grasslands have a less robust root system to anchor the soil, resulting in lower soil stability and making landslides more likely. Although secondary dryland forests are often covered by tree vegetation, landslides can still occur due to disturbances or changes from their original condition caused by human activities. Unlike primary dryland forests, landslides can still happen in these areas, even without human activities, due to other factors influencing soil stability. It's crucial to understand that steep slopes and heavy rainfall are critical factors that can trigger landslides, underscoring the urgency of studying these elements. Most of the primary dryland forests in the Rongkong Watershed are located on very steep slopes with high rainfall.

The higher the elevation of an area, the greater the potential gravitational energy, which makes soil and rocks more active (Wu et al. 2023). In higher areas, groundwater pressure is higher due to more rainfall infiltrating the soil. High groundwater pressure can cause the soil to become more saturated and soft, which increases the likelihood of landslides. High elevations, especially on steep slopes, tend to support the occurrence of landslides (Li et al. 2021; Dunham et al. 2022).

Figure 5.D presents a graph of the FR values for the elevation of the Rongkong Watershed. The elevation class with an FR value greater than 1 is between 500 and 1,500 meters above sea level (1.86). Meanwhile, the elevation from 1,500 to 2,500 masl shows a value of 1, which represents the average FR value; unlike the landslide study by Li et al. (2021), landslide occurrences in the Rongkong Watershed decrease at elevations of 1500 meters and above, marked by a decline in the FR value. A similar finding was reported in the study by Zhou et al. (2016), which stated that landslides are more frequent at mid-elevations, specifically between 900-1,300 masl and 1,200-2,000 masl. Landslides at these mid-elevations occur due to human activities, such as deforestation, which reduces or even eliminates vegetation that helps maintain slope stability. This is further exacerbated by the high rainfall and steep slopes in the Rongkong Watershed, which facilitate the occurrence of landslides.

According to the Ministry of Public Works Regulation Number 22/PRT/M/2007, one of the factors that contribute to landslides is the type of rock/lithology. Lithology is an important controlling factor (Bahrami et al. 2019; Pourghasemi et al. 2020; Wu et al. 2020; Conforti and Ietto 2021; Yu et al. 2021; Rahaman et al. 2024). The strength of the rock can determine how easily or how difficult it is for the rock to break or shift. Rocks with fragile or fragmented structures are more prone to landslides because they are more easily affected by pressure and ground movement. On steeper slopes, more material is crushed for certain types of material, leading to larger landslides (Katz et al. 2014). In the Rongkong Watershed, there are nine types of rock formations: Latimojong Formation, Matano Formation, Ultramafic Complex, Alluvium, Tufa Barufu, Toraja Formation, Intrusive Rocks, Suit Dondo, and Lamasi Volcano Rocks. The FR values for each lithology class are shown in Figure 5.E.

Based on Figure 5.E, the Suit Dondo rock type has an FR value greater than 1, specifically 1.93, indicating a strong correlation with landslide occurrences in the Rongkong Watershed. Suit Dondo rocks generally have a coarse to medium texture and high hardness. Landslides can occur when hard rocks undergo weathering (Saputra and Heriyadi 2019; Silwal et al. 2024). According to Komadja et al. (2020), weathering of rocks causes slope instability, which triggers landslides. Especially on very steep slopes and with high rainfall, these rocks may fracture and lead to landslides.

Based on Figure 5.F, it can be seen that the distance from the river with an FR value greater than 1 is greater than 300 meters (1.08). According to Cheng et al. (2021), the distance from the river is one of the factors that significantly influences landslides. Slopes near rivers are more prone to landslides (Hidayah et al. 2017; Hua et al. 2020; Ali et al. 2021; Mahalingam and Kim 2021; Naik and Palakuzhiyil 2024). softening the soil, which weakens slope stability. A different finding was observed in the Rongkong Watershed, where landslides were more frequent at distances greater than 300 meters. Similarly, in the study by Abedin (2020), the distance from the river had little influence on landslide occurrences. Although the distance from the river is far, landslides in the Rongkong Watershed can still occur due to other factors, such as very

steep slopes, high rainfall, and land cover in the form of shrubs and grasslands.

The distance from roads within the Rongkong Watershed is shown in Figure 5.G, the road >2,000 meters (1.84). This value indicates a high correlation between landslide occurrences and the distance from the road in the >2000 m class. According to Hidayah et al. (2017), the distance between the road and the slope can trigger landslides due to vehicle traffic around the slope. The closer the slope is to the road, the greater the likelihood of a landslide (Teimouri and Nalivan 2020; Ye et al. 2022). In contrast to the Rongkong Watershed, landslides in this area are more frequent in that the distance from the road did not significantly affect landslide occurrences, as indicated by the lowest weight value among all the factors. This is also consistent with the research of Abedin (2020), which found that most landslides occur within 2000 meters of the road. This is likely due to other factors influencing landslide occurrences in the area, such as high rainfall and slope steepness, which is dominated by moderate to very steep gradients.

There are three forms of the Earth's surface: convex, indicated by positive values; concave, indicated by negative values; and flat, indicated by zero values. Concave areas of the Earth's surface tend to have a higher risk of landslides compared to convex areas. This is because concave slopes can retain more water after heavy rainfall and hold it for longer periods, causing the soil to reach saturation and lose strength, making it more prone to landslides. Zhuang et al. (2018) stated that landslides are more common on concave slopes. In Figure 5.H, curvature (concave) classes with an FR value greater than 1 are the concave and flat classes. The concave class has an FR value of 1.54, while the flat class has an FR value of 1.10, indicating a strong correlation with landslide occurrences in the Rongkong Watershed. This is due to the possibility of flat areas forming in highlands as a result of geological processes such as sedimentation or erosion. Flat areas on steep slopes, such as terraces, tend to collect rainwater, causing the soil to become saturated and triggering landslides, especially during periods of high rainfall.

One significant factor affecting landslide occurrences is the slope aspect (Gorokhovich and Vustianiuk 2021; Qi et al. 2021); varying levels of rainfall, sunlight, and wind influence slopes facing different directions. Slopes that receive more rainfall tend to be more vulnerable to landslides compared to those facing other directions (Cellek 2021). Additionally, wind direction can also affect landslides. Indirectly, strong winds can exert pressure on slopes from a specific direction, increasing the stress on the soil or rock material on that slope, thereby disrupting slope stability and increasing the risk of landslides, especially if the slope is already unstable.

Figure 5.I is a graph showing the FR values for slope aspect. The FR value greater than 1 is found in the southeast slope direction (1.20), followed by the east direction (1.18), south direction (1.17), northeast direction (1.12), and southwest direction (1.01). It can be observed that the FR value increases from the north to the southeast and then decreases again toward the northwest direction. This is consistent with the study by Naseer et al. (2021), which found that slopes facing the sun are generally more exposed to direct sunlight, accelerating weathering processes and increasing the risk of landslides. South-facing slopes are also the most susceptible to landslides (Bahadur et al. 2020; Li et al. 2021). When the sun is in the south, rainfall tends to be higher due to the large amount of evaporation from the Indian Ocean. Zhuang et al. (2018) also found that landslides were more dominant on slopes facing southeast. Wu et al. (2020) added that east-facing slopes are more prone to landslides.

Vegetation can help maintain slope stability by preventing erosion and soil movement. The denser the vegetation, the stronger the soil is bound by plant roots, thereby reducing the likelihood of landslides. The FR value of vegetation density is presented in Figure 5.J.

According to the study by Deng et al. (2022), most landslides occur on slopes with sparse vegetation and are less frequent in areas with high vegetation density. High vegetation cover plays a crucial role in reducing landslide risk because it helps support slope stability and aids in landslide mitigation. Gholami et al. (2019) also stated that vegetation density significantly influences landslide occurrence, with landslide frequency decreasing as vegetation density increases. However, this study found that the highest FR values were actually in areas with dense vegetation, with a value of 1.36, followed by areas with sparse vegetation (1.25) and moderately dense vegetation (1.07). This is certainly influenced by other factors at the study site, such as steep slopes, which dominate the area with a very steep gradient covering 60,089.67 hectares, and high rainfall. It's important to note that the vegetation density index or NDVI, while useful in providing information about the presence or density of vegetation, cannot provide information about the quality of the vegetation, particularly the species diversity in the study area, which could help prevent landslides. This highlights the need for further research and development in this area.

Discussion

Landslide susceptibility in the Rongkong Watershed

The landslide susceptibility map of the Rongkong Watershed (Figure 6) was created based on the LSI values, which represent the levels of very low, low, moderate, high, and very high landslide susceptibility (Chen et al. 2014). Figure 7 shows the percentage of landslide susceptibility in the Rongkong Watershed. It is calculated by dividing the area of the susceptibility class by the total area of the Rongkong watershed, multiplied by 100.

The very low susceptibility class covers an area of 46,588.50 ha (26.95%) and includes 79 villages. The largest area of low susceptibility is in Lawewe Village (Baebunta Selatan District), with 2,824.812 ha, followed by Wara Village (Malangke Barat District), with 2,687.800 ha, and Lembang-lembang Village (Baebunta Selatan District) with 2,266.173 ha. Dryland agriculture, rice fields, and settlements dominate this class.

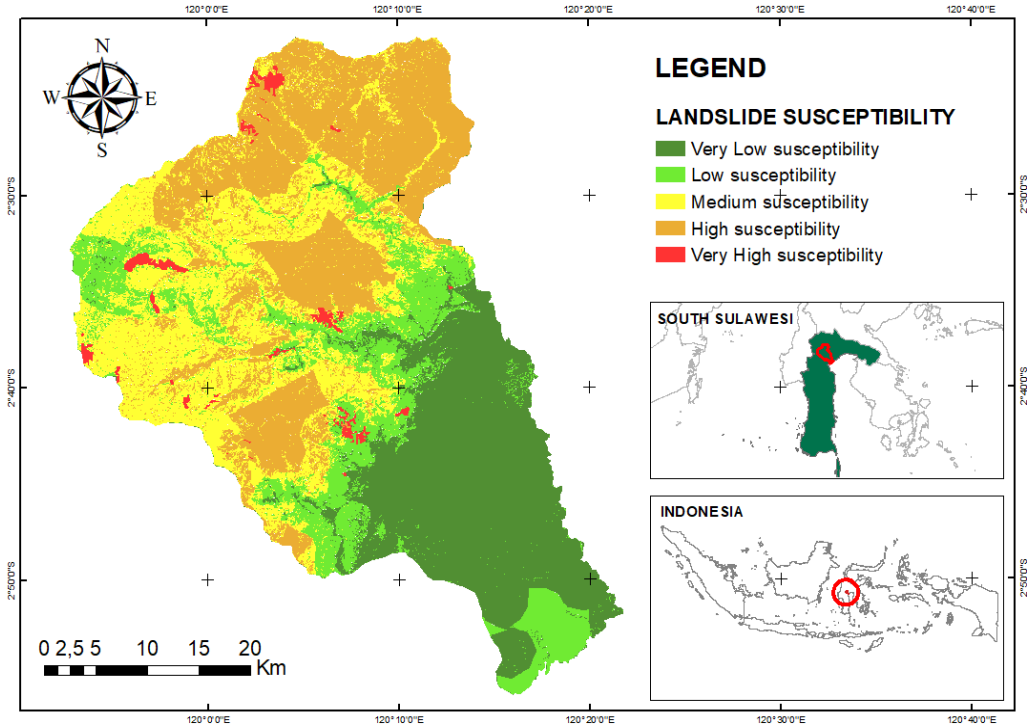


Figure 6. Landslide susceptibility map of the Rongkong Watershed, South Sulawesi, Indonesia

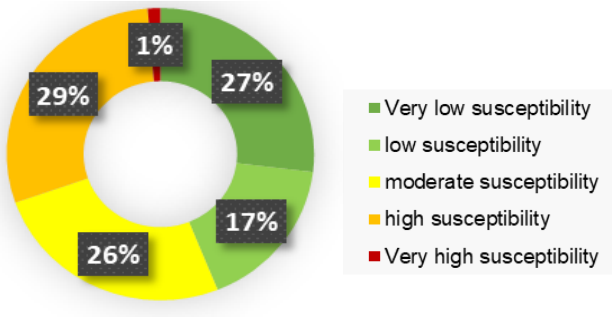


Figure 7. Landslides susceptibility level percentage in Rongkong Watershed, South Sulawesi, Indonesia

The low susceptibility class covers an area of 29,339.90 ha (16.97%) and includes 75 villages. The village with the largest area of low susceptibility is Malimbu Village (Sabbang District) at 2,983.20 ha, followed by Pombakka Village (Malangke Barat District) at 2,247.23 ha, and Tandung Village (Sabbang District) at 2,061.51 ha. Secondary dryland forest cover, plantations, and mixed dryland agriculture and shrubland dominate this class.

The moderate susceptibility level covers an area of 44,436.06 ha (25.70%) and includes 28 villages. The village with the highest moderate landslide susceptibility is Tandung Village (Sabbang District) at 7,425.09 ha, followed by Malimbu Village (Sabbang District) at 3,416.22 ha and Siteba Village (Walenrang Utara District) at 3,363.79 ha. This class is dominated by secondary dryland forest cover, mixed dryland agriculture and shrubland, and primary dryland forest.

The high susceptibility class covers an area of 50,226.70 ha (29.05%) and includes 23 villages. Maipi Village (Masamba District) ranks first for the highest area of high landslide susceptibility, measuring 9,278.84 ha, followed by Kanandede Village (Limbong District) at 7,975.83 ha and Baebunta Village (Baebunta District) at 6,519.30 ha. This class is also dominated by secondary dryland forest cover, primary dryland forest, and mixed dryland agriculture and shrubland.

The very high susceptibility class encompasses an area of 2,287.52 ha (1.32%) and includes 15 villages. The village with the largest area is Maipi Village (Masamba District) at 587.48 ha, followed by Pongko Village (Walenrang Utara District) at 322.48 ha, and Tandung Village (Sabbang District) at 286.84 ha. This class is dominated by shrubland cover, secondary dryland forest, and grassland. Although the very high susceptibility class represents only 1.34% of the total area of the Rongkong Watershed, the area of 2,287.52 ha is not insignificant. Furthermore, the high susceptibility class has the largest area, reaching 29.05%, and the moderate susceptibility class covers 25.70%. Therefore, it is essential to remain vigilant regarding the potential for landslides to occur.

Land use direction for the Rongkong Watershed

Land use is one of the factors that influences environmental conditions. Improper land use can have detrimental effects on the environment, including increased erosion, heightened surface runoff, and an elevated risk of landslides and flooding. Determining land use directions based on landslide susceptibility levels is a crucial step in spatial planning and disaster risk management. According

to Eker and Aydin (2016), a risk-based approach is essential in land use planning to minimize the impacts of landslides. Furthermore, Lillesand and Kiefer (2015) stated that disaster risk management is a key component of sustainable development strategies aimed at reducing losses and supporting community resilience. Landslide susceptibility maps can be utilized as a supportive tool in decision-making to implement better land use planning (Roccati et al. 2021).

The direction of land use is based on the results of the analysis of landslide susceptibility levels in the Rongkong Watershed. It takes into account the types of land use in areas categorized by their susceptibility to landslides. Land use that does not conform to spatial planning guidelines in landslide-prone areas will be directed to prevent landslide risks. Based on the levels of landslide susceptibility in the Rongkong Watershed, land use directions are provided in accordance with spatial planning guidelines outlined in Ministerial Regulation No. 22/PRT/M/2007. In areas with very high and high landslide susceptibility, there are settlements, rice fields, grasslands, plantations, and shrublands. These areas are designated as protected areas or conservation zones. Agricultural activities and the development of residential centers, along with supporting facilities for social and economic activities, should be avoided, except for facilities that directly improve environmental quality, such as drainage systems and other environmental infrastructure networks.

In areas with moderate landslide susceptibility containing rice fields, settlements, plantations, shrublands, and grasslands, land use is directed to function as limited controlled cultivation areas, such as the implementation of agroforestry systems. Activities related to the components of spatial structure should adhere to the environmental carrying capacity and comply with the provisions set forth in Government Regulation No. 27 of 1999 concerning Environmental Impact Assessment.

In areas with low and very low landslide susceptibility, land can be utilized for residential activities, mining, production forests, urban forests, plantations, agriculture, fisheries, livestock, tourism, or other activities while still adhering to Government Regulation No. 27 of 1999 concerning Environmental Impact Assessment. In the Rongkong Watershed, land use in areas with low and very low susceptibility levels is already in accordance with regulations.

The findings regarding the landslide susceptibility level provide important information to the local community about potential risks in their area, particularly for the communities in Maipi, Kanandede, and Baebunta Villages, which are identified as areas with very high landslide risk. With a better understanding, the community can become more alert and prepared for potential disasters, such as avoiding certain activities in high-risk areas. Additionally, by providing accurate and applicable information to the local community, this research helps them make wiser, sustainability-oriented decisions, thereby minimizing the negative impacts of future landslides. The suggested land use guidance is crucial for minimizing natural disaster risks, improving land productivity, and supporting the community's well-being. With the implementation of the recommended strategies, land management can be conducted more effectively and efficiently, providing long-term benefits in terms of economy, environment, and society and offering hope for a safer future.

However, socio-economic challenges may arise in implementing these recommendations. Most of the people in landslide-prone areas depend on land use for agriculture, livestock, or settlement. Relocation or land-use changes could lead to the risk of losing livelihoods and increase economic burdens. Additionally, limited access to resources, such as funding for implementing mitigation practices or supporting technologies, could present significant barriers. Therefore, an approach involving the local community, such as providing economic incentives, ongoing education, and government support, is essential to overcoming these challenges and ensuring the successful implementation of the recommendations.

In conclusion, land use directions are established to control landslides, with areas of very high and high susceptibility directed to become protected or conservation areas. In contrast, areas with moderate susceptibility are designated for limited cultivation with strict controls, such as the implementation of agroforestry systems. The results of this study can serve as a primary basis in spatial planning, particularly in identifying and designating protected or conservation areas in regions with very high and high landslide susceptibility. Local governments need to strengthen regulations and supervision of development in these areas to minimize disaster risks. Additionally, this study emphasizes the importance of synergistic collaboration between the government, non-governmental organizations, academia, and local communities in designing and implementing comprehensive risk mitigation strategies. This approach ensures that the research findings are not merely academic documents but are translated into policies and concrete actions that effectively reduce disaster impacts.

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Diversity and biomass of understory vegetation which might increase fire risk in Mount Rinjani National Park, Lombok Island, Indonesia

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Abstract. *Metananda AA, Suhubdy, Mertha IG, Soekardono, Afrianto WF,* Ar NH. *2025. Diversity and biomass of understory vegetation which might increase fire risk in Mount Rinjani National Park, Lombok Island, Indonesia. Asian J For 9: 67-74.* Human activities in the grassland surrounding Mount Rinjani National Park (MRNP), Lombok Island, Indonesia are prevalent, increasing the susceptibility to fires during the dry season. This study assessed the diversity and biomass of understory species which might enhance the risk of fires in the MRNP. Data collection on species diversity was carried out through exploration (non-plot) and creation of 120 sampling plots in Sikur and Sembalun Sub-district. In total, there were 263 species of the understory plants were identified, comprising 71% herbs, 26% shrubs, and 3% lianas. Poaceae and Asteraceae had the largest number of genus and species with the dominance of pioneer species *Themeda triandra*, suggesting that the grasslands in MRNP have not yet reached climax. This species was among the most preferred natural grasses for grazing cows at the study location, indicating intricate relationship between local communities and grassland ecosystem in the MRNP. Over a span of two years, the dry biomass in the area can reach a thickness of 10 cm, with an estimated weight of 5.7 Mg ha^{-1}. The accumulation of high amount of dry biomass poses high risk of fires. The findings of this study offer a substantial foundation for comprehensive interventions in ecosystem management and forest fire risk mitigation, as well as supporting more planned and sustainable conservation efforts.

Keywords: Ecosystem, herbs, lianas, pioneer, shrubs

INTRODUCTION

Annual forest fires result in significant losses in various sectors (Thoha et al. 2022). In ecological aspect, the impacts of fires include the loss of biodiversity and air pollution, adversely affecting air quality and human health. In terms of economics, fires influence agriculture, tourism, and the livelihood of residents. Apart from human-induced, fires might be triggered by natural causes including lightning, particularly cloud-to-ground lightning strikes (Tacconi and Ruchiat 2006) which typically occur during the dry season (Bond 2019). In the Indonesian context, forest fires are more often caused by human activities, such as land clearing for agricultural activities especially during the dry season and El Niño periods (Edwards et al. 2020). However, fires initiated by human activities tend to have more severe and unpredictable consequences (Alvarado et al. 2017). Fires caused by human activity are more challenging to control due to their irregular distribution and the often-inaccessible locations where they occur. Factors influencing forest fires include climate, weather, fire behaviors (i.e., intensity, wildfire circumstance, and spread), and biomass in the form of vegetation type which serves as fuel (Loehman et al. 2014). Post-disturbance ecosystems, such as those affected by wildfires, often retain biological legacies that influence recovery (Swanson et al. 2011).

Savannas account for 30 percent of net terrestrial primary production and the majority (~50-70 percent) of the annual global fire area (Lehmann et al. 2014). In savanna ecosystems, fires significantly impact soil nutrient conditions, altering the availability of essential elements like nitrogen and phosphorus (Nghalipo et al. 2019). Apart as a form of disturbances, fires might serve as a regeneration process that maintains the balance of natural ecosystems (Afrianto et al. 2017, 2020). Fires in savanna ecosystem facilitate the regeneration of grasses (Moritz et al. 2014). Grasslands are influenced by abiotic components such as fire, which produce feedback on soil and plant properties (Reinhart et al. 2016; Werner et al. 2021). At the beginning of the rainy season, plant species in the burned area turn green faster than those in unburned areas, demonstrating that fires in the savanna can maintain grassland condition (Kral et al. 2024). Fire intensity has been found to enhance the resilience of nitrogen utilization, accelerating the recovery of species diversity, including

dominant plant species. Thus, fire intensity influences species divergence in savannas (Song et al. 2019).

Savanna generally has sparse tree cover with extensive grasses and shrubs, thus creating hotter, drier and windy microclimates which facilitate fires (Hoffmann et al. 2012). In the savanna ecosystem of Mount Rinjani National Park (MRNP), Lombok Island, Indonesia, the incidence of fires fluctuates annually (Sutomo and van Etten 2018). A key factor influencing savanna fire regimes is the composition of grasses that serve as fuel, with their characteristics significantly affecting fire behavior (Simpson et al. 2022). According to Sutomo et al. (2021) demonstrated distinct floristic differences between savanna and forest and between savanna and the boundary while noting similarities between forest and the boundary; however, environmental data revealed separation solely between savanna and forest. Previous studies in the MRNP primarily focused on the diversity of flora along hiking trails, forested areas, and species diversity boundaries (Mansur et al. 2016; Sutomo et al. 2021).

The relationship between understory vegetation and wildfire risk is complex, as various species exhibit differing flammability characteristics influenced by their biomass and ecological context (Neary et al. 1999). Understory vegetation and biomass contribute to wildfire risk, particularly in pine flatwoods, where greater biomass and flammability characteristics increase ignitability, sustainability, and combustibility, facilitating wildfire spread and necessitating firewise planning for wildland-urban interface homes (Behm et al. 2004). Studies indicate that areas with significant understory growth post-wildfire can lead to increased fire recurrence due to the accumulation of fuels (Coppoletta et al. 2016). This study assessed the diversity of understory species and the biomass-related factors contributing to fires in the MRNP.

MATERIALS AND METHODS

Study area

The study was conducted in the Mount Rinjani National Park (MNRP) area and its surrounding communities, specifically in villages directly bordering the park (Figure 1). The study locations were selected purposively by considering community activities in the grasslands/shrublands and fire-prone areas within the national park from year to year. Mount Rinjani National Park, Lombok Island, West Nusa Tenggara province, Indonesia is a nature conservation area designated based on the Minister of Forestry Decree Number SK. 298/Menhut-II/2005, dated August 3, 2005, with a designated area of 41,330 ha. The MRNP area is geographically located between 116°17'30"E-116°33'30"E and 8°17'30"S-8°33'00"S. Administratively, MRNP spans three regencies: North Lombok District (12,357.67 hectares or 29.9%, comprising two districts and 16 villages), Central Lombok District (6,819.45 hectares or 16.50%, comprising two districts and five villages), and East Lombok District (22,152.88 hectares or 53.60%, comprising 10 districts and 17 villages). This study focused on two specific sub-districts, Sikur (78.27 km²) and Sembalun (217.80 km²), chosen as representative locations for the regional divisions within MRNP.

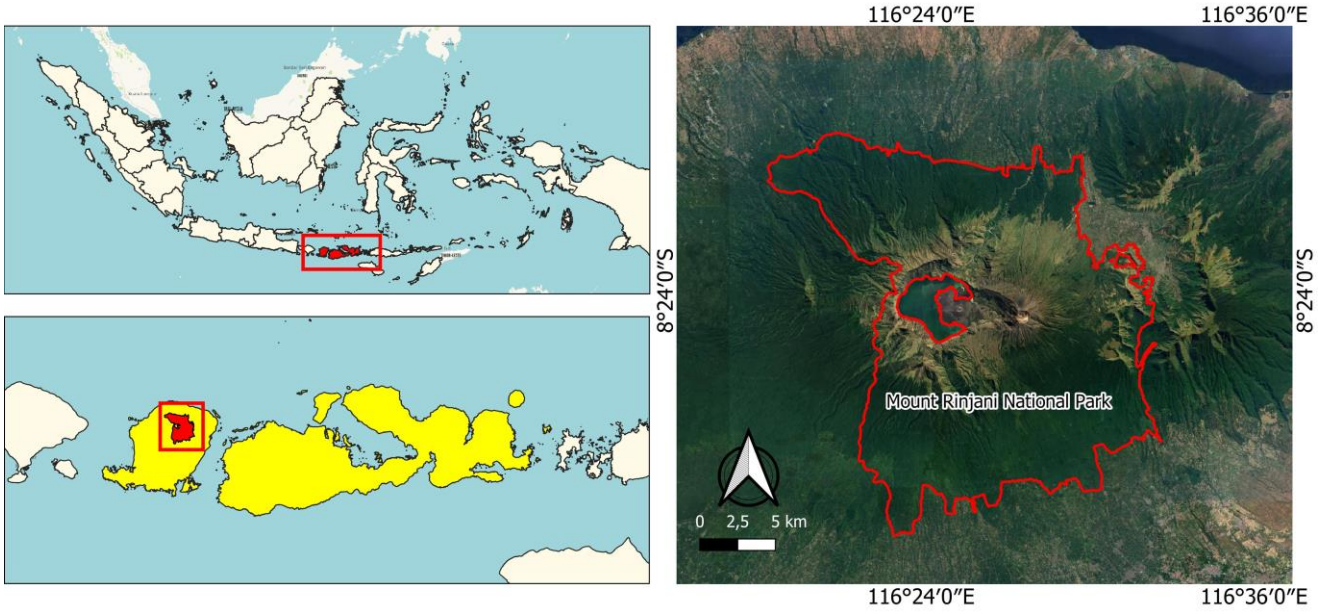

Figure 1. Map of the Mount Rinjani National Park (MRNP), Lombok Island, West Nusa Tenggara Province, Indonesia

The determination of grassland locations to study was based on the interpretation of satellite imagery, which was subsequently verified through field observations. To assess vegetation diversity, multiple plots were established in representative areas within the MRNP. The species-area curve was utilized to determine optimal plot size. A 1 × 1 m square sample plot (SP) was used to record the number of identified plant species, and a second SP was added with twice the size of the first SP until no additional new species were discovered (species addition <5%) (Kusmana 1997). The total plots were 120 plots. Sample plots were placed using random sampling, which is deemed suitable for homogeneous study locations and vegetation. Another method of identifying the list of understory species in the MRNP was to explore the entire national park area. This data was obtained during the current limited time and includes the justified results of previous explorations conducted by researchers in the MRNP.

Procedures

To analyze the potential of litter biomass as fire fuel, a double plot method was employed. The plots, measuring 1 × 1 m, were consistent in size with those used in the species diversity survey. All understory vegetation within the plots was cut and weighed to determine its fresh weight. Similarly, litter within the plots was collected and weighed separately. The plants were then separated into stems and leaves to measure their total wet weight. Subsamples of 100 g were taken from each stem and leaf of the understory plants (if the total weight was less than 100 g, the entire sample was used as the subsample) and dried in an oven for 2 × 24 hours at 80°C.

Data analysis

Vegetation data were collected to assess the importance of the understory obtained at the research location. the following formulas were used for vegetation analysis purposes based on Mueller-Dumbois and Ellenberg (1974).

Density of plant species (D):

$$D = \frac{\text{Number of individuals of all types}}{\text{Area of all sample plots}}$$

Relative Density (RD):

$$DR = \frac{\text{Density of a species}}{\text{Density of all species}} \text{ x } 100\%$$

Frequency of plant species (F):

$$F = \frac{\text{Number of sampled areas where species occured}}{\text{Number of total sampled areas}}$$

Relative Frequency (RF):

$$FR = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \text{ x } 100\%$$

Coverage (C):

$$C = \frac{\text{Number of vegetation cover of all types}}{\text{Area of all sample plots}}$$

Relative Coverage (RC):

$$RC = \frac{\text{Vegation Cover of a species}}{\text{Vegatation Cover of all species}} \text{ x } 100\%$$

Biomass

$$\text{Total dry weight} = \frac{\text{Dry weight of the subsample}}{\text{Wet weight of the subsample}} \text{ x Total wet weight}$$

RESULTS AND DISCUSSION

Habitus and genera composition

The study results identified 263 understory species, including herb, liana, and shrubs, within MRNP. Based on the single-plot analysis, the understory composition was predominantly herbs (71%), followed by shrubs (26%), and lianas (3%) (Figure 2). Following a fire, endemic or native species play a significant role in ecosystem recovery and in maintaining understory diversity. Endemic species often have specific adaptations, such as fire resistance and the ability to germinate and regenerate post-fire, enabling them to thrive under such conditions. The presence of native species not only accelerates the rehabilitation process but also helps maintain ecosystem balance by controlling the aggression of alien species that harm the structure of regional vegetation (Afrianto et al. 2020). Grassland formations in the MRNP, as well as in other Indonesian parks such as Bali Barat National Park and Baluran National Park, are generally dominated by Gramineae/Poaceae and their associated herbaceous species, particularly in arid savanna ecosystems (Sutomo and van Etten 2021). In the soil seed banks of Mount Ciremai National Park and Kuningan Botanic Gardens, herbaceous plants were found to dominate over woody plants (Ekasari et al. 2021). Understory plant communities serve as effective ecological indicators to determine forest health, as they provide ecosystem services, such as nutrient cycling, productivity, ecosystem self-regeneration, and organic matter decomposition (Deng et al. 2023).

Based on taxonomical analysis at the genus and species levels, the study location was primarily dominated by the families Poaceae and Asteraceae (Figure 3). Poaceae comprised 20 genera, followed by Asteraceae with 17 genera, Rubiaceae with 7 genera, Lamiaceae with 5 genera, and Fabaceae 4 with genera. The species diversity of members of the Asteraceae was higher than members of Poaceae. While Asteraceae exhibited higher species diversity, individual genera within Poaceae often contained multiple species. Field observations revealed that Asteraceae species formed associations with Poaceae, particularly young plants. These Asteraceae species often act as pioneer species, colonizing grassland areas. This pattern aligns with the understory composition of Lore Lindu National Park, where Asteraceae is also a dominant family (Ramadhanil et al. 2008). The Asteraceae family is recognized as the most prominent family of flowering plants, comprising approximately 1600 genera and 25,000 species worldwide (Rolnik and Olas 2021). Generally, species in the Asteraceae family have historically been

used for food and medicine purposes due to their bioactive content and potential applications (Bessada et al. 2015).

Moreover, based on the overall floristic composition data, the understory species identified were primarily pioneer species, suggesting that this ecosystem has not reached its ecological climax and has experienced disturbances in the past. A similar condition was observed in Mount Merapi National Park, where understory species dominated the area as pioneer plants following the 2010 eruption (Afrianto et al. 2020). A study on post-fire vegetation changes in Rimba Panjang revealed that understory increased from 12 species to 17 species plants over eight years (Firdaus et al. 2017). Species from the different successional stages exhibited distinct patterns of trait distribution, and other vital characteristics predicted species turnover during succession (Chai et al. 2016). In the climax ecosystems, vegetation tends to be dense with high humidity, creating conditions less susceptible to fire. In contrast, ecosystems that have not yet climaxed tend to have lower moisture levels, especially in savannas that are directly exposed to sunlight without obstructions. This condition causes the savanna ecosystem in MRNP more vulnerable to fires. Additionally, cattle activity disrupts the grass ecosystem from reaching its climax. Consequently, fire and grazing are recognized as key factors in maintaining grassland ecosystem and preventing its transition to another form (van Steenis et al. 2006).

Species composition

The Fabaceae and Cyperaceae families exhibited disproportionate species richness relative to their number of genera (Figure 4). The Fabaceae family included four genera with nine species, while Cyperaceae comprised a single genus with four species. The genera *Desmodium* and *Cyperus* were particularly species-rich within their respective families. Monk et al. (2000) noted the widespread distribution of *Cyperus* and *Desmodium* in grasslands undergoing a succession process toward community stability. These genera have been also reported to dominate open grazing lands in *Chapra* (Kumari and Jha 2016). *Themeda triandra* (Poaceae) emerged as the most dominant grass species on the Sembalun hiking trail (Figure 5), which is a popular tourist destination heavily visited by visitors (Ayuni and Priyana 2019). *Themeda triandra* has spread widely to almost all regions in Australia and is estimated to have originated in the Asian savanna approximately 1.5 million years ago (Dunning et al. 2017).

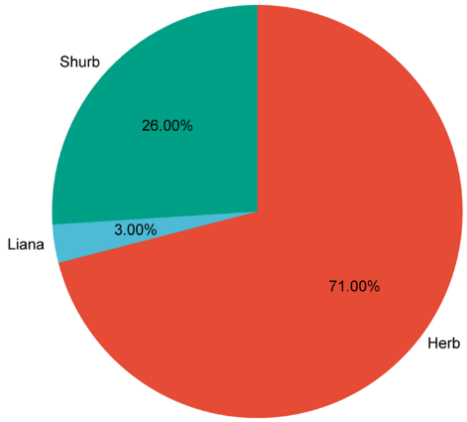

Figure 2. Proportion of vegetation habitus in the MRNP, West Nusa Tenggara Province, Indonesia

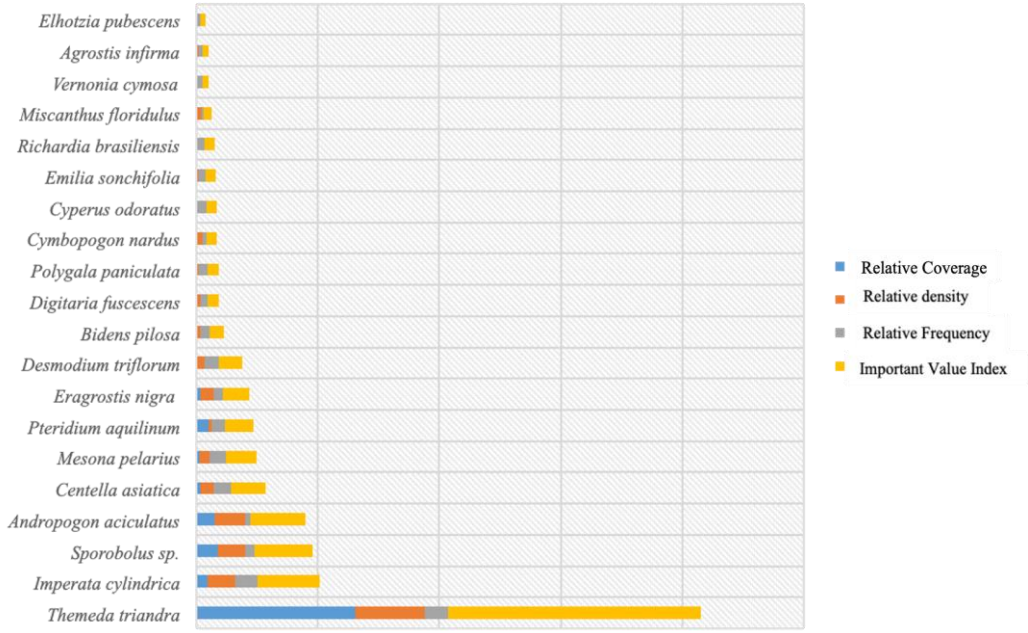

Figure 3. Results of vegetation analysis in the MRNP, West Nusa Tenggara Province, Indonesia

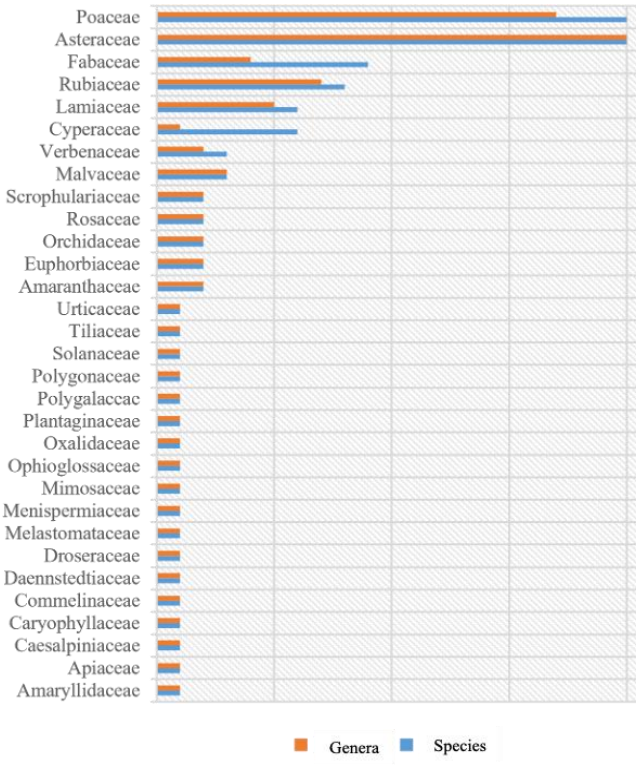

Figure 4. Proportion of the number of genera and species in the MRNP, West Nusa Tenggara Province, Indonesia

Additionally, the awn length and average annual temperature have a positive relationship (Cavanagh et al. 2024). In the short term, the dominance of alien species can reduce the variety of native species and modify ecosystem processes (Bartha et al. 2014). In the long term, this dominance can lead to continuous changes in community structure and ecosystem function, diminishing the ecosystem's stability against disruption and its capacity to sustain critical ecological processes (Heard et al. 2012). The important value index (IVI) of *T. triandra* was the highest and significantly different from other subdominant Poaceae types such as *Imperata cylindrica*, *Sporobolus* sp., and *Chrysopogon aciculatus*. This finding indicates an unhealthy grass community, suggesting historical disturbances in the past. Based on interviews with MRNP staff, forest fires frequently occur on Mount Rinjani due to human activities, particularly the deliberate burning of grasslands to attract deer to new growth areas. Similar conditions have been observed in Sumbawa, Timor, and Sumba, where grass is burned to provide fresh grass for wildlife and livestock.

Field observations indicate that *T. triandra*, *I. cylindrica*, *Sporobolus* sp., and *Capillipedium parviflorum* are the most preferred grass species for cattle grazing in the MRNP. Continuous grazing by cattle causes the grass to regenerate, leading to persistent ecological disturbance in the grassland. Therefore, efforts are needed to regulate the scale of grazing and implement adaptive management to optimize its benefits (Mudongo et al. 2016). Grazing activities in understory vegetation with palatable native species can combine conservation efforts with production integration methods that reduce the incidence of burning (Herrera et al. 2021). According to van Steenis (2010), in climax mixed vegetation areas, there is insufficient fuel load to sustain widespread fires, even if ignited. Thus, promoting the formation of climax vegetation can be an effective strategy to mitigate fire risks.

The grasses identified in this study can be categorized into two groups: tall grasses and carpet grasses (Figure 6). Tall grasses include species and shrubs that reach height exceeding 50 cm, while carpet grasses encompass species that do not grow taller than 7 cm. The tall grasses and their associations include *T. triandra*, *I. cylindrica*, *Sporobolus* sp., *Agrostis inflata*, *Miscanthus floridulus*, *E. nigra*, *Elsholtzia pubescens*, *Inula cappa*, *Chromolaena odorata*, and *Cymbopogon nardus*. Understory species classified as carpet grasses and their associations include *C. aciculatus*, *Digitaria nuda*, *D. fuscescens*, *Eleusine indica*, *Centella asiatica*, *Richardia brasiliensis*, and *Desmodium triflorum*. Savannas in MRNP experience prolonged drought periods every year. The term “humid savanna” refers to areas with a dry period of 2.5-5 months, while “dry savanna” refers to areas with a dry period of 5-7.5 months. Savanna types in this region include: i. savanna covered with grass and bushes (non-canopy); ii. tree/shrub savanna, characterized by trees and bushes with a canopy of less than 2%; iii. wooded savanna, with a tree canopy between 2 and 15%; iv. forested savanna, containing trees with canopy cover of 20-30%; v. open forest, a savanna covered by trees with canopy cover of 50% (Mistry and Beradi 2014).

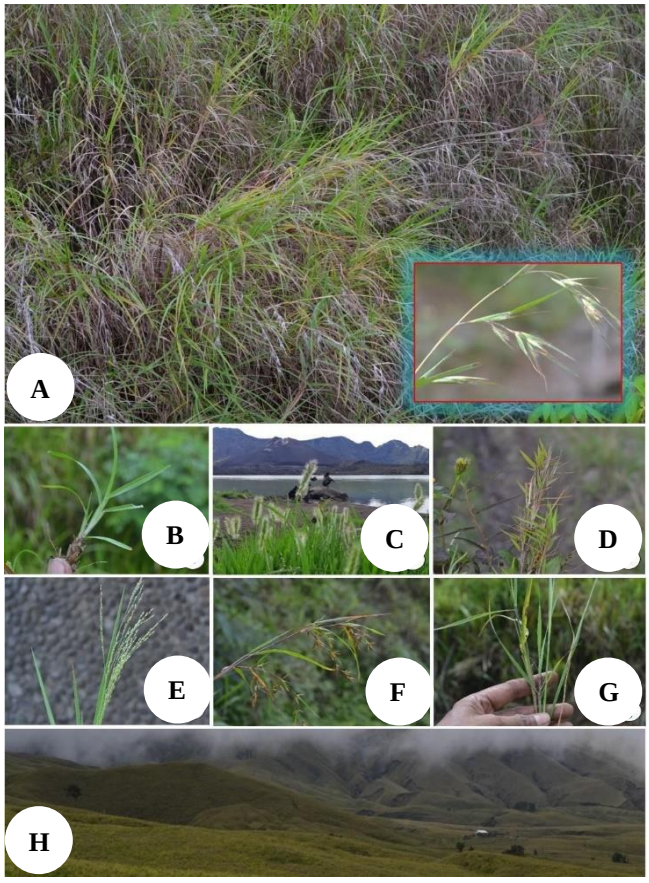

Figure 5. A. *Themeda triandra* (Poaceae); B. *Chrysopogon aciculatus* (Poaceae); C. *Polypogon monspeliensis* (Poaceae); D. *Pogonatherum paniceum* (Poaceae); E. *Panicum repens* (Poaceae); F. *Apluda mutica* (Poaceae); G. *C. parviflorum* (Poaceae); H. the expanse of grasslands in the MRNP

Figure 6. Community of carpet and tall grasses in the MRNP: A. Carpet grass; and B. Tall grass

Savanna ecosystem is present in several conservation areas, especially national parks such as Alas Purwo, Bromo Tengger Semeru, Baluran, West Bali, Gunung Rinjani, Komodo, Kelimutu, and Wasur National Park. National parks are natural conservation areas with original ecosystems managed through a zoning system and utilized for research, scientific and education purposes and some extent of tourism and recreation activities. The savanna in national parks serves as a unique attraction. Managing ecosystem balance by preventing erosion, producing organic material, and serving as a food source for various wildlife species, is vital for savanna vegetation. Natural grasslands function most effectively in decreasing erosion and runoff during extended precipitation events (72 hours) (Hu et al. 2023). Additionally, fire activity significantly affects below-ground ecosystem processes, causing fire-driven soil carbon (C) losses. These losses are often presumed to arise primarily in the upper soil layers because the duplicated explosion of above-ground biomass limits organic matter intake into the surface soil (Pellegrini et al. 2020). This is due to the short-lived nature of the roots of savanna vegetation, resulting in a buildup of decomposing organic matter in the soil.

Biomass

The result showed that the dry biomass can reach a thickness of 10 cm over two years, with a potential of 5.7 Mg ha^{-1}. This biomass significantly increases the likelihood of fire ignition. The composition and structure of the grasses are affected by the release of carbon stored in the biomass of understory plants during processes like decomposition or fire. The dry plants or litter with a thickness of about 10 cm can produce heat resulted from fermentation which becomes a fire source. This litter can also burn due to sunlight reflected in a focused manner by glass bottle waste and aluminum beverage cans left by visitors. The hazard analysis indicates that visitor activities are also considered the highest risk in MRNP (Jasthin et al. 2024). In addition, the litter can also become flammable due to periodic lightning strikes (Nampak et al. 2021). Previous research has documented a range of understory biomass values across various regions. In the temperate regions of the Himalayas, biomass ranged from 2.4 to 7.64 Mg ha^{-1} (Wani et al. 2016). Ahmad et al. (2018) recorded biomass values ranging from 1.1 to 2.6 Mg ha^{-1} in Kumrat Valley, Pakistan, while forests in the eastern Himalayas exhibited biomass values between 1.95 and 3.77 Mg ha^{-1} (Tashi et al. 2017). Ali et al. (2019) documented understory biomass values of 1.9 to 2.1 Mg ha^{-1} in Hubei province, Central China. In Himalayan forests, Dar and Sundarapandian (2015) observed biomass ranging from 0.16 to 2.36 Mg ha^{-1}. Haq et al. (2023) reported an average understory carbon stock of 2.79 Mg C ha^{-1} in the forests of Jammu and Kashmir. In the northwestern Himalayas, biomass values were recorded between 4.28 and 11.08 Mg ha^{-1} (Banday et al. 2018). Amir et al. (2018) noted an average understory carbon stock of 0.86 Mg C ha^{-1} in the *Pinus* forests of Pakistan. Mannan et al. (2018) measured carbon stocks in Magallah Hills National Park, Pakistan, with understory values of 2.3±0.27 Mg C ha^{-1} and 1.81±0.41 Mg C ha^{-1}. In rubber monoculture systems, understory biomass was estimated at 0.94 Mg ha^{-1}; in rubber agroforestry systems, the biomass was slightly lower at 0.84 Mg ha^{-1} (Muhdi et al. 2020).

In conclusion, the presence of understory plant communities in Mount Rinjani National Park can serve as effective ecological indicators for assessing forest health based on the number of species present. The ecosystem conditions are categorized as not yet reaching climax. Findings on the dominance of species, such as Poaceae and Asteraceae, can inform strategies for vegetation management, invasive species control, and planning for forest fire prevention and mitigation. Information on biomass values and the dominance of certain plant species can assist in designing forest fire prevention strategies. These findings also provide a foundation for further research on vegetation dynamics in various national parks and other conservation areas. Additional research can offer deeper insights into the interactions between species and the impacts of environmental changes on the structure of understory plant communities. This study is only limited to addressing understory vegetation and biomass. Future research will address its major community types and environmental, edaphic, and climatic variables to provide a more comprehensive understanding and context for the findings.

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The market of forest payments for environmental services in Vietnam after fifteen years of its implementation

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Abstract. *Pham TL, Mai TTX, Ngo T. 2025. The market of forest payments for environmental services in Vietnam after fifteen years of its implementation. Asian J For 9: 75-81*. Sustainable development is a core concern for most countries and entities across the globe despite the fact that there is a trade-off between environmental sustainability and economic growth. Many countries are focusing on Sustainable Development Goals (SDGs), such as SDG11: Sustainable cities and communities, SDG14: Life below water, and SDG15: Life on land. Meanwhile, the people still face challenges like unemployment and poverty, worsened by the recent pandemic. Innovative tools like Payments for Environmental Services (PES) have gained importance, and Vietnam was the first ASEAN country to implement forest PES (FPES) in 2008. Over the past 15 years, despite its achievements, such as raising individual income and government budget generation, some challenges still persist, including administrative inefficiencies and market inequalities. This study re-examined the development of Vietnam's FPES market, highlighting its contributions to the national and provincial budgets, forest protection, and cash income for forest owners. Importantly, the study also analyzed the society's awareness and knowledge of the FPES market, particularly in terms of market participants and price mechanism. We found that ongoing improvements in official training and education, as well as market mechanisms, are needed to enhance public awareness and participation in the FPES market. The integration of poverty alleviation and (forest) environmental protection in Vietnam is a collective responsibility, and this study aims to engage the audience in this crucial task.

Keywords: Forest, market development, Payments for Environmental Services (PES), poverty, Sustainable Development Goals (SDGs)

Abbreviations: ES: Environmental Services, FPES: Forest Payments for Environmental Services, ICDPs: Integrated Conservation and Development Projects, PES: Payments for Environmental Services, SDGs: Sustainable Development Goals, SFEs/SFCs: State Forest Enterprises or Companies, VNFF: Vietnam Forest Protection and Development Fund

INTRODUCTION

Sustainable development is a core concern for most countries and entities across the globe despite the fact that there is a trade-off between environmental sustainability and economic growth (Stern 2004; Mardani et al. 2019; Ngo et al. 2024). At a macro level, many countries are focusing on the Sustainable Development Goals (United Nations 2024), such as SDG11: Sustainable cities and communities, SDG14: Life below water, and SDG15: Life on land, to make sure that environmental protection is monitored alongside development. More importantly, at the micro-level, the people are still facing the problems of unemployment, hunger, and poverty (e.g., SDG01, SDG02, and SDG08), especially due to the recent COVID-19 pandemic (Dang et al. 2023; Nguyen-Anh et al. 2023; Sridhar et al. 2023).

It would be more difficult for the poor to participate in environmental-friendly activities or Environmental Services (ES), as their foremost target is not the environment; thus, alleviating poverty is the only solution (Pagiola et al. 2005). Integrated Conservation and Development Projects (ICDPs) and sustainable forest management, among others, are two major management tools intended to deal with both poverty and environmental issues simultaneously (Barrett and Arcese 1995; Siry et al. 2005). However, their results are still limited (Wunder 2005). In this sense, it is no surprise that innovative tools such as Payments for Environmental Services (PES) (Michel et al. 2016) are important for this goal (Wunder 2008; Tacconi 2012). The fundamental principle of PES is that external beneficiaries of ES (i.e., the service buyers) should make direct, contractual, and conditional payments to local landholders and users (i.e., the service sellers or producers) in exchange for their adoption of practices that promote ecosystem conservation and restoration (Pagiola et al. 2005; Wunder 2008). Such a market-based incentive led to an expansion of PES applications, especially in developing economies (Pagiola 2008; Pattanayak et al. 2010; Wunder et al. 2020).

In Vietnam, the forests have been dominantly governed by state control via a system of State Forest Enterprises or Companies (SFEs/SFCs), with a gradual shift toward market-based policies toward forest protection and conservation (McElwee 2016; Cochard et al. 2020). In 2008, Forest PES (FPES) was piloted in Son La and Lam Dong, two mountainous provinces that host large groups of poor ethnic minority communities and, respectively are in the Northern and Central Highlands areas of Vietnam, to deliver innovative and market-based social, agricultural and environmental programs (To and Dressler 2019). The

encouraged results of the pilot programs led to the implementation of Decree No. 99 (Vietnamese Government 2010) to cover additional provinces and to re-confirm the Vietnam Forest Protection and Development Fund (VNFF) as the national body for all FPES activities in the country (VNFF 2024). Consequently, the FPES has been observed as a 'breakthrough' in the Vietnamese forestry sector's history that helped create a new source of income for ES producers, a budget generator for provincial governments, and, more importantly, a new (financial) mechanism for forest protection (MARD 2010; Thuy et al. 2013; VNFF 2014).

Despite the 'successfulness' of the piloted and extended FPES programs in Vietnam, after more than 15 years of operation, it has not been carried out as a 'true' PES, as assessed by Thuy et al. (2013). Other limitations include the administrative oriented, inequality, and asymmetry between participants of the ES market (Loft et al. 2017; Chu et al. 2019; Do et al. 2022; Gallemore et al. 2024). Among others, the inefficiency of PES as a market-based framework is the most critical reason since it conflicts with the core definition of PES (Wunder 2008; Pattanayak et al. 2010). In this sense, it is important to re-examine the market for FPES in Vietnam, including the producers, buyers, equilibrium price, and relevant institutions. Therefore, this study aims to provide an assessment of the market for FPES in Vietnam in the past decades.

The rest of the paper is constructed as follows. The next section briefly reviews some relevant literature on (F)PES, with a special focus on the Vietnamese context. After that, we present the methodologies utilized, and then discuss the relevant findings. The lastly section concludes the paper.

MATERIALS AND METHODS

Study area

This study aims to examine the current situation and serves as a basis to indicate the limitations of the development of the FPES in Vietnam. Then, to do that, interview questionnaires were used to obtain information on the age, income, and occupation of interviewees, especially concentrating on the understanding of people in terms of ES in particular and (F)PES in general, assessments of ES users about the current payment level for ES, ES users willingness to pay an additional amount to benefit better ES (such as fresh air, more beautiful natural landscapes, among others). All collected information was used to study the current situation and served as a basis to indicate the limitations of the implementation process of FPES in Vietnam.

Following the non-probability sampling method (Brimont and Karsenty 2015; Raes et al. 2017), we surveyed 300 participants in highly representative areas such as Hanoi, Ho Chi Minh City, Thai Binh, Gia Lai, and Dak Nong (see Figure 1), with 60 questionnaires for each city or province. Hanoi and Ho Chi Minh City are the two largest cities of Vietnam with high population density and thus, have more ES beneficiaries. Gia Lai and Dak Nong, on the other hand, are two provinces with large forest areas that have implemented several FPES programs. Meanwhile, Thai Binh, a purely agricultural province without forest areas, is used as a control province to examine the spillover effect of FPES even in places without any implementations.

Data collection

FPES achievement/limitation analysis

In this stage, content analysis was used to examine previous literature, including official reports from the national and provincial agencies, on the implementation and development of the FPES program in Vietnam. As such, the findings could inform both the FPES's achievements and limitations.

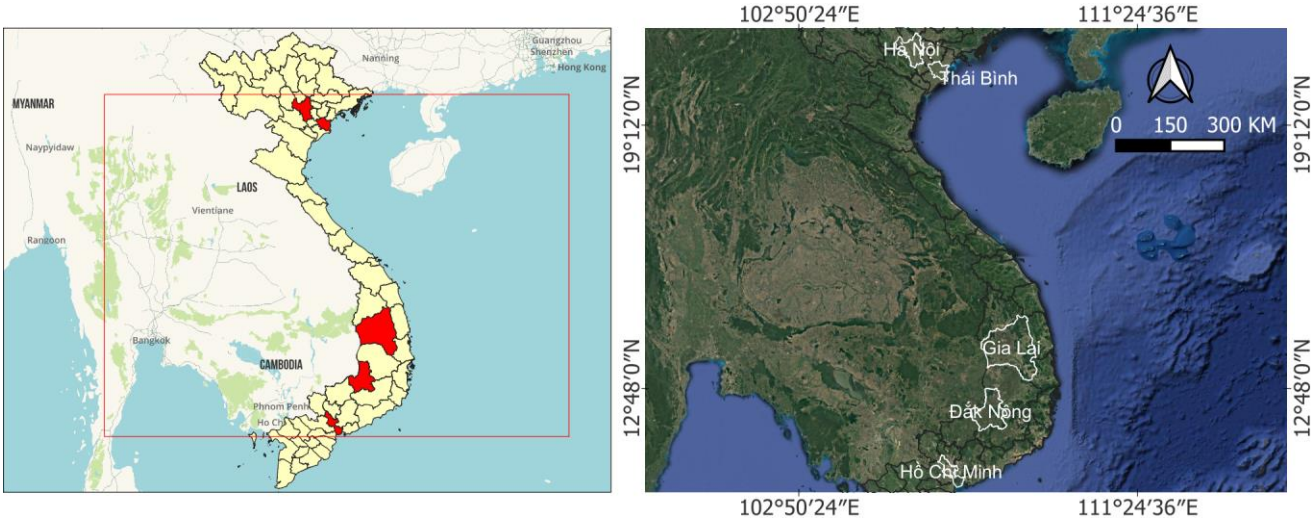

Figure 1. Location of the five cities/provinces of the FPES survey in Vietnam

FPES awareness survey

To guarantee high accuracy from respondents, we designed such questionnaires based on both qualitative and content analysis methods. It means that the questions raised are not only in the form of multiple-choice but also open-ended questions so that respondents can propose their additional opinions. On the other hand, we also represented many answers to each question to avoid inadvertent answers from respondents. The age of participants ranges from 24 to 60 years old with income ranges from 5 to 10 million VND/month (equivalent to about 200 to 400 USD, respectively, with 1 USD ≈ 25,000 VND), representing the poor community in Vietnam. Research subjects are selected at this age because they are the main subjects of payments for environmental services, and most of them already have stable jobs and incomes; thereby, they can clarify the issue: Whether service beneficiaries (who must pay for services they use) understand services and amounts they are paying for. This expresses the reliability of answers. In addition, we also used the random interview method for research samples. Because we did not focus on FPES participants (e.g., forest owners or service buyers) but the society's awareness and understanding of FPES, and given that the nation's population surpassed 100 million people, random sampling would ensure higher representation while also limit sampling bias. Accordingly, this method woulds guarantee the reliability of our research results.

The questionnaire consisted of two parts: the first is about general information about interviewees, including information about age, educational background, occupation, average income level, and living area, and the second part is the main survey on the participant's understanding of ES and FPES. For this second part, the questions concentrated on assessing the respect and understanding level of people about the environment and ES to be provided, people's perspectives on the FPES that they are benefiting from as well as their willingness to make an additional payment for such benefits (e.g., fresh air, clean water, cooler climate).

RESULTS AND DISCUSSION

Fundamental achievements for the market for FPES in Vietnam

Over the past 15 years, the Vietnamese government has made great efforts in promulgating legal regulations and policies to form a legal corridor to promote the marketization of payments for environmental services. Vietnam is one of the first countries in Asia to promulgate a national program on FPES (To and Dressler 2019). Although many difficulties still exist (see Section 2.2 above), Vietnam has built a policy system for FPES. The most prominent policies are Decree No. 05/2008/ND-CP and its four attached guidelines and Decree No. 99/2010/ND-CP and the 13 attached guidelines. Up to 2018, the government has issued 23 documents related to the FPES. Although these policies are still infancy, they have helped form a basic ground for the implementation and development of the FPES market in Vietnam (VNFF 2024) in terms of monitoring, producers, buyers, and price.

Firstly, the institutions and regulations for the FPES market had been established, resulting in a system of managing agents for the FPES market that plays an important intermediary role in its payment mechanism. To date, under the VNFF, 47 local and provincial funds are operating in Vietnam. Moreover, VNFF has also signed nearly 1000 entrusted contracts, an important momentum to develop the market for FPES in the country (VNFF 2024). Figure 2 represents the growth of the VNFF system over the 2009-2020 period. Such development at the provincial level is important because it helps to improve the negotiation capacity, information accessibility, and participation ability of ES producers, especially ethnic minorities. In this sense, the provincial VNFFs would gradually play the role of a financial intermediary between ES participants and maintain the fundamentals of the ES market in Vietnam.

Secondly, the number of ES participants in the FPES market has also increased significantly. For instance, from 2016 to 2020, the number of ES producers as households, individuals, and communities had increased by more than 31% (see Figure 3), providing more than 6.5 million hectares of protected forests, accounting for about 45% of the national forest area (VNFF 2024).

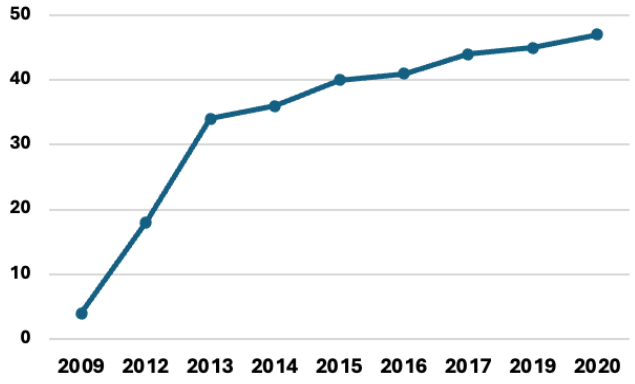

Figure 2. Number of provincial VNFFs over time (VNFF 2024)

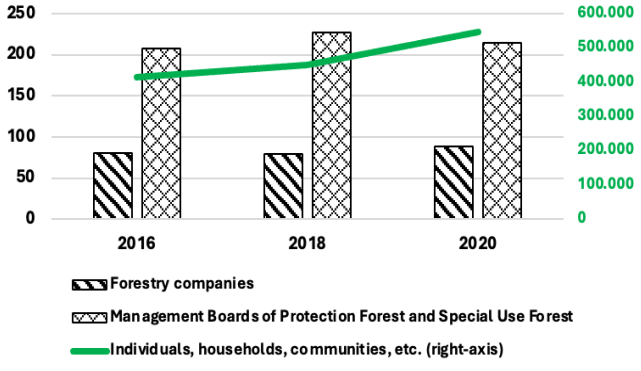

Figure 3. The development of FPES producers in Vietnam (VNFF 2024)

ES are currently provided to 387 hydropower stations, 191 clean water suppliers, 17 eco-tourism agents, and 266 industry facilities. Overall, the total number of ES buyers has increased by more than seven times and a third, respectively, compared to 2010 and 2018 (Table 1). Table 1 also reports that the major buyers in the Vietnamese FPES market are hydropower stations. While the number of industry facilities (and clean water suppliers) has increased over time, the number of participants of eco-tourism agents instead dropped in recent years, which might be due to the impacts of the COVID-19 pandemic on the tourism industry (GSO 2024; Vu et al. 2024).

Thirdly, the number of transactions in the FPES market has also increased, resulting in a significant contribution to the national and provincial budget revenues. As reported by the VNFF, the total FPES amount collected in 2020 was more than 2.5 trillion VND, equivalent to about 110 million USD (although it has dropped from the peak of more than 2.9 trillion VND or 126 million USD before COVID-19). It helped contribute to 20% of the annual cash income of more than 540 thousand ES individual/household producers (see also Figure 2), playing an important role in the win-win setting of FPES in Vietnam in terms of both poverty alleviation and forest protection/conservation (VNFF 2024). As discussed by Thuy et al. (2013), the prices or payment rates of the forest ES in the market are controlled by the government, which makes the FPES deviate from a true competitive market. However, it is understandable that the ES can be seen as positive externalities, and thus, given the Vietnamese context, government interventions are justified (Mankiw 2020).

Re-examining the market for FPES in Vietnam

We re-examine the development of the FPES market in Vietnam by first looking at the environment and ES awareness. It is noted that more and more forest owners have realized their responsibilities for providing the ES and with a clearer understanding of the areas, scope, and boundaries of FPES (Nguyen et al. 2022; Nguyen et al. 2024). From there, the capacity and efficiency of forest management, use, and protection are improved, contributing to the implementation of forestry development strategies. Table 2 reports the results of our survey using 234 valid responses out of 300 questionnaires from five cities/provinces in Vietnam (Dak Nong, Hanoi, Ho Chi Minh City, Pleiku, and Thai Binh). Accordingly, it shows that most respondents are aware of the benefits of the environment and understand the importance of forests and other ecosystems to their lives. For instance, the roles of providing food, water, and other raw materials, as well as mitigating natural disasters and other climate protection of the environment, were recognized by 82.63 and 77.61% of the respondents, respectively (see Q1 of Table 2). Most of them also believe that the forest is important in land protection, soil erosion and flood prevention (92.66%) and in climate freshening and cooling (81.85%) – see Q3 of Table 2. As a result, 88.03% of the participants agreed that (F)PES is necessary – see Q4 of Table 2. This is the basis for moving towards the marketization of payments for environmental services in Vietnam in the coming time.

Table 1. Number of buyers in the Vietnamese FPES market (2010-2020)

FPES Buyers	2010	2014	2015	2016	2018	2020
Hydropower stations	4	235	285	324	387	387
Clean water suppliers	3	72	80	88	150	191
Eco-Tourism agents	5	44	44	59	76	17
Industry facilities	0	0	0	15	44	266
Total	12	351	409	486	657	861

Source: VNFF (2024)

Table 2. The awareness of the environment and FPES in Vietnam

Q1. Which benefits/services does the environment provide to you and your family?	
Provide food, clean water, and raw materials	82.63
Act as a waste storage place	48.26
Mitigate natural disasters, climate regulation, watershed protection	77.61
Assure the soil improvement, soil nutrient regulation	67.18
Provide entertainment, aesthetic, cultural, and educational services	50.58
Guarantee biodiversity conservation	58.30
Q3. Which benefits/services does the forest provide to the community?	
Provide wood, timbers, and other forest products other than wood	78.38
Absorb and store carbon	79.54
Protect and prevent soil erosion, floods	92.66
Store and supply water sources for daily life and production	73.75
Keep the climate fresher and cooler	81.85
Provide giving-birth places, natural breeds, and foods	65.64
Provide tourism products	64.09
Q4. In your opinion, do we need to pay for such benefits/services?	
Yes, it is necessary	88.03

Note: This table summarises the proportion of the answers with yes or agree (in percentage)

On the other hand, the understanding of the respondents on (F)PES is still incomplete, with only 58.97% recognizing the term, mainly via the media (Q6 of Table 3). While it indicates a certain level of socialization and universalization of (F)PES in Vietnamese society, it comes with a con. Without official training and education, society does not fully understand (F)PES and its market-based mechanism. Particularly, many respondents wrongly defined the (F)PES as the monetary amount to remedy environmental pollution (48.72%) or for pollution/waste treatment services (52.14%). Notably, nearly a third of the respondents (31.20%) believe that (F)PES is the allowable fee to pollute the environment.

The knowledge of the FPES market is also diverse. While most respondents (88.46%) agreed that everyone should be involved in FPES as ES beneficiaries, only around a third of them (or less) identified tourism companies, hydropower plants, clean water suppliers, and industry facilities as ES buyers in the market (Q8 of Table 4).

In terms of ES producers, two-thirds of the respondents believe that the ones in charge of environment protection should receive the ES payments (Q9 of Table 4); this finding is linked to Q7 of Table 3 and strengthens our argument that official training and education are needed to improve FPES knowledge of the Vietnamese society. As for the price in the market, most respondents accept the monitoring role of the government and agree that the current FPES rates for hydropower and clean water companies are reasonable. Around 20% of them, however, believe that the rates are still low and could be increased, so to contribute more to the win-win solution of FPES. As a result, 77.78% of the respondents are willing to pay an additional amount to receive more benefits/services from the environment (Q16 of Table 4). We further argue that it indicates the potential to increase FPES price, or even let it be defined by the buyers and sellers, in expanding the Vietnamese FPES market.

Table 3. The knowledge of FPES

Q6. Where did you learn about FPES?	
Television, radio, magazine, newspaper	35.90
Internet	38.03
Traning and Education	14.53
Q7. In your opinion, what is (F)PES?	
An amount to remedy environmental pollution	48.72
An amount for environmental protection and biodiversity conservation	68.80
An amount for the benefits of environmental benefits/services	48.29
An amount to pollute the environment	31.20
An amount for pollution/waste treatment services	52.14

Note: This table summarises the proportion of the answers with Yes or Agree (in percentage)

Table 4. The knowledge of the market for FPES

Q8. Who should pay for the benefits/services provided by the environment?	
Everyone	88.46
State authorities and agencies	20.09
Tourism companies	34.62
Hydropower and Clean water suppliers	29.06
Industry facilities	28.63
Q9. Who should receive such payments?	
Government and relevant agencies	38.46
Forest owners and contractors	15.38
Households, individuals, and communities living at water sources	10.68
Households, individuals, and agencies in charge of forest protection	68.80
Q14. How do you evaluate the current rate of 36VND/kWh of electricity in FPES?	
High	5.98
Low	19.23
Reasonable	63.68
Q15. How do you evaluate the current rate of 52VND/m3 of clean water in FPES?	
High	9.83
Low	17.95
Reasonable	61.11
Q16. To receive more benefits/services from the environment, are you willing to	
Paying extra for FPES	77.78

Note: This table summarises the proportion of the answers with Yes or Agree (in percentage)

In conclusion, in parallel with global economic development, improvement of people's living standards (especially for the poor and minority communities) and environmental protection and conservation are becoming more important, reflected in the SDGs agenda. This study re-examined the development of the FPES market in Vietnam, the first ASEAN country to implement this tool since 2008, by looking at the role of the government, the achievements of the FPES over the past fifteen years, and the knowledge or awareness of the society regarding the market for FPES (i.e., producers, buyers, and price). Accordingly, we confirmed that the marketization of FPES in Vietnam created significant revenues for the national and provincial budgets for forest protection and conservation, generated about 20% of cash incomes for forest owners, and expanded the area of protected forests. On the one hand, the market for FPES has been developed in terms of regulations, market participants (both ES producers and buyers), and socialization. On the other hand, there is a need for improvements in terms of official training and education, as well as market price mechanism, to expand the awareness and participation of the society toward a market-based FPES. When implemented, these improvements will ensure a win-win solution for poverty alleviation and environmental protection a positive impact that we are committed to monitoring.

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Review: Ethno-mycological perception towards wood ear fungi (*Auricularia* spp.) in and around the Indian Subcontinent

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Abstract. *Giri S, Paul P, Pradhan P. 2025. Review: Ethno-mycological perception towards wood ear fungi (*Auricularia *spp.) in and around the Indian Subcontinent. Asian J For 9: 82-96.* The genus *Auricularia*, commonly called wood ear fungi, is a notable group of basidiomycetes valued for their culinary, medicinal, and nutraceutical properties. These fungi, widely distributed across tropical, subtropical, and temperate regions, play a crucial ecological role as saprophytes and potential plant parasites. Domesticated for over 2,000 years in East Asia, *Auricularia* spp. has been integral to traditional Chinese medicine, treating ailments such as sore throats, ophthalmia, and staphylococcal infections. Their bioactive compounds exhibit antiviral, antibacterial, antiparasitic, and immune-enhancing properties, with *Auricularia auricula-judae* is notable for its lovastatin content, beneficial in managing hypercholesterolemia. In the Indian subcontinent, *Auricularia* spp. hold significant ethnomycological value, particularly among indigenous communities in the Northeastern states, as well as in Bhutan and Nepal. However, their usage varies, with communities of Tibeto-Burman language family integrating them deeply into culinary and medicinal practices, while communities of Austro-Asiatic language family remain less familiar. This disparity in use is influenced by factors such as cultural practices, availability, and the transmission of traditional knowledge. Despite their economic potential, commercial cultivation in the region is underdeveloped, contrasting with China's dominance in global *Auricularia* production. With improved cultivation techniques, awareness, and market strategies, these fungi could bolster rural economies. The present review explores the ethno-mycological perception towards the genus *Auricularia* in and around the Indian sub-continent, highlighting their cultural, medicinal, and economic significance.

Keywords: Basidiomycetes, culinary practice, folk medicine, non-timber forest products, subsistence

INTRODUCTION

Mycophily has been integral to human culture since prehistoric times. The spore-producing fruitbodies of Basidiomycetes and Ascomycetes have enchanted humans through their beauty and various values based on their aesthetic, culinary, monetary, and nutraceutical properties (Giri et al. 2012a, 2013). Macrofungi or mushrooms, especially wild ones, are prized non-timber forest products (NTFPs), and they have been used across the globe by mycophilic societies (Jones et al. 1994).

The genus *Auricularia* a typical member of the family Auriculariaceae, is found in almost all terrestrial ecosystems except alpine regions (Wang et al. 2016; Wu et al. 2015, 2021). Auriculariales has 13 species documented for human use, of which, 10 are consumed by humans, and four have medicinal value (Boa 2004). *Auricularia mesenterica* (Dicks.) Pers. (Wu et al. 2014), and *A. auricula-judae* (Bull.) Quél., have been treated as a species complex (Wu et al. 2015). *Auricularia* grows upon diverse substrate types as saprophytes and plays crucial role in the forest ecosystem by degrading dead trees, fallen trunks, and rotten branches (Dai and Bau 2007; Baldrian and Lindahl 2011; Priya et al. 2016). The basidiocarps of *Auricularia* are generally called wood ear fungus due to their resemblance to the human ear, and they hold mythological significance linked to Judas (Choudhury and Sarma 2014; Kejariwal 2023). Members of *Auricularia* exhibit considerable morphological plasticity, partly because they lack distinct identifying features (Wong and Wells 1987). Additionally, some species show seasonal color variations (Choudhury and Sarma 2014). To aid in the identification of *Auricularia* species, González-Colón and Maldonado-Ramírez (2017) developed a comprehensive data sheet. Beyond morphological traits, species boundaries have been delineated through phylogenetic analyses. Studies by Malysheva and Bulakh (2014), Wu et al. (2015), Bandara et al. (2015, 2017) have refined the classification within this genus through combination of rpb2 and ITS sequence data. Basidiocarps of *Auricularia* species are recognized as low-calorie dietary options and rich in biologically active polysaccharides and essential amino acids. They provide essential minerals such as iron, calcium, potassium, and zinc (Kadnikova et al. 2015). Notably, wild *A. auricula-judae* has the highest magnesium content (2,014 mg/kg) among wild mushrooms (Shin et al. 2007). The species also contain about 30% protein by dry weight and serve as a key source of vitamins (Chang and Miles 2004). Polysaccharides from *Auricularia* are known to inhibit hepatocellular carcinoma proliferation, promote apoptosis,

and restrict cell migration (Shan et al. 2017). They also possess antiviral, antimicrobial, antiparasitic, and blood pressure-regulating components (Ukai et al. 1983; Yang et al. 2005; Giri et al. 2012b), help regulate intestinal flora (Zhang et al. 2020), may slow aging (Xu et al. 2016; Qian et al. 2020), and enhance the immune system (Bao et al. 2020).

In Chinese traditional medicine, *Auricularia* species find topical usage for sore throat, ophthalmia, staphylococcal infections, tonsillitis, atherosclerosis, hemorrhoids, and laryngocele (Hall et al. 2003; Kadnikova et al. 2015). They are also recognized as substances that prevent thrombosis (Yoon et al. 2003) and reduce cytotoxicity (Oke and Aslim 2011). *Auricularia auricula-judae* is notable for its high lovastatin content, which suppresses the activity of 3-hydroxy-3-methyl-glutaryl coenzyme A reductase, beneficial for hypercholesterolemia (Pushpa et al. 2016). However, *A. polytricha* contains soluble oxalates, and those prone to hyperoxaluria or kidney stones should avoid it (Nile and Park 2014).

Auricularia, despite being cosmopolitan plant saprophytes, and possibly plant parasites, have seen increased domestication, owing to their medicinal potential and nutritional value (Chang and Miles 2004). Ranking fourth among cultivated mushroom groups, they preceded *Agaricus*, *Lentinula*, and *Pleurotus* in significance (Zhang et al. 2017). China dominates global production, contributing 90% of the total output. In 2018, China produced 674,000 tons of *Auricularia*, generating 37.46 billion yuan (5.13 billion USD) in revenue and 6.15 billion yuan (0.84 billion USD) from exports (Li and Bi 2021). Exports primarily go to Japan and South-East Asia, with a steady annual growth rate of 3.96% up to 2020 (Wang et al. 2022a). While *Auricularia* species are reported as edible in 24 countries, their recognition for food value is noted in at least 10 countries, including East Asian nations, Korea, Japan, and parts of Africa (Boa 2004). This review explores the ethno-mycological perception towards genus *Auricularia* in and around the Indian subcontinent.

ETHNOMYCOLOGICAL PERSPECTIVES OF *Auricularia* spp. AROUND INDIAN SUB-CONTINENT

Auricularia species have a deep-rooted significance across various cultures, serving as a vital component in both culinary and medicinal practices. Historically, the Chinese pioneered the collection and artificial cultivation of wild *Auricularia* dating back to 300-600 BC, with its culinary use documented since 600 AD (Cheng and Tu 1978; Chang 1993). These mushrooms have been intricately linked to cultural practices, being consumed as a delicacy, used in traditional medicine, and appreciated for their nutritional benefits.

In countries such as China, Japan, and the Philippines, *Auricularia* spp. are highly valued for their texture and taste, making them a staple in local cuisines. In China, *Auricularia heimuer* (黑木耳-hēimù'ěr) and *A. cornea* (毛木耳-máomù'ěr) are commercially cultivated, contributing to a market value of approximately US$4 billion annually (Wang et al. 2022b). Similarly, *Auricularia auricula-judae* and *A. polytricha*, collectively known as *kikurage* are integral to various dishes in Japan, although domestic production only meets 8.4% of the demand, with the rest imported from China (Tabuchi et al. 2021). Indigenous communities in the Philippines, such as the Aeta and Gaddang, consume *A. auricula-judae* and *A. polytricha*, known locally as *kuwat malabalugbogdagis* and *taingang daga* (De Leon et al. 2012; Lazo et al. 2015). Tibetan communities also utilize (du: na ~~z~~u [*na ju*]) as food (Winkler 2008; Kang et al. 2016). In Thailand, *Auricularia* species are traditionally consumed and are locally known as *hed hoo noo* (Jones et al. 1994). In Malaysia, these species are recognized by several vernacular names, including *cendawan memeh*, *cendawan telinga kera*, and *kulat telinga* (Chang and Lee 2004; Shin et al. 2007; Abd Razak et al. 2013), highlighting the regional significance of *Auricularia* in myco culinary practices.

Auricularia spp. have also been recognized for their medicinal properties, particularly in Korea and Europe. Korean traditional medicine acknowledges the therapeutic benefits of *A. auricula-judae*, as documented in 'Dong Yi Bao Jian' by Heo Jun in 1613. In Europe, these mushrooms have been used for disease prevention since the 18th and 19th centuries (Berch et al. 2007; Sekara et al. 2015; Yao et al. 2019). In many regions, *Auricularia* spp. serve as an important food commodity. In Indonesia, the Pamona community uses *Auricularia* spp. viz. *jamur kuping*, *tanggorugoru*, *talinga mbalesu* for both culinary and medicinal purposes (Yusran et al. 2024). In Tanzania, these mushrooms are referred to as *uyoga hindi* and are widely consumed (Härkönen 2002). Additionally, in Kenya, *Auricularia delicata* and *A. polytricha* are harvested for food and medicine (Onyango et al. 2016). The Gbagyi people of Nigeria consume *A. auricula-judae*, locally known as *kpunbwa munu* (Oso 1975; Kelly et al. 2015). *Huntsul* in Ethiopia (Sitotaw et al. 2020) and *Kpunbwa munu* in Nigeria (Oso 1975; Kelly et al. 2015) refer to edible species of *Auricularia*.

Auricularia spp. have gained appreciation worldwide, with their use documented in diverse regions including Fiji, Peru, and Brazil. In Fiji, these species are considered edible, while in Peru and Brazil, *Auricularia fuscosuccinea* and *A. delicata* are integral to local diets (Prance 1984; Remotti and Colan 1990; Obodai and Apetorgbor 2001). Furthermore, their historical significance is noted in early Hawaiian culture, with exports to San Francisco recorded during the end of 1800s (Schenck and Dudley 1999).

The use of *Auricularia* spp. across different cultures showcases a trend towards their dual role as both a food source and a medicinal resource (Table 1). They are commonly incorporated into traditional dishes for their unique texture and nutritional benefits. The mushrooms are often dried and preserved, ensuring their availability during off-seasons. Medicinally, they are valued for their health benefits, with historical texts and modern studies highlighting their role in disease prevention and overall well-being. Their widespread cultivation and commercialization, particularly in China, highlight their economic importance, making them a significant commodity in global markets.

Table 1. Ethnomycological utilization of *Auricularia* spp. around Indian subcontinent

Region/country	Species of *Auricularia* utilized	Uses	Reference(s)
China	*Auricularia heimuer, Auricularia cornea*	Food	Cheng and Tu (1978); Chang (1993); Wang et al. (2022b)
Korea	*Auricularia auricula-judae*	Medicines	Heo (1613)
Europe	*Auricularia* spp.	Medicines	Sekara et al. (2015); Berch et al. (2007); Yao et al. (2019)
Tibet	*Auricularia auricula-judae*	Food	Winkler (2008); Kang et al. (2016)
Japan	*Auricularia polytricha, Auricularia auricula-judae*	Food	Tabuchi et al. (2021)
Philippines	*Auricularia auricula-judae, Auricularia fuscosuccinea, Auricularia polytricha*	Food	De Leon et al. (2012); Lazo et al. (2015); Corazon and Licyayo (2018)
Indonesia	*Auricularia auricula-judae, Auricularia nigricans*	Food, medicines	Burkhill (1935); Irawati et al. (2012); Yusran et al. (2024)
Malaysia	*Auricularia* spp.	Food	Chang and Lee (2004); Abd Razak et al. (2013); Shin et al. (2007)
Vietnam	*Auricularia* spp.	Food	Boa (2004)
Thailand	*Auricularia* spp.	Food	Jones et al. (1994)
Tanzania	*Auricularia polytricha, Auricularia fuscosuccinea, Auricularia delicata*	Food	Härkönen et al. (1994); Härkönen (2002); Juma et al. (2016)
Kenya	*Auricularia delicata, Auricularia polytricha*	Food, medicines	Onyango et al. (2016)
Bénin and Togo	*Auricularia cornea*	Food	Boa (2004); Osarenkhoe et al. (2014)
Nigeria	*Auricularia auricula-judae*	Food	Oso (1975); Kelly et al. (2015)
Ethiopia	*Auricularia* spp.	Food	Sitotaw et al. (2020)
Democratic Republic of Congo	*Auricularia cornea, Auricularia delicata, Auricularia polytricha, Auricularia tenuis,*	Food	Rammeloo and Walleyn (1993); Milenge Kamalebo et al. (2018)
Burundi and Rwanda	*Auricularia delicata, Auricularia auricula-judae*	Food	Degreef et al. (2016)
Ghana	*Auricularia auricula-judae*	Medicines	Obodai and Apetorgbor (2001)
Mozambique	*Auricularia auricula-judae*	Food	Wilson et al. (1989)
Malawi	*Auricularia auricula-judae, Auricularia delicata*	Food	Rammeloo and Walleyn (1993)
Chile	*Auricularia auricula-judae, Auricularia polytricha*	Food	FAO (1998)
Madagascar	*Auricularia auricula-judae*	Food	Bouriquet (1970)
Mexico	*Auricularia delicata, Auricularia fuscosuccinea, Auricularia mesenterica, Auricularia polytricha*	Food	Boa (2004); Villarreal and Perez-Moreno (1989)
Peru	*Auricularia delicata, Auricularia fuscosuccinea*	Food	Remotti and Colan (1990)
Guatemala	*Auricularia delicata*	Food	Flores (2002)
Brazil	*Auricularia fuscosuccinea*	Food	Prance (1984)
Fiji	*Auricularia* spp.	Food	Obodai and Apetorgbor (2001)
New Zealand	*Auricularia* spp.	Export	Stamets (2003)

ETHNOMYCOLOGICAL PERSPECTIVES OF *Auricularia* spp. IN THE INDIAN SUBCONTINENT

Globally, over 2189 macrofungi species of macrofungi have been identified as edible (Rai et al. 2005; Li et al. 2021), out of which about 283 are available in India (Purkayastha and Chandra 1985), apart from 100 medicinal fungi (Debnath et al. 2019). The Indian subcontinent has a special reservoir for ethnomycology as evidenced by records of mushroom utility in ancient medical treatise, Charaka Samhita (Thatoi and Singdevsachan 2014). Though India has rich macrofungal diversity, most traditional knowledge about mushrooms has been suggested to come from Northeastern countries like China, Japan, Korea, and Russia (Karwa and Rai 2010).

In India, *Auricularia* spp. is collected and consumed in many Northeastern states (Sharma and Kumar 2011). They are reportedly consumed in Western Assam by Garos, Bodos, Adivashis, and Rajbangshi. Garo people also use *A. auricula-judae* to cure ailments like rheumatic pain and minor injuries (Sarma et al. 2010). *Auricularia auricula-judae* is reported to be utilized by the Bodo and Kachari communities inhabiting the buffer region of the Nameri National Park, Assam (Choudhury and Sarma 2014). In Nameri National Park, fruitbodies of *A. auricula-judae* are mostly collected by elder women after taking necessary precautions to be fit for consumption. The fruitbodies are used in soups and salads, along with other ingredients. Medicinal values and practice of *A. auricula-judae* adjoining the localities of Nameri National Park include their use in the treatment of eye irritation, and cold, as a tonic along with ginger and basil leaves in sore throat after proper sterilization by moist stream for several hours and treatment of jaundice along with hot water (Choudhury and Sarma 2014). *Auricularia auricula-judae* is among the mushrooms consumed by the people of Ultapani Reserve Forest, within Manas Biosphere Reserve (Paul et al. 2015). *Auricularia delicata* is considered edible in the mycophagic tradition of Garos and Bodos in Western Assam and this mushroom also finds use to stop bleeding in local traditional healing practices (Sarma et al. 2010).

Auricularia delicata (Mont. ex Fr.) Henn. (called *ozenabi* by Mao subtribe of Naga; *yaonupa* by Poumei subtribe of Naga; *sonabi* by Naga, *uchina* by Meitei, *shiokhanavar* by Tangkhul tribe of Naga, *pachop* by Kuki community of Manipur and generally referred in Ima markets of Imphal as *uchi-na*) are consumed by the respective tribes. The Tangkhul tribe of Naga uses *A. polytrica* as food. They eat the fungi either fried or cooked with pulses. The price of the fungi ranges from Rs. 50-70 (USD 0.58-0.81) in the local market of Ukhrul District, Manipur (Salam and Jamir 2018). In the Thadou tribe of the Kuki community, *Auricularia delicata* is commonly referred to as *pachop*, which is also used to denote *A. auricula-judae* (Singson et al. 2015). Despite extensive ethnomycological research on other tribes in Manipur, the Thadou tribe has been less studied, with the notable report by Singson et al. (2015) highlighting that *A. auricula-judae* and *Schizophyllum commune* are the primary mushrooms utilized by them. In Manipur, mushrooms are typically prepared by frying them (fresh or dried) with soaked peas, mentha, and potatoes. They fetch a price of Rs. 20-30 per kilogram in the Ima market (Srivastav et al. 2009; Devi et al. 2010; Pfoze et al. 2011). However, *Auricularia delicata* commands a higher price in markets of Mao Gate, Senapati, Kangpokpi, and Motbung in Senapati District, where collectors sell it for an average of Rs. 338 (USD 3.90) per kilogram and vendors for Rs. 470 (USD 5.42) per kilogram (Pfoze et al. 2012). This price discrepancy reflects the high demand and value of *A. delicata* in these regions.

The tribes of Nagaland, including Ao, Angami, Chakhesang, Chang, Khemungan, Konyak, Lotha, Pachury, Phom, Rengma, Sangtam, Sema, Yimchunger, and Zeliang, residing in and around forested regions such as Lahorijan, Puliebzie, Zakhama, Pherma, Mankoi, Chungtia, Nongkham, Namcha, and Tigit, are known to consume *Auricularia auricula-judae* and utilize it for medicinal purposes (Kumar et al. 2013). Ao et al. (2016) also noted the sale of dried *A. auricula-judae* alongside other wild edible mushrooms in markets across Mokokchung, Zunheboto, Kohima, Tuensang, Phek, and Wokha. These mushrooms are sold throughout the year, depending on the availability of local stocks.

Interestingly, the Ao tribe of Mokokchung District in Nagaland has been reported to prioritize the medicinal use of *A. auricula-judae* over its consumption as food (Kumar et al. 2014). Meanwhile, in the Kohima district, locals consume a variety of wild mushrooms, including *Agaricus* spp., *Auricularia delicata*, *Calvatia gigantea*, *Lentinus* spp., *Lycoperdon* sp., *Pleurotus* spp., *Termitomyces eurrhizus*, and *Tricholoma* spp. as part of their diet (Tanti et al. 2011). In the same study, *Schizophyllum commune*, a mushroom that grows year-round, was reported to sell for approximately Rs. 300 per kilogram in local markets, while no mention was made of the marketing of *A. delicata*.

In Meghalaya, the Khasi tribe has a history of extensive wild mushrooms utilization in subsistence and traditional systems of health (Das et al. 2014). However, with growing urbanization, and changes in the food habits accruing due to it, the ancient tradition of gathering and consuming wild mushrooms by the local Khasi tribals is slowly on the decline (Agrahar-Murugkar and Subbulakshmi 2005). In Meghalaya, various wild edible mushrooms are collected and consumed by the Khasi and Jaintia tribes living in regions such as Jingkiengmawkdok, Lapalang, Mawlai, Mawphlang, Mawsmai, Shillong Peak, Shyrwat, and Upper Shillong Reserve Forests. Notable species include *Agaricus bisporus* (locally called *tit bol*), *Albatrellus ellisii*, *Armillaria mellea*, *Boletus edulis*, *Calvatia gigantea*, *Cantharellus cibarius* (locally called *tit khang paipylleng*), *Clavaria flava* (locally called *tit thynatsyiar*), *Clavulina cinerea*, *Clavulina cristata*, *Gomphus floccosus*, *Inocybe* aff. *sphaerospora*, *Laccaria laccata*, *Lactarius* spp. (locally called *tit doh* or *tit tung*), *Lentinus edodes*, *Ramaria* spp. (locally called *tit lbonghati*), *Russula* spp., *Suillus bovinus*, and *Tricholoma viridiolivaceum*. These mushrooms are not only consumed locally but are also marketed, reflecting their importance in local diets and economies, as documented by various studies (Agrahar-Murugkar and Subbulakshmi 2005; Khaund and Joshi 2013, 2014; Das et al. 2014; Kalita et al. 2016). Despite the rich diversity of mushrooms utilized and marketed in these areas, research indicates that *Auricularia* spp. are not among the mushrooms commonly used or sold by these tribes. Although *A. delicata* has been reported in Meghalaya (Kumar et al. 2015), it is not a significant part of the local mushroom economy or cuisine in the region.

In Arunachal Pradesh, the Garo tribe collects mushrooms for their own consumption and selling in the market. They primarily collect *Auricularia auricula-judae*, *A. delicata*, and *A. polytricha*. *Auricularia delicata* is locally called *imbuk*, and *A. polytricha* is called *takek marek* in the Garo language (Singh et al. 2015). In Mizoram, *Auricularia auricula-judae* is called *pu Vana beng* and is eaten by the local community (Lalrinawmi et al. 2017). In Tripura, a study by Roy Das et al. (2017) documented thirteen edible macrofungi from the local market belonging to eight genera, including *Lentinus* spp., *Pleurotus* spp., and *Termitomyces* spp. However, they did not find evidence of the edibility of *Auricularia* in Tripura. In Sikkim the *Auricularia cornea* is locally called *kane chyau* or *namcho shamo*, is edible however it is not so liked by the communities for its leathery texture (Das 2010; Wangdi 2019).

In Himachal Pradesh, *Amanita citrina*, *Amatita fulva*, *Laccaria laccata*, *L. pubescens*, *Russula lepida*, *R. mairei* are reported of local culinary use in Mcleodganj (Sharma and Gautam 2015). Similarly, other reported mushrooms of culinary use across the state by Sharma and Gautam (2015) include *Agaricus sylvicola* and *Hygrocybe nivea* from Dharamshala, *Agaricus comtulus* and *Hygrocybe coccinea* from Jhatingri, *Cantharellus cibarius* and *Lepista nuda* from Khajjiar, *Agaricus arvensis* from Shimla, *Agaricus campestris* from Kullu, *Amanita caesarea* from Janjehli, *Conocybe tenera* from Kufri, *Pleurotus cystidiosus* from Palampur, *Lentinus cladopus* from Bhadrol. Savitri and Bhalla (2007) have reported *Humaria hemisphaerica* (locally *kanifru*), *Cantharellus cibarius* (locally *peelichhatri*) and *Ramaria botrytoides* (locally *siun*) to be consumed as vegetable or vegetable curry by tribal

communities of Chamba, Kangra, Kinnaur, Kullu, Mandi areas of the state, and Chauhan et al. (2014) have reported *Agaricus campestris* (locally called *kammu*, *khorpotey*, *shong*), *Gyromitra* sp. (locally called *chianjuh*), *Helvella compressa* (locally called *aayokan*, *maein*), *Hygrophorus* sp. (locally called *rachela*), *Lactarius deliciosus* (*chanmoo*, *jadmoh*, *migang*), *Lycoperdon* sp. (*lalari*, *lalrishal*), *Morchella conica* (*gopal*, *guchhi*), *M. deliciosa* (*gopal*, *guchhi*), *M. esculenta* (*chlango*, *guchhi jamoo*, *shaime*), *Ramaria botrytis* (*mooh*), *Rhizopogon vulgaris* (*khorpatey*, *migang*), *Sparassis crispa* (*aayokan*, *kathmooh*, *mohin*, *moohcho-sho*) to be utilized by the residents (without naming particular tribe) of seventeen villages under Nichar, Kalpa and Poohs of Kinnaur District in Himachal Pradesh. The above studies indicate that there is no tradition of *Auricularia* spp. being utilized by the local tribes and communities, though, studies on antioxidant activity (Puttaraju et al. 2006) and nutritional values (Kumari et al. 2015) of *Auricularia polytricha* collected from Himachal Pradesh have been reported.

Amongst 620 edible plants of Uttarakhand, Shah (2015) has reported several mushrooms like *Agaricus campestris*, *Armillaria mellea*, *Cantharellus cibarius*, *Clavulinopsis fusiformis*, *Craterellus cornucopioides*, *Flammulina velutipes*, *Lactarius deliciosus*, *Lycoperdon pyriforme*, *Morchella esculenta*, *Pleurotus ostreatus*, *Polyporus grammocephalus* as edible from Uttarakhand, however, the book does not have a record of *Auricularia* being utilized in Uttarakhand. *Gymnopilus junonius* is reported for local culinary use in Nainital, Uttarakhand (Sharma and Gautam 2015). In Jaunsar, Chakrata of Dehradun, *Auricularia auricula-judae* (locally known as *kanode* or *kanchatta* = ear mushroom) and *A. polytrica* (locally known as *kanode*) are reported to be consumed by the Nepali community. Additionally, *Auricularia auricula-judae* is reported to be used as a medication for ear pus (Kumar et al. 2017).

Amongst the edible fleshy fungi utilized by the populace of Chunar, Gorakhpur, Varanasi, and Vindhyachal in Eastern Uttar Pradesh, there is no mention of *Auricularia* spp. being utilized in culinary practices (Ram et al. 2010; Chandrawati et al. 2014; Vishwakarma et al. 2017).

The local villagers, Nepalis and Van Gujjar residing in Baniyakund, Chopta, Devariyatal, Kund, Mandal, Nagdev-Jhandidhar, Tungnath Trek, and Ukhimath areas of Garhwal Himalaya are reported by Bhatt et al. (2016) to consume *Amanita hemibapha*, *Boletus edulis*, *Cantharellus cibarius*, *C. minor*, *Craterellus cornucopioides*, *Grifola frondosa*, *Hydnum repandum*, *Lactarius deliciosus*, *L. subindigo*, *Lactifluus hygrophoroides*, *Marasmius oreades*, *Morchella esculenta*, *Russula brevipes*, *R. virescens*, and *Strobilomyces floccopus*. However, the report of Bhatt et al. (2016) does not reflect myco culinary preference of local people towards *Auricularia* spp. and such lack of awareness about edibility of *Auricularia* spp. in Garhwal Himalaya has also been hinted by Semwal et al. (2014). Amongst the reported mushrooms used for medicinal purposes globally, which are available in Garhwal Himalaya like *Agaricus campestris*, *Cantharellus cibarius*, *Coprinus comatus*, *Ganoderma lucidum*, *Hydnum repandum*, *Morchella exculenta* (Vishwakarma et al. 2011), there is no mention of *Auricularia* spp.

However, Tibetan refugees (Tibeto-Burman Population) living in Garhwal Himalaya are reported to consume locally occurring *Auricularia auricula-judae* and *A. polytricha* who refer to these mushrooms as Muro (Semwal et al. 2014). The Tibetans use to collect the species from the wild and consume it fresh and dried as well. The Tibetan culinary culture, dried fungi are commonly prepared by a method that involves 10-20 minutes soaking in hot water, followed by frying process that includes onions and additional ingredients (Semwal et al. 2014).

According to Pala et al. (2013), *Auricularia auricula-judae* (locally called *rudh papad*) grows gregariously upon Walnut trees and black locust trees in Chadoora, Hirpora, Keller, and Shopian areas of Kashmir and are recommended by local herbalists as remedial food for patients with cold, hypertension, jaundice, sore throat, sore eyes, and as astringent. Female and child members of the Gaddi and Shippi tribes of Jammu and Kashmir are reported to collect *Auricularia* spp. along with other mushrooms like morels for consumption (Choudhary et al. 2015). In Jammu Province of Jammu and Kashmir, many mushrooms like *Coprinus comatus*, *Geopora arenicola*, *Inocybe splendens*, *Ramaria* spp., *Sparassis crispa*, *Termitomyces striatus* are consumed by locals (Kumar and Sharma 2009; Sharma and Gautam 2015). However, the said report does not enlist *Auricularia* spp.

West Bengal has reports of 31 edible mushrooms utilized by indigenous communities as food (Dutta and Acharya 2014). Amongst these people from the Himalayan Hill region of West Bengal, especially the Kalimpong subdivision (as far as Lava-Lolaygaon) of the Darjeeling district are known to consume *Auricularia auricula-judae* (Dutta and Acharya 2014). Locally called *kane* or *baje kane chiyaou* or *kan chatka* [*kaan*=Ear, *chiau*=Mushroom in Nepali], the local collectors use to collect fruitbodies of *Auricularia* spp., from the wild, sun dry and sell in the local haat bazaar (market) in Kalimpong, fetching as much as INR 1,200/kg or 13.86 USD/kg, especially during marriage season.

Although local collections of *Auricularia* are reportedly marketed in Darjeeling town (Acharya et al. 2004) and are used in Tibetan dishes like *shapta*, *shaptak* or *thenthuk* (Figure 1), which includes meat pieces and hot water-soaked local vermicelli made from rice, known as *fing* in a soupy base, which is available in Tibetan restaurants in Darjeeling and Kalimpong, it is noteworthy that many residents of Darjeeling town are unaware of their edibility. However, locals do consume other myco-commodities, such as the cultivated *Pleurotus* species (available most of the year) and wild edible mushrooms like *Entoloma lividoalbum* and *Grifola frondosa*, during the monsoon season when they are available. In Kalimpong, the traditional Nepali culinary method for preparing *Auricularia* species is a derivative from Tibetan cuisine, which involves soaking the dried basidiocarps in hot water for 10-20 minutes before frying them with onions and *fing* (Dutta and Acharya 2014).

Figure 1. Tibetan dish of Chicken *shapta, shaptak* or *thenthuk* along with rice noodles (*fing*), broccoli, and brownish *Auricularia* basidiocarps (Photographed in Darjeeling by PP)

As is the case for *Auricularia*, it is typically a village dwelling species of Lateritic region of West Bengal comprising of parts of Bankura, Burdwan, Birbhum, Murshidabad, and West Midnapur Districts (Pradhan et al. 2012, 2013) and Sundarban area of West Bengal (Dutta et al. 2013). A study by Singha et al. (2020) conducted in the Gurguripal forest of West Medinipur highlighted that the Bhumija, Kheria, Kurmi, Lodha, Munda, Oraon, and Santal communities utilize *A. auricula* (locally known as *kan chhatu*) to treat earaches, ear infections, and manage cardiovascular diseases, diabetes, and hypertension. Santals, the Austro-Asiatic tribe of the pre-Aryan period, living in the Lateritic tract of West Bengal, are known to consume a good number of macrofungi. However, their myco culinary practice does not incorporate locally abundant and frequent *Auricularia* spp. (Pradhan et al. 2010).

Similarly, studies conducted in Odisha by Sachan et al. (2013) and Panda and Tayung (2015) documented the ethno-utilization of 14 and 19 species of wild edible mushrooms, respectively, from the Similipal Biosphere Reserve and the districts of Mayurbhanj, Keonjhar, and Balasore. These studies revealed that Austro-Asiatic tribes including the Bathudi, Bhumija, Bhuyan, Birhor, Ho, Khadia (or Kharia), Kolha, Kudumi, Mankidia (or Mankdias), Munda, and Santal do not utilize *Auricularia* spp. for either food or medicinal purposes. Kandha tribe of hilly areas of Junagarh and Thuamul Rampur areas of Kalahandi District, Odisha are reported to use nine species of wild edible mushrooms, which are consumed by the tribals as curry preparation and dried and preserved (Panda and Padhy 2007). However, this report also does not suggest the use of *Auricularia* spp. by Kandha people.

Tribal populations comprise a substantial portion of Madhya Pradesh and Chhattisgarh, constituting 25% of their combined population (Rajak and Rai 2005). A comprehensive ethnomycological study conducted by Rajak and Rai (2005) across 120 tribal localities in these states documented the utilization of 23 *Russula* species, nine *Lactarius* species, two species each of *Cantharellus* and *Termitomyces*, and single species of *Astraeus* sp., *Calvatia* sp., *Clitocybe gibba*, *Lentinus cladopus*, *Lycoperdon* sp., *Pleurotus florida*, and *Scleroderma* sp. by the local tribal communities. Notably, the study did not reveal any evidence of *Auricularia* spp. consumption among these tribal populations. During the ethnobotanical study of Baiga, Kanwar, Kol, and Pradhan tribes of the Amarkantak-Achanakmar Biosphere Reserve (spanning Anuppur and Dindori Districts of Madhya Pradesh, and Bilaspur District of Chhattisgarh), Kapale et al. (2013) found that three wild mushrooms with local names of *bhodu*, *chirkhu*, and *spittu* were being sold in the local market. However, their scientific identity is not mentioned in the report.

In an ethno-pharmacological study conducted by Soni (2013) in Belapani, Dhavaipani, Jaampani, and Sarodhdadar Villages in Chilpi forest range in Karwarda District of Chhattisgarh, questionnaire surveys revealed that besides 18 plants, there was no utilization of wild mushrooms, including *Auricularia* spp. in traditional medicinal practice by native Baiga and Gond tribes and their indigenous medicine man (Vaidyas or Guniyas). In Jharkhand, Srivastava and Soreng (2014) through their surveys in Khunti forest and adjoining markets have reported the local collection and consumption of *Boletus edulis*, *Calvatia*, *Geastrum*, *Lycoperdon*, *Macrolepiota procera*, and species of *Termitomyces*. However, *Auricularia* spp. were not found to be used by the locals.

Distribution of *Auricularia* in Chennai, Tamil Nadu has been documented (Manjunathan et al. 2011; Pithchai et al. 2015), and even nutritional values of locally collected *A. polytricha* have been evaluated (Manjunathan et al. 2011; Usha and Suguna 2014), yet they have not reported the use of the wood ear mushroom by the local population. Even *Auricularia* spp. is not listed amongst the 12 edible and 19 medicinal mushrooms collected by Pushpa and Purushothama (2012) from Bangalore, Karnataka. However, *Auricularia auricula-judae* (locally called *murukan kumizh*) along with edible wild mushrooms belonging to the genus *Grifola*, *Lentinus*, *Pleurotus*, *Termitomyces*, *Volvaria* are reported to be consumed by the Kaani Tribe of Kanyakumari District of Tamil Nadu as alternative source of protein (Johnsy et al. 2011; Davidson et al. 2012). The Kaani tribe incorporate *Auricularia* mushrooms into their culinary practices by collecting the fruitbodies, cleaning them, and then gently pounding them with an equal quantity of rice in a wooden mortar. This mixture is subsequently boiled with a small amount of water. To enhance flavor and aroma, salt, spices, and wild green chilies are added. The final dish is typically served alongside cooked rice or tapioca. Some Kaani individuals incorporate grated coconut into this preparation (Davidson et al. 2012). Furthermore, *Auricularia auricula-judae* holds medicinal significance within the Irula tribal community of the Walayar Valley, located in the southern Western Ghats of Coimbatore District, Tamil Nadu. Venkatachalapathi and Paulsamy (2016) documented the use of this fungus by the Irula tribe for treating common ailments such as fever, cough, and fungal infections.

Wayanad (in Kerala) with adjoining regions of Tamil Nadu has a native population of around 11 tribal

communities viz. Adiya, Kattunaikkar, Kurichya, Kuruma, Kurumar, Mullukurumar, Naykkar, Oorali, Ooralikurumar, Paniya, and Vallukurumar. Amongst them the study of Varghese et al. (2010) has revealed that amongst them the tribes of Kattunaikkar, Kuruma and Paniya are known to collect wild mushrooms. The mushrooms utilized by these three tribes were *Agaricus silvaticus*, *Cantharellus* spp., *Coprinus comatus*, *Laccaria laccata*, *Lentinus* spp., *Lepista sordida*, *Oudemansiella* spp., *Phlebopus portentosus*, *Pleurotus* spp., *Russula congoana*, *Termitomyces* spp. (Varghese et al. 2010), yet in the report there is no mention of *Auricularia* spp. finding ethno-utilization by the local tribes.

There are reports of the occurrence of *Auricularia* spp. from the Melghat forest Tiger Reserve of Maharashtra in India (Karwa and Rai 2010), Mantha, Jalna of Maharashtra (Kakde and Gaikwad 2014), and Gautala Wildlife Sanctuary (Gavhane et al. 2015). However, in Rajasthan the report by Sharma et al. (1992) lack the details of local utilization and consumption of *Auricularia* spp. In Gujrat, *Auricularia* spp. has been reported to be available (Rajput et al. 2015), yet it does not find a place in the list of 12 species of wild edible mushrooms utilized by tribal people of Mahal forest range of Gujarat (Parihar et al. 2015).

In Bhutan, *Auricularia* spp. are harvested from the regions of Pangkhar, Shingkhar, Tangsibi, and Ura, and sold to dealers at prices ranging from Nu. 1600-2300 (USD 18.48-26.56) per lamshu (lamshu is indigenous weighing system which equals approximately 200 g), with an average price of Nu. 1888 per lamshu or 21.80 USD/ 200 g. These mushrooms are ultimately sold in the Chinese markets of Northern Bhutan (Tshering et al. 2012). *Auricularia auricula-judae* (locally called *jilli namcho*) is popular in Bhutanese cuisine (Vantomme et al. 2002). However, not all of the populace consumed *Auricularia* spp. in Bhutan and some even did not have any idea about its edibility (Tshering et al. 2012). Nepal has a long tradition of collecting wild edible fungi and many species have been reported to be utilized for food and medicine in the Western Terai region of the Country (Aryal and Budathoki 2013). Although the export volume of *A. auricula-judae* is only next to the Morels (Adhikari 2000b) in Nepal, there is very little mention of *Auricularia* spp. being utilized in the country. Indigenous people (including Tharu communities) living in Parroha Village Development Committee of Rupandehi District, Nepal are reported to consume *Ganoderma* (*chyau*), *Morchella* (*guchi-chyau*), *Pleurotus* (*chyau*) (Acharya and Acharya 2010), yet it seems there is no utilization of *Auricularia* spp. Amongst the few reports of utilization *Auricularia* spp. from Nepal comes from the Tibeto-Burman tribes of Tamang (Pandey et al. 2006), Sherpa (Giri and Rana 2008), and discreet local utilization in the Nagarjun area of Kathmandu Valley (Joshi and Joshi 2008) and Majphal area of Dolpa district (Devkota 2008). Tamangs belong to the most dedicated mycophagous society of Nepal. They are not only one of the important ethnic groups but also the largest community of the Tibeto-Burman language family of Nepal. Their religion originates from Tibet and they follow "Lamaism" most of their lives still gravitate around the forests and retain primeval forests, and the culture is rooted in the old beliefs, taboos, folklore, and traditional attitudes (Pandey et al. 2006). Tamang community of Bhedetar, Dakshinkali, Langtang, Namobuddha, Sundarijal, and Talku areas of Nepal, refer to *Auricularia* spp. as *chipley shyamo*, *kaney shyamo*, *nabhyang shyamo*, and *thalthaley shyamo*, and use them as food, especially for making soup in Langtang (Pandey et al. 2006). In Sagarmatha National Park, the Sherpa community, particularly those residing near the forests of Chire (Kunde area), Deboche, and Omakha (Pangboche area), identify *Auricularia polytricha* as *durkha chyau*, where *durkha* translates to 'hard cheese', and *chyau* refers to 'mushroom' in local dialect. This species commonly grows on *Rhododendron* trees and are traditionally left to dry naturally on the trees until winter. Once dried, the mushrooms are harvested and consumed raw, with their texture resembling that of hard cheese (Giri and Rana 2008). In Kathmandu, *Auricularia auricula-judae* (locally *thalthaley chyau*) is reported to be of culinary use. However, along with other mushrooms like *Clavulinopsis fusiformis* (*kesari chyau*), *Coprinus comatus* (*gobrey chyau*), *Exobasidium butleri* (*pani pokey chyau*), and *Lactarius piperatus* (*dudhey chyau*). *Auricularia auricula-judae* is considered just edible and not delicious (Adhikari et al. 2005). *Auricularia mesenterica* growing on dead wood is reported from Maipokhari of Ilam District, Nepal, but the work does not report its local utilization (Adhikari 2000a). *Auricularia delicata* has also been reported as edible from Nepal (Adhikari 1999). Brahmin class of Hindus specializing as priests of sacred learning across generations in India and Nepal are purely vegetarians and are not reported to use mushrooms primarily because in their sect, the flesh of mushrooms is considered like the flesh of animals due to their flavor and taste (Christensen and Larsen 2005; Semwal et al. 2014).

Pakistan has a history of collections of *Morchella conica* and *M. esculenta* which dominate the local market and contribute to the economy in rural areas (Christensen and Larsen 2005). *Auricularia auriculae-judae* is a naturally occurring saprophytic mushroom in Pakistan (Khan et al. 2016). *Auricularia auricula-judae* and *A. polytricha* along with *Cantharellus* are considered edible in Kaghan Valley of Pakistan. In Kaghan Valley, *Auricularia polytricha* is also mentioned to be used for medicinal purposes (Sultana and Qreshi 2007). In the report of Kamal et al. (2009), mushroom consumption and cultivation in Bangladesh is dominated by Pleurotus, followed by *Agaricus*, *Calocybe*, *Volvariella*, and *Auricularia*, however, the later lacks consumption detail in the report. In Bangladesh, Khan et al. (2009) have tried the cultivation of *Auricularia* spp. upon straw and sawdust; however, there is no mention of their local utilization. Kamal et al. (2009) have assessed the temperature and humidity conditions of Bangladesh and found it to be ideal for the cultivation of *Auricularia* spp. Ediriweera et al. (2015) have studied the growth of *A. polytricha* in various lignocellulosic substrates of Sri Lanka. However, the study cites medicinal usage in China, yet there is no mention of local utilization in Sri Lanka (Table 2).

Table 2. Ethnomycological utilization of *Auricularia* spp. in the Indian subcontinent

Region	Tribes/communities	Species utilized	Usage	Reference(s)
Assam	Garos, Bodos, Adivashis, Rajbangshi, Kachari	*A. auricula-judae*, *A. delicata*	Consumed, medicinal uses (rheumatic pain, eye irritation, jaundice)	Sarma et al. (2010); Sharma and Kumar (2011); Choudhury and Sarma (2014)
Manipur	Naga (major subtribe: Mao, Poumei, Tangkhul), Maitei, Kuki (major subtribe: Thadou)	*A. auricula-judae*, *A. delicata*, *A. polytricha*	Consumed, medicinal uses	Srivastav et al. (2009); Devi et al. (2010); Pfoze et al. (2011); Singson et al. (2015); Salam and Jamir (2018)
Nagaland	Chakhesang, Angami, Zeliang, Ao	*A. auricula-judae*, *A. delicata*	Consumed, medicinal uses	Kumar et al. (2013, 2014); Ao et al. (2016)
Arunachal Pradesh	Garo	*A. auricula-judae*, *A. delicata, A. polytricha*	Consumed, sold in market	Singh et al. (2015)
Mizoram	Lusei, Chakma	*A. auricula-judae*	Consumed	Lalrinawmi et al. (2017)
Meghalaya	Khasi, Jaintia	Various wild mushrooms	Not significant for *Auricularia* spp.	Agrahar-Murugkar and Subbulakshmi (2005); Khaund and Joshi (2013, 2014); Das et al. (2014); Kalita et al. (2016)
Tripura	-	-	Not significant for *Auricularia* spp.	Roy Das et al. (2017)
Sikkim	Local communities	*A. cornea*	Consumed, not popular	Das (2010); Wangdi (2019)
Himachal Pradesh	-	-	Not significant for *Auricularia* spp.	Puttaraju et al. (2006); Savitri and Bhalla (2007); Chauhan et al. (2014); Sharma and Gautam (2015); Kumari et al. (2015)
Uttarakhand	Nepali community, Tibetan refugees	*A. auricula-judae*, *A. polytricha*	Consumed, medicinal uses	Shah (2015); Sharma and Gautam (2015); Kumar et al. (2017); Semwal et al. (2014)
Jammu and Kashmir	Gaddi, Shippi, various others	*A. auricula-judae*	Consumed, medicinal uses	Kumar and Sharma (2009); Pala et al. (2013); Choudhary et al. (2015); Sharma and Gautam (2015)
West Bengal	Tibeto-Burman, Santal, Kheria, Munda, Bhumija, Oraon, Lodha and Kurmi	*A. auricula-judae*	Consumed by Tibeto-Burman Communities, sold in markets of Kalimpong; used for medicinal purposes by Austro-Asiatic tribes	Acharya et al. (2004); Pradhan et al. (2010, 2013); Dutta and Acharya (2014); Dutta et al. (2013), Singha et al. (2020)
Odisha	Various tribes	Various wild mushrooms	Not significant for *Auricularia* spp.	Panda and Padhy (2007); Sachan et al. (2013); Panda and Tayung (2015)
Madhya Pradesh and Chhattisgarh	Baiga, Kol, Kanwar, Pradhan	Various wild mushrooms	Not significant for *Auricularia* spp.	Rajak and Rai (2005); Kapale et al. (2013); Soni (2013)
Jharkhand	Various tribes	Various wild mushrooms	Not significant for *Auricularia* spp.	Srivastava and Soreng (2014)
Tamil Nadu	Kaani, Irula	*A. auricula-judae*	Consumed, medicinal uses (fever, coughs)	Johnsy et al. (2011); Davidson et al. (2012); Venkatachalapathi and Paulsamy (2016)
Karnataka	Kaani	*A. auricula-judae*	Food	Pushpa and Purushothama (2012)
Kerala	Paniya, Kuruma, Kattunaikkar,	Various wild mushrooms	Not significant for *Auricularia* spp.	Varghese et al. (2010)
Maharashtra	Various tribes	Various wild mushrooms	Reported occurrence, utilization not significant for *Auricularia* spp.	Karwa and Rai (2010); Gavhane et al. (2015); Kakde and Gaikwad (2014)
Gujarat	Various tribes	Various wild mushrooms	Reported occurrence, utilization not significant for *Auricularia* spp.	Rajput et al. (2015); Parihar et al. (2015)
Bhutan	Local communities	*A. auricula-judae*	Consumed, sold in markets	Vantomme et al. (2002); Tshering et al. (2012)
Nepal	Tamang, Sherpa	*A. auricula-judae*, *A. polytricha*	Consumed, medicinal uses	Pandey et al. (2006); Giri and Rana (2008); Adhikari (2000b, 2005); Joshi and Joshi (2008)
Pakistan	Various tribes	*A. auricula-judae*, *A. polytricha*	Consumed, medicinal uses	Christensen and Larsen (2005); Sultana and Qreshi (2007); Khan et al. (2016)
Bangladesh	Various tribes	Various wild mushrooms	Cultivation reported, but utilization not significant for *Auricularia* spp.	Kamal et al. (2009); Khan et al. (2009)
Sri Lanka	Various communities	Various wild mushrooms	Cultivation reported, but utilization not significant for *Auricularia* spp.	Ediriweera et al. (2015)

HABITATS OF *Auricularia* spp. IN THE INDIAN SUB-CONTINENT

Fungi dependent on specific substrates demonstrate wide host specificity, with their diversity closely tied to the plant host diversity, showing stronger correlations at the family level than within infra-familial groups (Pradhan et al. 2013; Giri and Pradhan 2023). However, *Auricularia* spp. are common to both monocots and dicots alike, and widely recognized for their saprophytic and lignicolous nature, primarily thriving on dead and fallen wood. Their distribution and growth patterns vary significantly across India. In the Garhwal Himalaya, these fungi are typically found between June and mid-October, corresponding to the monsoon season (Semwal et al. 2014). Conversely, in Assam, all *Auricularia* species, except for *A. polytricha*, are distributed throughout the year (Choudhury and Sarma 2014). Reports indicate that *Auricularia* spp. have been documented from a range of locations in India, including Bangalore in Karnataka, Manipur (Pushpa et al. 2016), Maharashtra, Kerala, and Madhya Pradesh (Nile and Park 2014). Furthermore, members of the Auriculariaceae family have also been recorded across the Northeastern Hills (Verma et al. 1987), Rajasthan (Sharma et al. 1992), and the Dhemaji District in Assam (Gogoi and Sarma 2012). However, Karun and Sridhar (2014) found that *Auricularia* spp. were absent from arboretums and plantations of *Acacia auriculiformis*, *Areca catechu*, and *Anacardium officinale* near Mangalore, Karnataka.

Auricularia auricula-judae (Bull.) Quél. exhibits a broad range of habitats and locations. In Assam, it is found on dead bamboo culms and *Psidium guajava* trees (Sarma et al. 2010; Paul et al. 2015), as well as on *Albizzia lucida*, *Bombax ceiba*, *Morus roxburghii*, and *Trewia nudiflora* (Choudhury and Sarma 2014). In the Meghalaya's East Khasi Hills, it is identified as a wood-rotting fungus (Lyngdoh and Dkhar 2014). In Nagaland, *Auricularia auricula-judae* grows on branches and dead stumps of subtropical and temperate trees, particularly species of *Alnus* (Ao et al. 2016). It is notably frequent and shows a high density on dead bamboo culms and underwood (Kumar et al. 2013). This species is also found in the Alongkima, Changtongya, Kubulong, Longchem, Mangkolemba, and Ongpangkong blocks of Mokokchung District in Nagaland, growing on dead wood (Kumar et al. 2014). In Basar, Arunachal Pradesh, it is identified as lignicolous (Singh et al. 2015). In the Kushmi Jungle of Gorakhpur District, Uttar Pradesh, it is parasitic on *Tecoma capensis*, growing in groups on healthy trees (Vishwakarma et al. 2017). The species also occurs in the Garhwal Himalaya, where it is found on the wood of *Bauhinia malabarica*, *Delonix regia*, *Grevillea robusta*, and *Quercus leucotrichophora* (Semwal et al. 2014). In the Walayar Valley of Coimbatore District and Kanyakumari District in Tamil Nadu, it grows upon the wood of deciduous shrubs and trees (Johnsy et al. 2011; Venkatachalapathi and Paulsamy 2016). In Bhadrachalam forest, Telangana, it is found on wood logs (Krishna et al. 2015). The species is also present in the villages of the Lateritic regions of West Bengal, where it is lignicolous and saprophytic (Pradhan et al. 2012, 2013; Singha et al. 2020), and in coastal villages of West Bengal, growing upon dead wood and logs (Dutta et al. 2013). Additionally, it is found in the forests of *Alnus*, *Lithocarpus*, and bamboo fringes in the Himalayan region of West Bengal, where it is saprophytic (Pradhan et al. 2016).

Auricularia delicata is reported from several locations as well. In Assam, it grows upon dead logs of *Semecarpus* species (Sarma et al. 2010). In Mao Gate, Senapati, Kangpokpi, and Motbung in the Senapati District of Manipur, it is found on dead wood in forests of *Alnus nepalensis*, *Castanopsis* species, *Quercus griffithii*, and *Quercus serrata* (Pfoze et al. 2012). It is also reported from Narpuh Reserve Forest of Meghalaya (Kumar et al. 2015) and in Basar, Arunachal Pradesh, where it is lignicolous (Singh et al. 2015). *Auricularia mesenterica* (Dicks.) Pers. has been observed in Maniram village of Gorakhpur District, Uttar Pradesh, where it grows saprobically in groups on decaying wood logs (Vishwakarma et al. 2017).

Auricularia nigricans (Sw.) Birkebak, Looney & Sánchez-García, sometimes reported as *A. polytricha*, is found in Assam upon dead bamboo culms (Sarma et al. 2010) and on *Albizzia procera*, *Delonix regia*, and *Sapium baccatum*, causing white rot (Choudhury and Sarma 2014). In Nagaland, it is reported to grow upon decaying logs and twigs (Ao et al. 2016). It is also present in Basar, Arunachal Pradesh, where it is lignicolous (Singh et al. 2015). In the Garhwal Himalaya, it is found on the wood of *Bauhinia malabarica*, *Delonix regia*, *Grevillea robusta*, and *Quercus leucotrichophora* (Semwal et al. 2014). In Himachal Pradesh, it is reported to grow on dead branches of *Ficus benghalensis* (Puttaraju et al. 2006). In Badhgahan Village of Gorakhpur District, Uttar Pradesh, it is parasitic on the *Mangifera indica* (Vishwakarma et al. 2017). In Kokam, Shoolpaneshwar Wildlife Sanctuary, and other areas of Gujarat, it is reported to grow upon the bark of trees such as *Butea* and *Mangifera* (Kokni et al. 2019). *Auricularia olivaceus* is found in the Shimla Tara Devi and Barot areas of Himachal Pradesh, where it grows gregariously upon old *Quercus incana* and under *Cedrus deodara* (Kumari et al. 2013). *Auricularia cornea* has been observed in Bardipada, Samgahan, Vangan, and Sati in Gujarat, where it grows on dead stems of *Butea* (Kokni et al. 2019). It is also found in Sikkim on dead and decaying wood (Wangdi 2019).

DISCUSSION

Traditionally, humans have favored soft-fleshed mushrooms for culinary use due to their ease of preparation and palatability. However, certain tough, leathery species, such as *Lentinus squarrosulus*, *Auricularia* spp., and *Schizophyllum commune*, have found a place in the diets of people in regions like China and several African countries. The nutritional richness and health benefits of these mushrooms make them an essential component of traditional folk healing practices (Rammeloo and Walleyn 1993; Härkönen 2002; Okwulehie et al. 2013; Osarenkhoe

et al. 2014; Chelela et al. 2015; Anno et al. 2016; Degreef et al. 2016; Onyango et al. 2016; Paul and Pradhan 2024). Among these, the genus *Auricularia* has gained considerable prominence, especially in East and South-East Asia, being celebrated as a delicacy in countries such as China, Japan, and Korea (Luo et al. 2009; Thakur 2014; Khaskheli et al. 2015; Tabuchi et al. 2021; Wang et al. 2022a). In contrast, *Auricularia* is generally considered bland and is less commonly consumed in the Western world, where it is often associated more with subsistence and ethnomedicine, particularly in Africa (Khan et al. 2016; Milenge Kamalebo et al. 2018).

Understanding the global spread and consumption of *Auricularia* mushrooms is complicated by the ambiguity in mycological literature, which often does not clarify whether a mushroom species categorized as "edible" is actively consumed by local populations (Boa 2004). For instance, while *Auricularia* spp. is classified as edible in studies like Purkayastha and Chandra (1985), local communities may avoid it due to a lack of culinary tradition. The development of mycogastronomy—a cultural practice encompassing the use of mushrooms in local cuisine—plays a vital role in shaping dietary habits. This cultural practice evolves as communities experiment with different edible fungi, not only contributing to subsistence but also providing an additional source of income for mushroom gatherers.

The habitat in which mushrooms are found also influences their culinary use. For example, *Grifola frondosa* thrives in *Lithocarpus* and *Quercus*-dominated forests in temperate montane regions and is unlikely to be consumed by residents of *Shorea robusta* forests in the plains. An interesting case is *Russula senecis*, which grows in both *Shorea robusta* and *Quercus* forests but is consumed only in regions dominated by *Shorea robusta*, where ethnic communities of Austro-Asiatic language family reside. This mushroom is not consumed in *Lithocarpus* or *Quercus*-dominated regions, which are home to Tibeto-Burman populations.

In the Indian subcontinent, leathery or rubbery species of *Auricularia* mushrooms are primarily consumed by Tibeto-Burman communities in the Northeastern states of India such as Assam, Manipur, and Nagaland as well as in Bhutan, Nepal, and parts of West Bengal like Kalimpong. Additionally, *Schizophyllum commune* is consumed by tribal populations in Manipur and Nagaland. This East-West belt of the Indian subcontinent represents a significant region for Oriental mycogastronomy, likely influenced by similar traditions in East and South-East Asia. However, there are notable exceptions, such as among the Khasi tribes of Meghalaya, who do not consume *Auricularia* spp. despite being geographically close. The Khasi, Jaintia, and other Mon-Khmer-speaking groups in India are part of Austro-Asiatic population which also has other Mundari speaking tribes like Lodha, Santal, Munda, suggesting that the absence of *Auricularia* in their diet may be linked to language and cultural heritage.

Further south in Tamil Nadu, the Irula and Kani tribes, part of the Dravidian language family, utilize *Auricularia* spp. for ethnomedicine and consumption, respectively. This raises intriguing questions about the role of subsistence and language in shaping mycogastronomy, as seen in these geographically distant yet culturally distinct tribes. The spread of *Auricularia* consumption in India may not be solely attributed to the influence of Tibeto-Burman groups; it may also be shaped by factors like trade, migration, and shared subsistence patterns with East and South-East Asia.

Despite the limited culinary use of *Auricularia* mushrooms in most parts of India and the absence of commercial farms dedicated to their cultivation (Thakur 2014), the country has made significant strides in research. Studies have focused on developing cultivation protocols (Bhandal and Mehta 1989; Kushwaha et al. 2006; Veena and Pandey 2012; Veeralakshmi et al. 2014), exploring the nutritional properties of the mushrooms (Goyal et al. 2010; Johnsy et al. 2011; Manikandan 2011; Manjunathan et al. 2011; Kumar et al. 2013; Usha and Suguna 2014; Kumari et al. 2015), and investigating their medicinal benefits, particularly their antioxidant properties and ability to activate nitric oxide synthase (Acharya et al. 2004). This body of research paves the way for the potential commercial exploitation of *Auricularia* in India.

Wild edible mushrooms offer numerous benefits to skilled collectors who can identify them and understand their edibility. Currently, the most prized and exported mushroom from the Indian subcontinent, besides *Ophiocordyceps*, is *Morchella* (commonly known as morel, locally *gucchi*), which is highly sought after in Europe and can fetch prices up to INR 5000.00/kg or 57.74 USD/kg (Christensen and Larsen 2005; Prasad et al. 2002). In contrast, *Auricularia* spp., though easily recognizable and available in wild and rural vegetation (Pradhan et al. 2013), are often neglected and not collected for utilization. However, in China, *Auricularia auricula*, which accounts for 90% of global production, is ranked fourth in importance among cultivated mushrooms, following *Agaricus*, *Lentinula* and *Pleurotus*, with its value widely recognized. Studies suggest that *Auricularia* is among the most frequent mushrooms in various wild habitats, with a relative frequency of around 46.8% (Dutta et al. 2013). Therefore, collecting, processing (e.g., cleaning, drying, pickling), and transporting or exporting *Auricularia* mushrooms to areas with high demand could create new income opportunities for rural collectors and cultivators.

CONCLUDING REMARK

Auricularia mushrooms have a long history of cultural, culinary, and medicinal significance, with their extensive domestication in China highlighting their economic potential. While widely integrated into East Asian diets and traditional medicine, their utilization varies across regions, influenced cultural practices and economic factors, and awareness levels. In the Indian subcontinent, their use is prominent among certain indigenous communities but remains limited in broader markets due to gap in broader socio-cultural acceptance and economic barriers. In contrast, western countries show minimal adoption beyond niche health-conscious consumers. Despite this disparity,

Auricularia spp. hold immense potential for expanded commercialization through improved cultivation practices, increased awareness, and strategic marketing. Addressing these challenges could enhance their role in both local and global economies, benefiting rural livelihoods and promoting their broader acceptance. Further research and initiatives aimed at integrating *Auricularia* spp. into diverse culinary and medicinal contexts could unlock significant economic and societal benefits.

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The effect of lateral bank erosion on the mangrove channel of Langkawi Island, Malaysia

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Abstract. *Hashim SS, Abd Aziz KN, Tajam J, Mohd FA, Roslani MA, Kamaruddin SA, Latif ZA, Maulud KNA, Ahmad A, Azahary WAHWM. 2025. The effect of lateral bank erosion on the mangrove channel of Langkawi Island, Malaysia. Asian J For 9: 97-107.* Mangrove forests, essential marine ecosystems that support marine life and economic activities, face threats from natural factors like monsoon seasons and artificial threats of human interventions. The extent of mangroves in channels depends on the hydrological properties of lateral erosion, necessitating a thorough assessment for conservation. This study utilizes erosion pins to observe lateral bank erosion in two different scenes of mangrove channels within Langkawi Island; the pristine (Selat Tuba) and the eventful channel (Sg. Kilim). Findings reveal varying erosion rates (0.03-0.62 m/year) in Sg. Kilim due to monsoon seasons and human activity influences, while Selat Tuba remains stable throughout the monsoon seasons with a ratio of 2.7:1. The study categorizes eroded banks into four distinct types based on erosion patterns across the upper, middle, and lower sections. The spatial differences in erosion types that influence the bank's conditions emphasize the need for tailored conservation approaches. Statistical analyses highlight significant variations in lateral erosion rates in Sg. Kilim underscores the impact of uncontrolled tourism activities. Sustainable management efforts should be prioritized to mitigate lateral erosion, especially in Selat Tuba, where human activities may exacerbate the issue in the future. This research provides valuable insights for coastal resource management, emphasizing the crucial role of maintaining mangrove channel bank stability.

Keywords: Anthropogenic impact, Langkawi, lateral bank erosion, mangrove channel, mangrove forest, monsoon season

INTRODUCTION

Mangrove ecosystems, characterized by a unique blend of terrestrials and marine, are home to numerous marine species and contribute billions of dollars worth of marine products and services to protect coastlines (Khan et al. 2024). Services presented by mangroves include protection from waves and storms, nursery grounds for various sea organisms, and carbon stocks in coastal regions. The mangrove channels of Langkawi Island are a study area that has many-faceted bio-diversity characteristics and a complex ecological environment. Lateral erosion of banks can dramatically modify the physical and biological features of mangrove channels. These roots help hold certain kinds of soil; nonetheless, in case of erosion, the functional structures of mangrove trees disappear and contribute to further coastline erosion (Islam et al. 2024). Some channels may develop within the mangrove areas and are important to the survival of mangrove forests as they are dietary and sediment-based, besides acting as means of transport (McLachlan et al. 2020). Stabilized tidal channels are as useful as stabilized coastal areas, and previous studies proved that mangrove ecosystems are very useful in preventing coastal erosion (Besset et al. 2019; Brunier et al. 2019). Nonetheless, the impact of lateral bank erosion inside and outside the mangrove channels has not been well studied in detail. This also becomes a concern because mangrove channels are anticipated to undergo SLR incidences. These ecosystems are also under numerous natural and anthropogenic pressures, especially lateral bank erosion. Consequently, mangrove ecosystems are increasingly degraded through various anthropogenic activities in areas like urbanization and deforestation, affecting their ability to perform these functions and the human communities that depend on them (Yahaya et al. 2024).

Researchers have noted that high sediment trapped on the mangrove system from upstream erosion reduces light penetration, which is important for the healthy growth of mangroves and affects water quality. Climate change and human-imposed change have led to lateral bank erosion and mangrove alterations. Therefore, understanding the

mechanisms of mangrove erosion will be critical in determining the ability or otherwise of the mangrove ecosystem to withstand future climate change (Kamlun et al. 2024; Roslani 2024; Sahari et al. 2024; Wong et al. 2024). Lateral erosion in mangrove channels can be defined as the slow process of losing the channel edges, and this plays an important role in local geomorphology since erosions are crucial in defining the channel (Li et al. 2021). This gentle but irresistible force of erosion can become the leading parameter by which the health and survivability of the mangrove channels will stand against these challenges. However, such erosions can, in one way or another, be classified as risky if, for instance, it advances the position of land and ecosystems. In this regard, the mangrove area, including the channels surrounding it over the past decades, has also been another commercial center like the tourism sector sustaining a country's focal economic factor and stability (Spalding and Parrett 2019).

Bank erosion may be measured at different temporal frequencies, spatial resolutions, and accuracies that will aid in evaluating and quantifying the different phases of the erosion cycle in lateral bank profiles. Essential documentation of mass failure events can go a long way in determining the comparative relative bank erosion process and evaluation of volume loss (Duró et al. 2018). Relative to this, the erosion pins might prove helpful in measuring the bank erosion processes over vast distances and provide an accurate and reliable method that could be applied in the vegetated mangrove channel (Myers et al. 2019). In this way, the study wants to provide specific findings that are valuable beyond academia and could help interest managers, scientists, and tourism authorities on-site. Therefore, this study sought to establish lateral bank erosion rates and analyze river channels' temporal and spatial variability in mangroves, as well as different monsoon seasons and land use activities. Studying the channel morphology and lateral bank erosion in the coastal mangrove ecosystem of Langkawi Island has not only research importance and general appreciation of these unique ecosystems, but it is critical for the concomitant social, economic, and cultural co-modalities that exist within such an environment.

MATERIALS AND METHODS

Study area

Langkawi is on the northern peninsula of Malaysia, and it is roughly 47,848.36 hectares in size. It is dominated by the climate of the Southeast Asia maritime continent monsoon (southwest monsoon and the northwest monsoon) that compromise of two indistinctive wet seasons (April to June with slight rain of 290 mm/month; July to October with heavy rainfall of 300mm/monthly) and one distinct dry season (November to March with mostly sunny and windy weather) (Mokhtar et al. 2019; Ayob et al. 2020). The marine ecosystem in Langkawi is influenced by the semi-diurnal tide of two high and two low tides of approximately equivalent height every lunar day (Din et al. 2017). Langkawi Island consists of six districts: Kuah, Ayer Hangat, Bohor, Kedawang, Padang Matsirat, and Ulu Melaka. Three primary islands are inhabited: Langkawi, Dayang Bunting, and Tuba Island (Azizan et al. 2018; Nizam et al. 2022). According to Figure 1, three central mangrove forests reside within this area on the island: (i) Kisap Forest Reserve; (ii) Kubang Badak; and (iii) Dayang Bunting Island. Only the mangrove channel in Dayang Bunting Island, namely Selat Tuba (with approximately six sq. km), and the mangrove channel in Kisap Forest Reserves, namely Sungai Kilim (approximately 100 sq. km), were selected in this study where Selat Tuba only has small and insignificant human activity, while Sg. Kilim has highly active human activities (Ismail et al. 2018; Suhaimi et al. 2018; Ibrahim et al. 2019). Both Selat Tuba and Sg. Kilim has similar geomorphological properties but has different intensities in anthropogenic activity. Hence, Selat Tuba is the best fit to represent the impact of monsoon seasons solely on mangrove channels, while Sg. Kilim mangrove channel exemplifies the natural impact of monsoon seasons and anthropogenic activity.

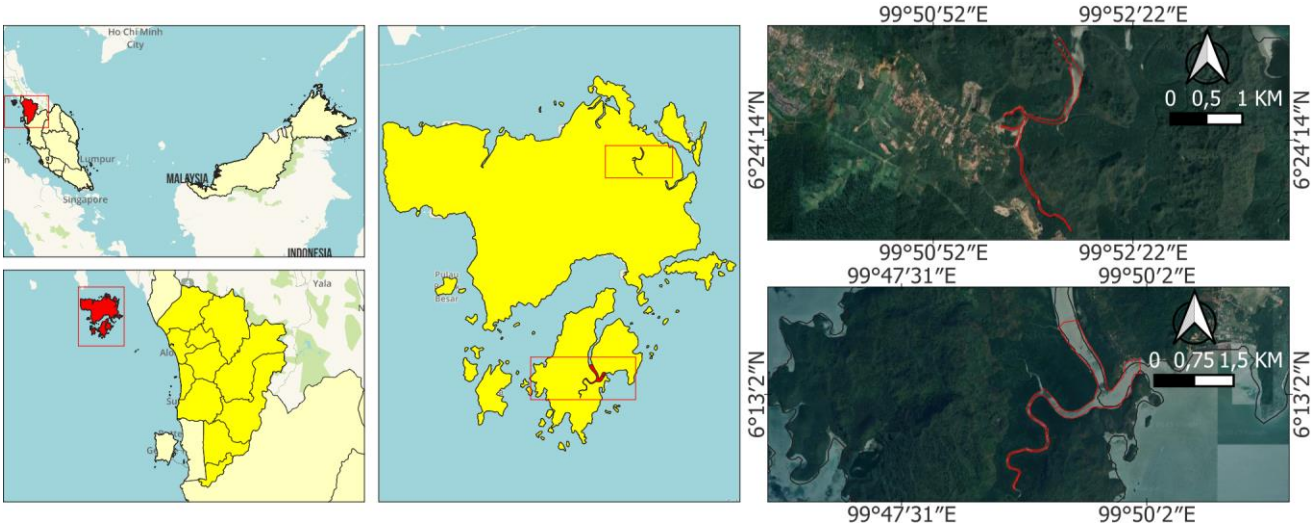


Figure 1. Map showing the location Sg. Kilim (*top right*) and Selat Tuba (bottom right), each influenced by distinct anthropogenic activities in Langkawi Island, Kedah Archipelago, Peninsular Malaysia

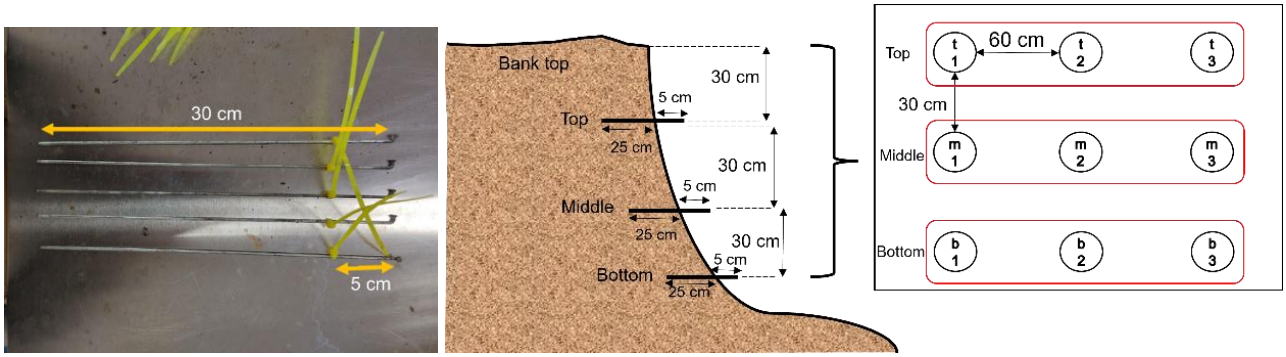


Figure 2. The setting of erosion pins on a 30 cm length metal erosion pins with a 5 cm marker and erosion pins setting on the studied mangrove channel banks. (Adapted from Zhang and Rutherfurt 2020)

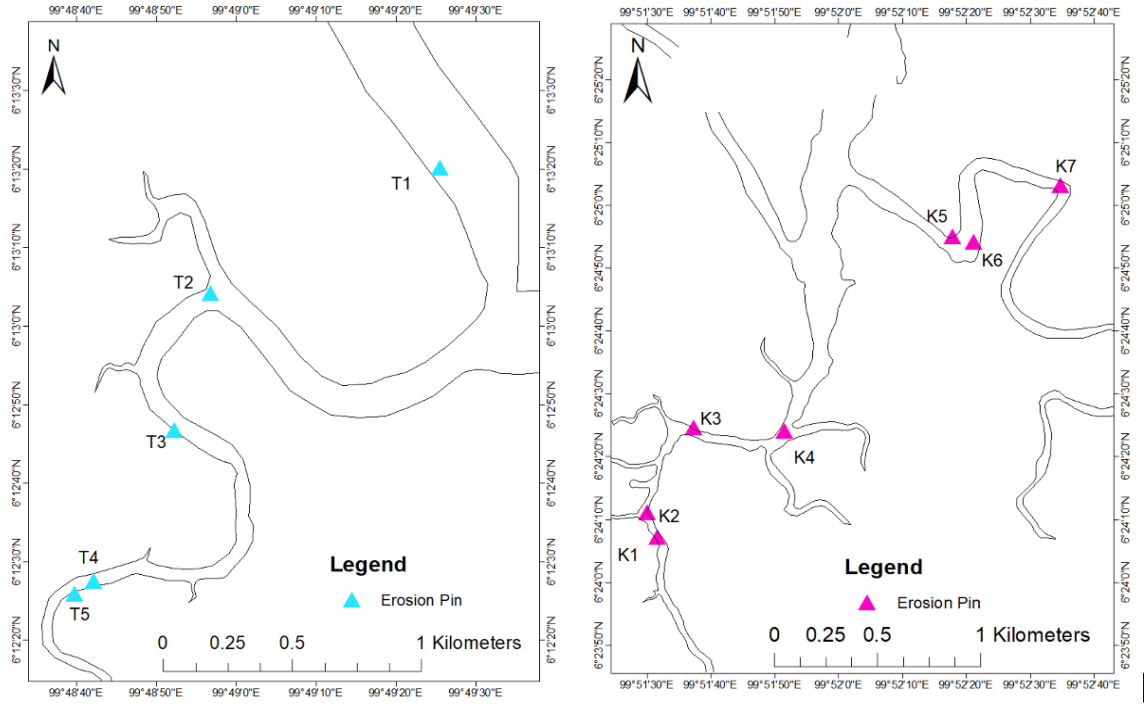


Figure 3. Erosion pin's locations in Selat Tuba and Sg. Kilim sites involved a thorough consideration of channel hydrology, with a specific emphasis on meandering sections where erosion is most prevalent and boat accessibility

Procedures

Erosion pin settings

Field measurements encompass a comprehensive survey of bank erosion to elucidate the erosion rate differences between highly human-active mangrove channels and pristine mangrove channels. Erosion pins are an important, direct, and straightforward method to access initial relative erosion status with minimal cost, not intrusive, and less technical skills are required compared to other complex methods (Myers et al. 2019). This method can help the stakeholders focus on any area that has severe erosion and thus save them time and resources in managing such a vast area (Zhang and Rutherfurt 2020). Therefore, based on Figure 2, this study utilized stainless steel bicycle spokes with dimensions of 30 cm total length and 2.5 mm diameter (Figure 2) as erosion pins, and these were installed at the mangrove channel bank, with 5 cm left exposed on the initial implementation. The erosion pins were systematically installed with height division of top, middle, and bottom based on the bank height and equally spaced for 30 cm each, while the replications of each height were equally spaced for 60 cm from one to another (Figure 2).

Field surveys of the pin erosion length reading were conducted every four intervals within a year based on the monsoon seasons in the area where the exposed pin length was measured with a ruler to the smallest unit of 0.01 cm. After a thorough search in the station, if the pin was not present, the reason was determined in the field as either erosion to the entire length of the pin or accumulation on top of the pin. As illustrated in Figure 3, the methodology for selecting pin erosion sites involved a thorough consideration of channel hydrology, with a specific emphasis on meandering sections where erosion is most

prevalent and considering boat accessibility to ensure a comprehensive approach (Vinh and Truong 2014).

Temporal and spatial erosion rates comparison

In order to investigate whether location, sampling points, bank height level, or season significantly influenced erosion processes, a statistical analysis was conducted to compare temporal and spatial differences between Selat Tuba and Sg. Kilim. Prior to selecting an appropriate test (ANOVA or Kruskal–Wallis), the Shapiro–Wilk test was performed to evaluate the normality of the erosion data. This step ensures that the chosen statistical method aligns with the data distribution, thereby providing a robust measure of the significance of any observed differences in erosion rates. The entire process of this study to investigate the lateral erosion mechanism in two distinct mangrove channels is summarised in Figure 4. Since the response data set is large and multifaceted, Estimated Marginal Means (EMM) were used to analyse responses, patterns, and tendencies concerning different pin placements as well as the different seasons. The EMMs offer enhanced insights into mean differences and trends in erosion rates for each combination of factors, thereby aiding in a more nuanced interpretation of the results.

RESULTS AND DISCUSSION

Lateral erosion rates

The findings reveal notable variations in lateral erosion rates among mangrove channel banks, where it is found that the highest annual lateral erosion rates are 0.62 and 0.61 m/year for Selat Tuba and Sg. Kilim, meanwhile, both study areas have minimum annual lateral erosion of as much as 0.03 to 0.06 m/year for Sg. Kilim and Selat Tuba, respectively. In terms of the seasonal lateral erosion, both inter-season and wet season in Selat Tuba recorded 0.30 m/month, representing the highest reading of lateral erosion on the bank in the area, whereas Sg. Kilim only has inter-season as the highest rates of seasonal lateral erosion (0.30 m/month). The summary of the lateral erosion rates for both Selat Tuba and Sg. Kilim are presented in Table 1.

The results of individual sampling points and in-situ representativeness are further illustrated in Tables 2 and 3. Each table highlights the erosion rate of each season (dry, wet and inter-monsoon) according to the height of the bank level (Figure 2) at two different locations. To summarise the annual erosion activity, the table also provides the annual lateral erosion rate generated from the cumulative seasonal erosion rates throughout the year. Therefore, Table 2 shows more details on the lateral bank erosion rate at Selat Tuba, while a detailed breakdown of the lateral bank erosion rate at Sg. Kilim is provided in Table 3.

Initially, an ANOVA approach was considered for analyzing the erosion rates for the study, but the Shapiro-Wilk test indicated that these data were not normally distributed ($p<0.05$). Consequently, a non-parametric Kruskal-Wallis test was employed to compare erosion levels across categories (location, sampling points, bank height, and season). The Kruskal-Wallis results showed that sampling point was the only significant factor affecting erosion ($p<0.001$). A post-hoc Dunn's test confirmed which specific sampling points differed significantly. In contrast, location, bank height, and season did not exhibit statistically significant effects on erosion ($p = 0.881$, 0.339, and 0.238, respectively). These findings suggest that lateral erosion rates did not vary significantly across different seasons and bank height division in the studied area.

However, the Estimated Marginal Mean (EMM) results revealed interesting nuances, particularly in the comparison between Selat Tuba and Sg. Kilim. Contrary to the general trend observed across the other bank zonation, Selat Tuba exhibited an inverse pattern compared to Sg. Kilim observed higher erosion at the bank middle and bottom zones in the wet season. Meanwhile, Sg. Kilim exhibited higher lateral rates in dry and inter-seasons compared to the wet season, with the bottom zone dominating the lateral erosion. This discrepancy between Selat Tuba and Sg. Kilim is visually evident in the EMM graph, where the inverse patterns are depicted in Figure 5. This underscores the importance of utilising EMMs for a more nuanced interpretation of the data, as overall statistical tests may overlook specific trends. The lack of statistical significance for the main effects in the Kruskal-Wallis test suggests that while Selat Tuba and Sg. Kilim may exhibit different erosion patterns; these differences are not statistically significant when considering the entire dataset.

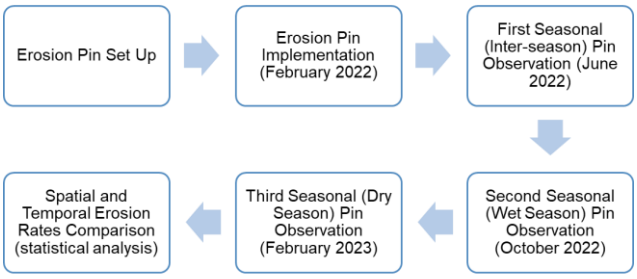


Figure 4. The study design map shows one year's worth of corrosive work within the mangrove channels to demonstrate the temporal progression and spatial dynamics of the investigated mangrove environment

Table 1. Summary of lateral erosion rates observed with erosion pins for both study areas focusing on stations with the lowest and highest erosion records.

	Selat Tuba			
Lateral erosion rates	**Inter-season (m/month)**	**Wet Season (m/month)**	**Dry Season (m/month)**	**Annual (m/year)**
Max	0.30 (T3)	0.30 (T1)	0.27 (T1)	0.62 (T1)
Min	0.00 (T3)	0.04 (T3)	0.01 (T2)	0.06 (T3)
	Sg. Kilim			
Lateral erosion rates	**Inter-season (m/month)**	**Wet Season (m/month)**	**Dry Season (m/month)**	**Annual (m/year)**
Max	0.30 (K3)	0.21 (K1)	0.25 (K5)	0.61 (K3)
Min	0.00 (K7)	0.01 (K7)	0.01 (K4)	0.03 (K7)

Table 2. Lateral erosion rates of Selat Tuba on top, middle and bottom sections with relation to in-situ bank conditions

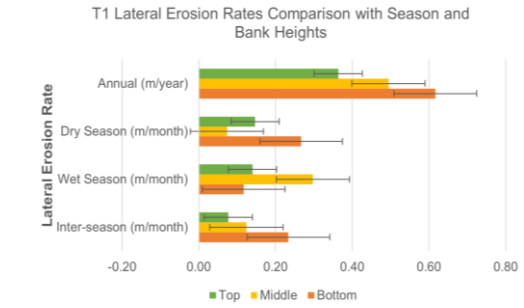
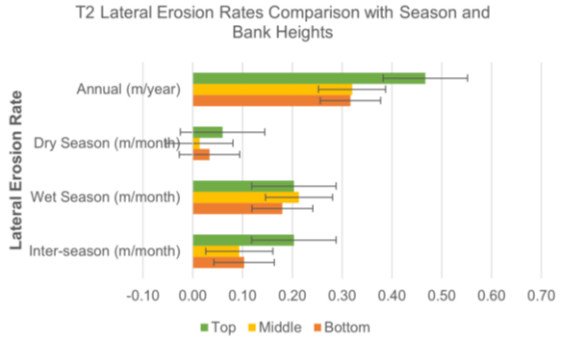
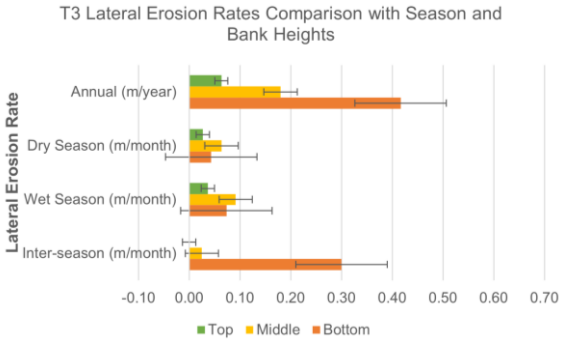
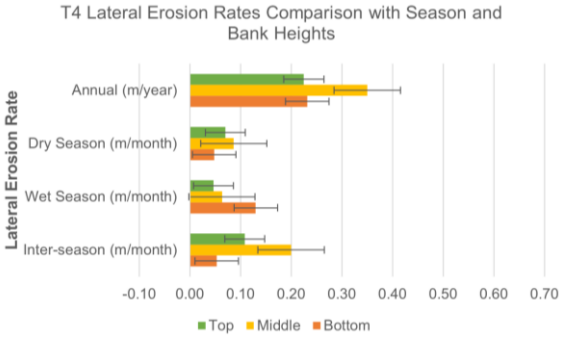
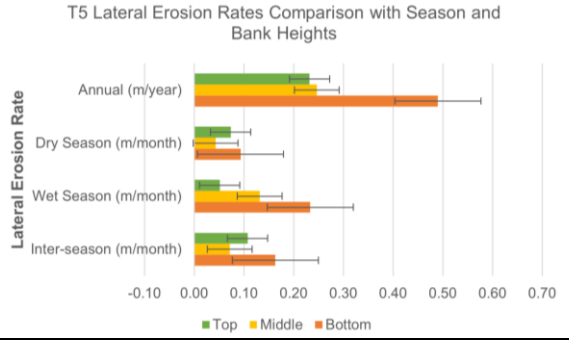
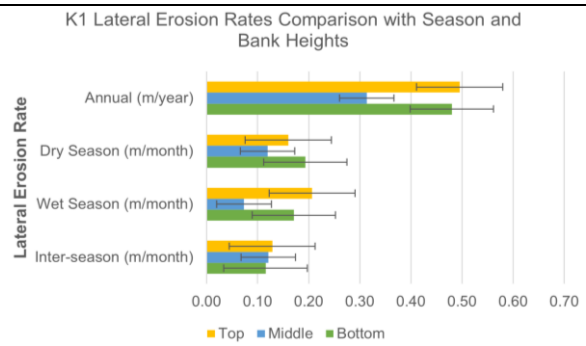
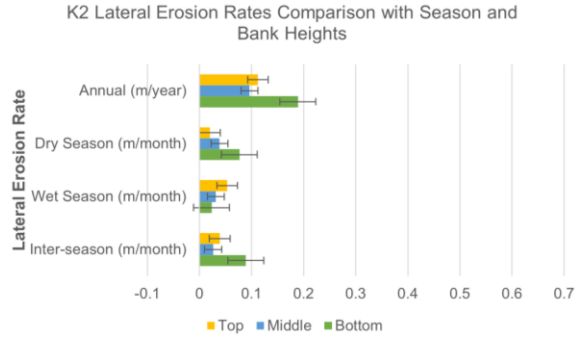
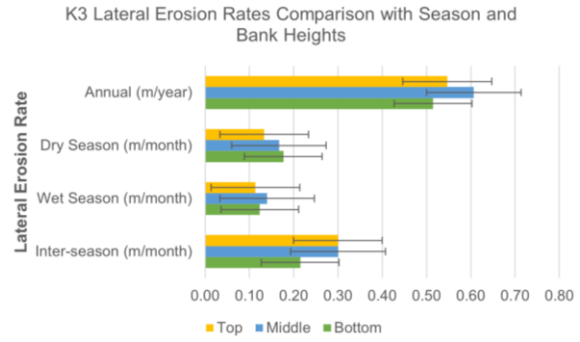
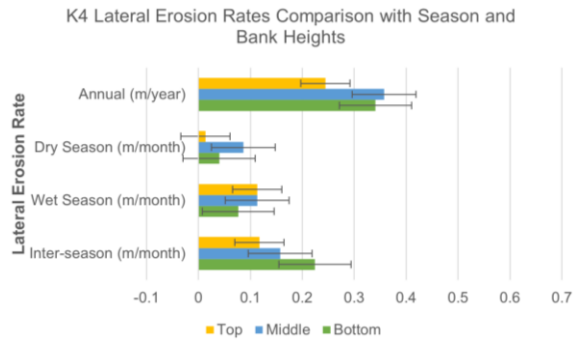
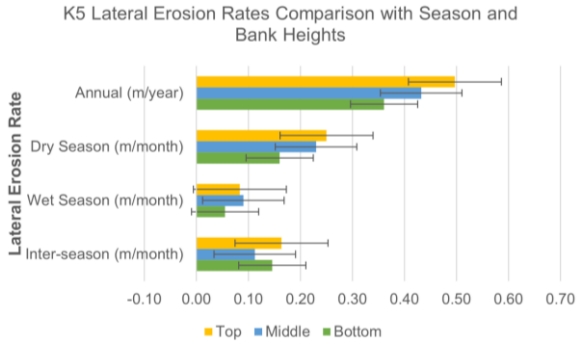
Lateral erosion rates with respective bank zones	**In-situ bank conditions**
	
	
	
	
	

Table 3. Lateral erosion rates of Sg. Kilim is on top, middle, and bottom sections with relations to in-situ bank conditions

Lateral erosion rates with respective bank zones	**In-situ bank condition**
	
	
	
	
	

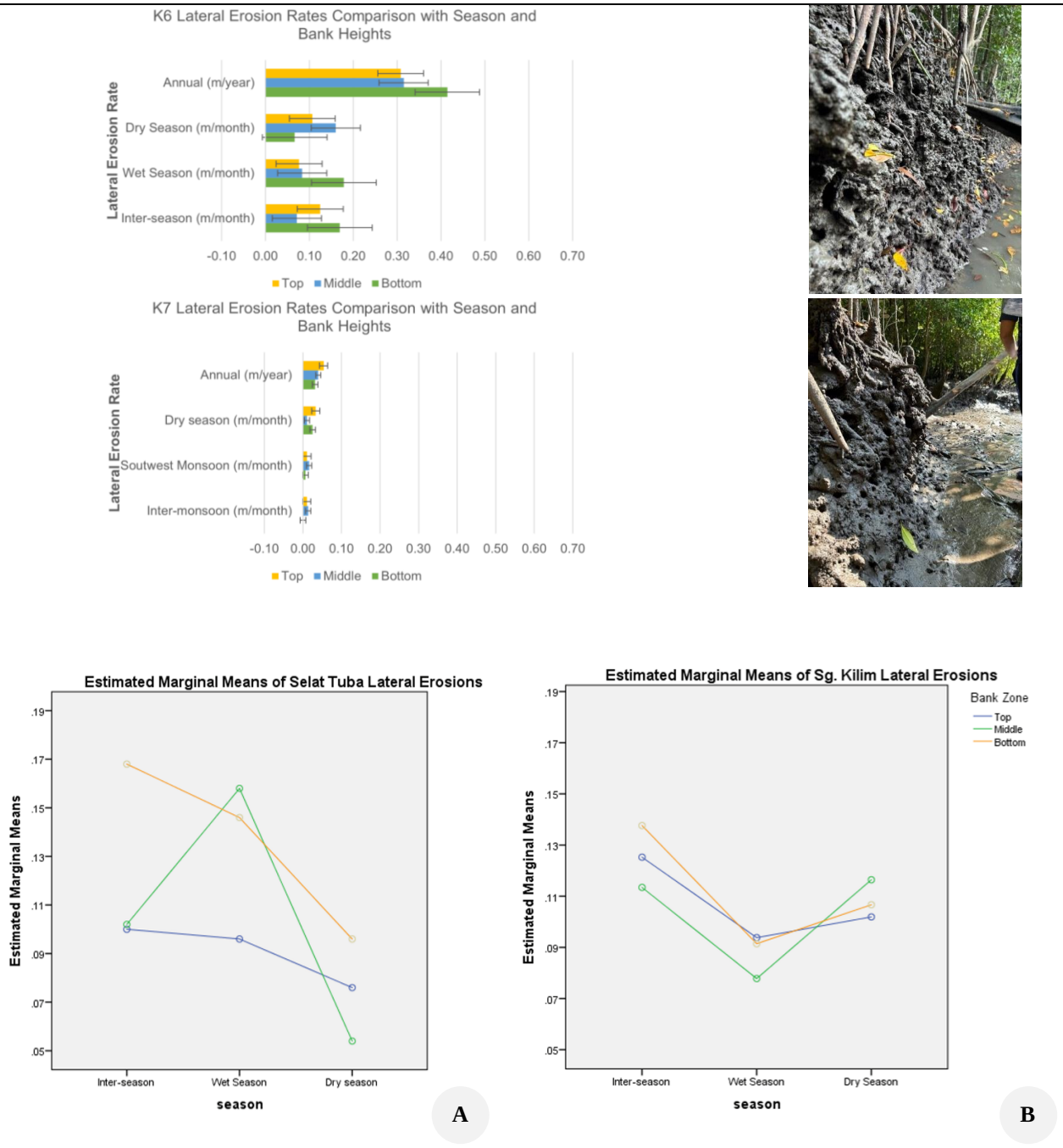


Figure 5. Estimated Marginal Mean (EMM) of A. Selat Tuba; and B. Sg. Kilim lateral erosion across the seasons and bank zonation

The study also observed some of the erosion patterns exhibited by the mangrove channel banks and attempted to categorize them into several types of categories. Mangrove channel bank conditions are distinguished by distinct types that are intricately shaped by a variety of hydrological properties prevalent in the surrounding area. Understanding the complex dynamics that govern these critical coastal ecosystems requires the classification of erosion types. Figure 6 depicts a visually intuitive representation of the different types of mangrove channel banks based on annual erosion process dominance in various zones of mangrove channel banks. An estimated four types of erosion patterns were identified, and the dominant erosion at different heights of bank level drives the pattern and final shape of the channel banks.

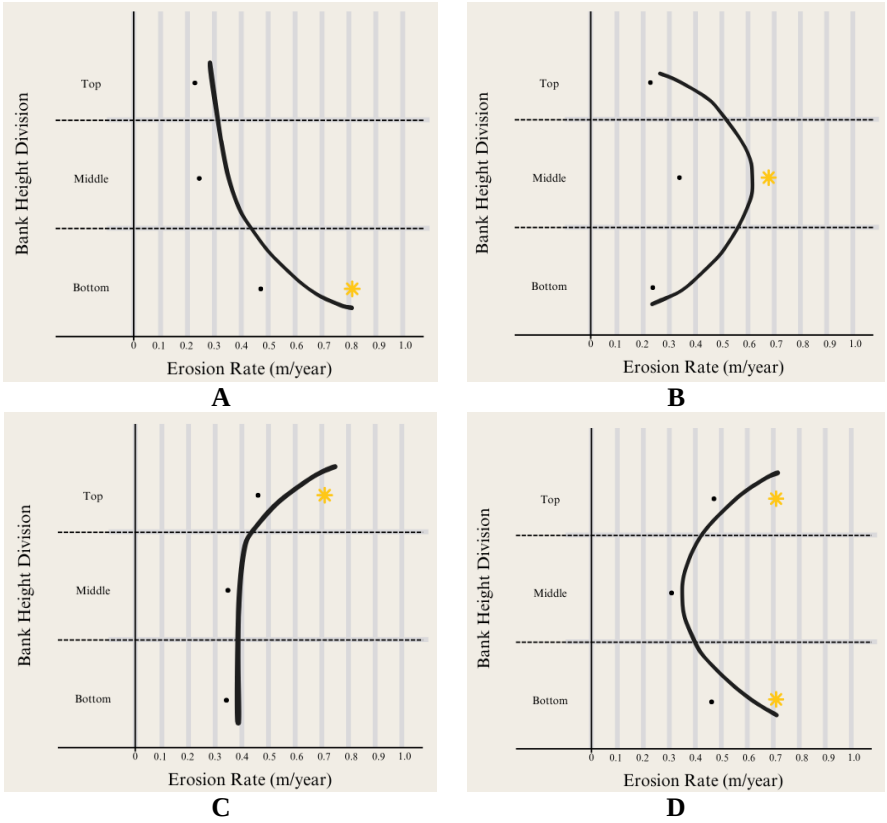


Figure 6. Lateral erosion trends in Selat Tuba and Sg. Kilim is classified into four types where: A. is type (example from T5); B. type ii (example from T4); C. type iii (example from T2); and D. type iv (example from K1), and the asterisk (*) defines the dominant zone of erosion, where type i has bottom erosion zone dominated, type ii is middle erosion zone dominated, type iii has top erosion zone dominated, and type iv have both top and bottom erosion zone dominated

Discussion

T1 in Selat Tuba is seen to be mainly experiencing the fluvial erosion of being located at the intersection of the open water area of Tuba Straits and the mangrove channel; thus, it is experiencing undercutting phenomena for a year cycle, where the bottom erosion is exceeding other erosion in the bank. This has led to a visible effect where bank failure has happened in this area, impacting the mangrove tree on the bank to be uprooted as well (Figure 7). Therefore, the distance from the coastal and open water is seen to be one of the natural factors influencing rates of lateral erosion in mangrove channels, and these rates can be amplified with the SLR, leading to the increasing vulnerability of mangroves at the station (Di Nitto et al. 2014). Meanwhile, another lateral erosion is less than 0.25 m/month across the season for all the bank zones in Selat Tuba station except T3 in inter-season, where the bottom zone experienced 0.30 m/month. This is due to T3 being located on high velocities of water flow in the outer bend of the channel (Engel and Rhoads 2017).

Conversely, in Sg. Kilim, which is famously known as an ecotourism destination, has relatively high lateral erosion, mainly during the dry season (November – March) and inter-seasons (April – June) where these are the peak periods for tourism to experience higher visitors in this area due to less rainfall, sunny and windy weather in Langkawi Island (Sapari et al. 2013). Thus, this area is experiencing a high number of visiting tourists, and indirectly, there is an increase in boating frequencies, which causes boat wakes to interact with channel banks and lead to erosion (Novak et al. 2021). This can be seen in K3 of Sg. Kilim, which is located near the boat jetty, experiences up to 0.30 m/month of lateral erosion for both top and middle zones in the respective inter-season and dry seasons.

Additionally, despite the wet season, which has relatively higher rainfall, K5 in Sg. Kilim also has higher lateral erosion rates in dry and inter-seasons (0.25 and 0.15 m/month), where this anomaly can be attributed to the location serving as a primary route for tourism activities, with boats frequently engaging in engine revving to attract eagles for feeding, causing the banks to experience the impact of this activity. Notably, K7 is also located along the same channel in Sg. Kilim experiences relatively mediocre lateral bank erosion throughout the one-year cycle (< 0.5 m/year) compared to other stations in the area. This disparity can be linked to the lower frequency of boat activities in the proximity of this station.

The variations of bank conditions are due to the geography of the location of the bank, where outer bends normally have the variation type i (T1, T3, T5, and K6) due to the higher water velocities in this area. Meanwhile, inner bend channels tend to have type iii (T2, K5, K7), signifying lower water velocities and allowing sediment to settle in this area (Hooke 2013; Li et al. 2021). Alternatively, straight channels tend to have type ii (T4), where the lateral erosion in this area is the initialization of channels to

transform into meandering and stabilize. However, K3 and K4 have similar type ii bank conditions despite being located on outer bends, and these sections are reported to have the highest lateral bank erosion in Sg. Kilim (~0.60 m/year). This high erosion rate is proven previously by the high wave energy traveling reported through the boating activities and causing the widening of the channel and bank shifting, indicated by the loss of mangrove territory in the area, which is also a sign the erosion process in the region is exceeding the plant anchoring power (Mohamad et al. 2018; Suhaimi et al. 2018; Kibler et al. 2022). These unusual bank conditions are further explained by the accumulated sediment from bank failure at the bank toe where when the bank collapses, the failure bank material fills up the bank toe by gravity, and this may be carried away by flow or remain deposited on the toe of the bank. According to Figure 8, this theory is demonstrated in Hasegawa (1981), where the bank failure processes can be estimated using a simple assumption that it occurs when the volume of zone A (sediment supply due to bank erosion) becomes equal to that of zone B (deposition).

The mangrove roots mainly dominated in the A area (Figure 8) where traveling water velocities are slowed down during the high tides, causing less erosion process, explaining the less prominent lateral erosion on the top region of the same K3 and K4 station (Arnold and Toran 2018; Kazemi et al. 2021). However, when the tides recede (ebb tide), or advance (flood tide) where the water levels are below the mangrove roots (middle area), the study observed that the erosion amplified with the traveling water and boat wakes impact without protection from mangrove roots and presence of bioturbation activities, explaining how erosion dominated the middle section. Meanwhile, type iv bank conditions are where the bank experiences fluvial erosion (undercutting) on the bottom bank zone but also aerial erosion (top bank zone), and this can significantly come from boat wake impact and sediment properties, where this type only can be seen as illustrated in Figure 9 at station K1 and K2 that is dominated with coarse gravels on the bank toe.

The variation of lateral channel bank erosion rates in this area is seen to be mainly resulting from three processes: (i) fluvial erosion caused by channel flow's lift and drag; (ii) subaerial erosion caused by dynamic soil moisture conditions, which is defined as weathering and weakening of bank material; or (iii) mass failure of the upper part of the bank due to gravity (Imanshoar et al. 2012). The observed erosion rate differences in the studied area highlight the importance of considering bank zonation in mangrove channel vulnerability assessments, emphasizing the need to consider the bank erosion profile to assess the vulnerability of the mangrove channel bank for tailored conservation and restoration strategies.

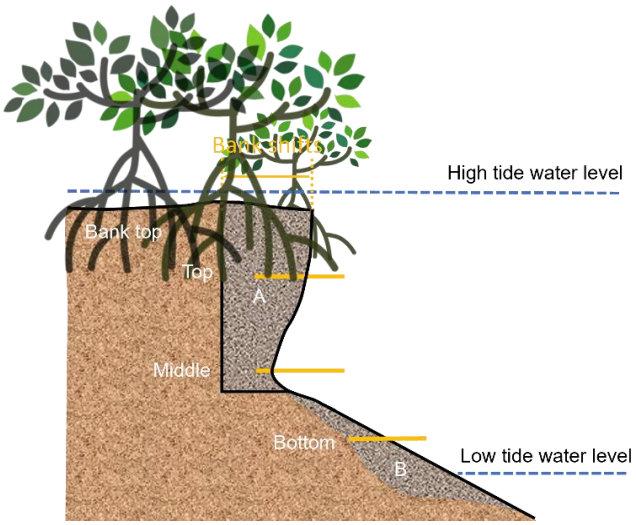


Figure 8. Bank shifting events are based on bank failure theory, where area B accumulates from the failure of area A with vegetation present (Adapted from Hasegawa 1981)

A **B**

Figure 7. A sediment cluster was found near the bank's bottom with: A. An erosion pin detached with it, indicating the bank failure; and B. Mangrove tree uprooting due to the bank failure at station T1

A B

Figure 9. Different bank sediment compositions at: A. K1; and B. K2 cause unique bank conditions, categorized as type iv, that influence the lateral bank erosion patterns

Following that, annual lateral erosion rates in Selat Tuba are seen to be significantly lesser than Sg. Kilim in the dry season has a ratio of 1:2.7, and this can be explained by the increased number of boat frequencies reported by the Langkawi Development Authority (LADA 2023) in Sg. Kilim during this season (November to March). This further signifies that the boating frequencies can suggestively alter and amplify the lateral erosion rates within the area, highlighting the impacts of tourism on mangrove ecosystems. Even though Selat Tuba is close to the open water, it exhibits relatively similar erosion rates despite differing human activities in the respective areas. This implies that in the case of increased human activities in the future, there might be possibilities for worse lateral erosion rates, hence a threat to both the extent and value of mangroves in the area. Hence, the significance of this work is in underlining the need to enhance the management of tourist destinations so that any future tourist development strategies would be sensitive to the problem of lateral erosion in the region.

In conclusion, this research provides further critical and essential information about lateral erosion dynamics of mangrove channels, explicitly focusing on the importance of zonation of channel banks to the sustainability of the mangrove systems. This study also suggests that seasonality contributes to influencing erosion rates, especially in Sg. Kilim, the erosion rates in the area can be amplified with the increase in human activity. The stability of mangrove channel banks becomes not just an ecological concern but a matter of strategic importance for those tasked with managing coastal resources and fostering sustainable practices. Future suggestions include the sediment budget and channel hydrology model development to understand the impact of monsoon seasons, sea level rise, and anthropogenic activity comprehensively on mangrove channels and facilitate the survivability of mangrove ecosystems.

ACKNOWLEDGEMENTS

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Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia

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Abstract. *Setyasih DMD, Putri RAS, Raharjo YAA, Izdihar RS, Kusumaningrum L, Setyawan AD. 2025. Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia. Asian J For 9: 108-114.* Forests are ecologically significant landscapes characterized by tree cover and high biodiversity. They play an important role in carbon sequestration and storage, contributing to climate regulation. Tawangmangu sub-district with its significant portion of forest land holds considerable potential for carbon sequestration. This study aims to assess the carbon storage potential and tree species composition in three villages within the Tawangmangu sub-district—Plumbon, Nglebak, and Sepanjang. Data were collected using a random sampling technique, with 20 plots (20 × 20 m) established at each site. Data such as identification of species and the circumference of each tree were measured. The collected data were analyzed using the Shannon-Wiener diversity index, biomass index, and carbon storage potential. A total of 30 tree species from 18 families were identified across the three villages, with the Fabaceae family being the most dominant. The species diversity index (H') values were 2.147 for Plumbon, 1.278 for Nglebak, and 2.456 for Sepanjang, indicating moderate species diversity and relatively stable ecosystem productivity. Biomass calculations revealed values of 462.81 kg/ha in Plumbon, 807.28 kg/ha in Nglebak, and 145.13 kg/ha in Sepanjang. Corresponding carbon stock estimates were 212,892 kg in Plumbon, 371,348 kg in Nglebak, and 66,759 kg in Sepanjang. The data indicate a positive correlation between biomass and carbon stock values. The variation in carbon storage across sites is likely influenced by species composition and site-specific ecological factors affecting carbon sequestration efficiency.

Keywords: Allometric equation, biomass, carbon sequestration, Central Java, tree diversity

INTRODUCTION

The Food and Agriculture Organization of the United Nations (FAO) defines a forest as a land area exceeding 0.5 hectares, with a tree canopy cover of more than 10% and a minimum tree height of 5 meters (Qin et al. 2021). Forests play a crucial role at local, regional, and global scales, supporting an estimated 1.6 billion people by providing livelihoods and income opportunities (Frick et al. 2018; Mukul et al. 2020). In addition to serving as habitats for diverse plant and animal species, forests offer essential ecological services, including climate regulation, carbon sequestration, biodiversity conservation, and oxygen production (Nurrochmat and Abdulah 2014). Furthermore, forests contribute to economic growth through the sustainable use of biodiversity resources (Mayasari et al. 2024).

Forests play a vital role in soil protection, preventing erosion, regulating atmospheric oxygen, and capturing and storing atmospheric carbon (Oulaana et al. 2023). Their ecological, economic, and social functions make them indispensable to maintaining environmental stability and supporting human well-being (Guntur et al. 2023). However, despite their ecological and economic significance, forest ecosystems face increasing threats from anthropogenic activities, including deforestation and forest degradation. Major drivers of forest loss include agricultural expansion, encroachment, and land-use conversion (Wahyuni and Suranto 2021). Deforestation is responsible for approximately 18-20% of global anthropogenic greenhouse gas (GHG) emissions (Mwakalukwa et al. 2023), contributing significantly to climate change. The loss of forest cover reduces carbon reserves, further exacerbating atmospheric carbon accumulation (Sumarlin et al. 2021).

Forests play a key role in climate change mitigation by absorbing and storing atmospheric carbon (Arianasari et al. 2021). Carbon sequestration occurs through photosynthesis, wherein plants absorb atmospheric carbon alongside water, facilitated by chlorophyll and sunlight (Rizaldi et al. 2021; Kusumaningrum and Izdihar 2022). Absorbed carbon is subsequently converted into organic matter and stored in biomass, with approximately 47% of total biomass consisting of carbon (Susanto et al. 2021; Fadillah et al. 2023). Over time, a portion of this stored carbon is released back into the atmosphere, contributing to the dynamic carbon cycle (Matuszkiewicz et al. 2021). Carbon stocks refer to the total amount of carbon stored in forests and other ecosystems, with fluctuations influenced by human-induced landscape modifications and vegetation changes (Selvia et al. 2023). Forest degradation diminishes carbon sequestration capacity, intensifying climate change effects (Nedhisa and Tjahjaningrum 2019). The live biomass

structure of a degraded forest is considerably altered, with proportionately more stems and coarse roots, and less leaves and fine roots, compared to a normal forest which may cause the lower carbon sequestration of the degraded forest than the undisturbed forest (Pandey et al. 2020). Therefore, quantifying carbon stocks is crucial for assessing forest health and the impacts of deforestation and degradation (Mauya et al. 2019). The carbon storage potential of forests is influenced by multiple factors, including stand density, aboveground biomass, species composition, and forest type (Choden et al. 2021).

Indonesia is one of the Southeast Asian countries with diverse topography. Tawangmangu Sub-district, located in Karanganyar District, Central Java, Indonesia has a mountainous topography due to its position on the slopes of Mount Lawu (Irianto et al. 2022). These environmental conditions support agroforestry practices, making the region suitable for horticultural crop cultivation, including fruit and vegetable farming (Negari et al. 2023). While a significant portion of forest land remains intact in Tawangmangu, it serves both ecological and economic functions for local communities. Given the extent of its forest cover, Tawangmangu sub-district holds considerable potential for carbon sequestration. This study aims to quantify carbon storage in three villages within the sub-district—Plumbon, Nglebak, and Sepanjang—and to identify the dominant tree species contributing to carbon sequestration in these areas.

MATERIALS AND METHODS

Study area

The research was conducted in March 2024 in three villages within Tawangmangu Sub-district, Karanganyar District, Central Java Province, Indonesia, i.e.: Plumbon Village (-7.652017°S, 111.102693°E), Nglebak Village (-7.666431°S, 111.107943°E), and Sepanjang Village (-7.676738°S, 111.103774° E) (Figure 1). These villages are situated at the foothills of Mount Lawu and are located at similar altitudes, with Plumbon Village at 781 meters above sea level (m asl.), Nglebak Village at 863 m asl., and Sepanjang Village at 927 m asl. (Dinas Kominfo Kabupaten Karanganyar 2019). Geographically, the research area is positioned at approximately 7°36'43"S and 111°3'27"E, covering a total area of 70.03 km² (Dinas Kominfo Kabupaten Karanganyar 2019). Tawangmangu Sub-district is characterized by hilly terrain with steep slopes and extensive forest cover (Sihombing and Agustinus 2023). The region experiences a cool climate, with nighttime temperatures ranging from 8 to 12°C and daytime temperatures fluctuating between 15 and 30°C (Prasetyo 2023). The area receives an average annual rainfall of 7,231.4 mm, with peak precipitation occurring between February and April (Shobirin 2020).

Procedures

In this study, primary data were collected through direct field observations. The data collection employed a random sampling method using 20 × 20 cm plots for tree measurements (Mwakalukwa et al. 2023), with a total of 60 plots across the research sites. Specifically, 20 plots were established in Plumbon Village, 20 in Nglebak Village, and 20 in Sepanjang Village. Within each plot, tree species were identified, and the circumference of each tree was measured. Trees classified at the tree level had a diameter greater than 20 cm (Haryadi 2017). The random sampling method is a statistical technique used to select a subset of data that is representative of a larger population. This approach ensures that each member of the population has an equal probability of being selected, thereby minimizing bias (Iliyasu and Etikan 2021).

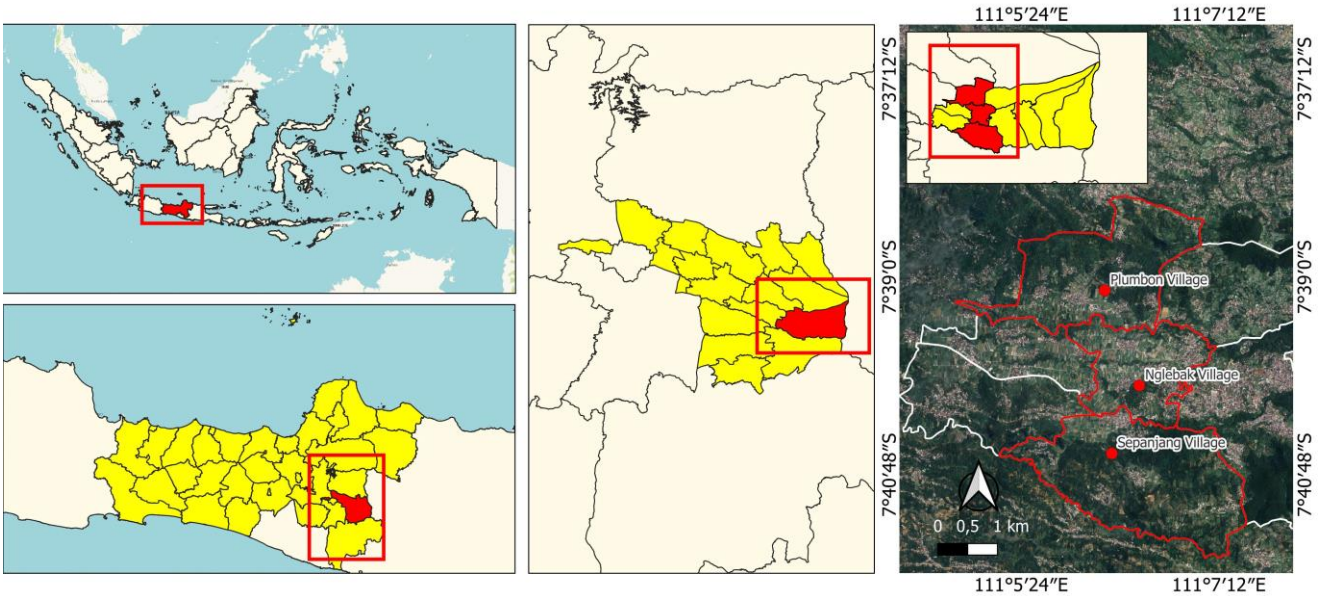

Figure 1. Research location in Tawangmangu Sub-district, Karanganyar District, Central Java, Indonesia: A. Plumbon VIllage, B. Nglebak Village, C. Sepanjang Village

Table 1. Biomass calculation formulas for certain species

Species	Allometric equation	Reference
Pinus merkusii Jungh. & de Vriese	$B = 0.0936 \times D^{2.4323}$	Siregar (2021)
Schima wallichii (DC.) Korth.	$B = 0.0936 \times D^{2.4323}$	Suhendang (2002)
Toona sureni (Blume) Merr.	$B = VK \times 390$ kg/m^3; $VK = 0.00013 \times D^{2.057}$	P3HH (2008)
Swietenia mahagoni (L.) Jacq.	$B = 0.048 \times D^{2.68}$	Adinugroho and Sidiyasa (2006)
Artocarpus heterophyllus Lam.	$B = 0.1792 \times D^{2.25112}$	Brown (1997)
Tectona grandis L.f.	$B = 0.370 \times D^{2.125}$	Aminudin (2008)
Acacia mangium Willd.	$B = 0.134741 \times D^{2.38}$	Irawan et al. (2020)

Data analysis

The collected data were analyzed to determine the diversity index and the potential carbon storage.

Index of diversity

The diversity index is a quantitative measure used to assess species richness and evenness within a given area or population (Augousti et al. 2021). Vegetation diversity was evaluated using the Shannon-Wiener index (Odum 1971):

$$\text{Index of Diversity (H')} = \Sigma \left[\frac{ni}{N} log \frac{ni}{N}\right]$$

Where:
ni : Number of individuals of a species
N : Total number of individuals of all species

Shannon-Wiener species diversity level:
H' < 1 : Low diversity
1 < H' < 3 : Medium diversity
H' > 1 : high diversity

Biomass

Biomass refers to the total dry weight of organic matter, expressed in kilograms or tons. Estimating the carbon stored in a tree requires first determining its biomass. Different species exhibit varying allometric relationships, necessitating species-specific allometric equations for accurate biomass estimation. The allometric equations for selected species identified in the study area are presented in Table 1.

For species lacking a specific biomass estimation formula, the allometric equation developed by Brown (1997) can be applied to estimate the biomass of trees growing in humid tropical regions:

$$B = \exp [-2.134 + 2.53 \ln (D)]$$

Where:
B : Biomass (kg)
D : Diameter of tree (cm)

To determine the biomass in a specific area, the formula by Danarto (2020) was used:

Biomass per unit area = Total Biomass (kg)/ Area (ha)

Carbon storage potential

According to Hairiah and Rahayu (2007), carbon stocks are estimated from biomass, with approximately 46% of the total biomass considered as carbon. Thus, the amount of stored carbon is estimated by multiplying the biomass by 0.46. The calculated carbon stock, initially expressed in kilograms, was then converted into tons for standardization.

Stored carbon = Biomass per unit area × 0.46

RESULTS AND DISCUSSION

Vegetation found in community forest area

Vegetation refers to the assemblage of tree species within a specific location, where interactions occur between different species, environmental conditions, and other living organisms (Agustina et al. 2022). In this study, 30 tree species belonging to 18 families were identified across 20 plots in Plumbon Village, Nglebak Village, and Sepanjang Village. The Fabaceae family had the highest species representation, with six species recorded. A comprehensive list of tree species found in the research area is presented in Table 2.

The tree species identified at the research site contribute to the composition and vegetation structure, providing ecological and economic benefits to the local community (Safitri et al. 2018). The study area, located on the slopes of Mount Lawu, contains vegetation that plays a crucial role in maintaining soil stability and preventing landslides (Indrajaya and Handayani 2008). In addition to their role in soil conservation, several tree species, such as pine (*Pinus merkusii* Jungh. & de Vriese), teak (*Tectona grandis* L.f.), acacia (*Acacia decurrens* (J.C.Wendl.) Willd.), and mahogany (*Swietenia mahagoni* (L.) Jacq), are valuable for timber production, serving as raw materials for furniture and paper manufacturing (Asmaini et al. 2023). The local community also cultivates fruit-bearing trees, including durian (*Durio zibethinus* L.), jackfruit (*Artocarpus heterophyllus* Lam.), mango (*Mangifera indica* L.), and avocado (*Persea americana* Mill.), primarily for fruit production. This practice has led to increased tree diversity within the research site. According to Table 2, the most abundant tree species in Plumbon Village was mahogany (*Swietenia mahagoni* (L.) Jacq), with 90 recorded individuals, while the least common species—*Alstonia scholaris* (L.) R.Br. (*pulai* tree), *Syzygium myrtifolium* Walp. (*pucuk merah* tree), *Terminalia catappa* L. (*ketapang* tree), and *Carica papaya* L. (*papaya* tree)—had only one individual each. In Nglebak Village, pine (*Pinus merkusii* Jungh. & de Vriese) was the dominant species, with 168 individuals, whereas *Alstonia scholaris* (L.) R.Br.

(*pulai* tree) and *Leucaena leucocephala* (Lam.) de Wit (*Petai cina* tree) were the least common, each represented by a single individual. In Sepanjang Village, the most frequently encountered species was *Toona sureni* (Blume) Merr. (Suren tree), with 47 individuals, while the least abundant species—*Breynia androgyna* (L.) Chakrab. & N.P.Balakr. (*katuk* tree), *Persea americana* Mill. (avocado tree), *Alstonia scholaris* (L.) R.Br. (*pulai* tree), *Mangifera foetida* Lour. (*pakel* tree), and *Mangifera indica* L. (mango tree)—each had only one recorded individual. Mahogany and pine trees dominate the area due to their adaptability to colder climates and high rainfall conditions, making them suitable for widespread cultivation. These species are frequently incorporated into agroforestry systems as shade trees. In contrast, less dominant tree species are mainly found in community gardens, where tree diversity is higher compared to monoculture plantations.

Tree diversity in Plumbon Village and Sepanjang Village exhibits relatively similar Shannon-Wiener diversity index values. However, Nglebak Village has a significantly lower diversity index compared to the other two locations. The species diversity in all three areas falls within the moderate diversity category, with values in the range of $1 < H' < 3$. Sepanjang Village recorded the highest species diversity with an H' value of 2.456, followed by Plumbon Village at 2.147, while Nglebak Village had the lowest diversity at 1.278. A higher number of species in an area generally corresponds to greater species diversity (Setiarno et al. 2020). Sepanjang Village contained 21 plant species, Plumbon Village had 20 species, and Nglebak Village had the least, with 13 species. Species diversity is influenced by plant distribution patterns and the adaptability of species within an area (Sari and Mukti 2019). The moderate species diversity observed across the three research locations suggests sufficient productivity (Amarullah et al. 2017) and indicates that the ecosystem remains relatively stable with moderate ecological pressure (Prastiyo et al. 2019). Additionally, environmental factors such as light availability, soil pH, temperature, and pollution levels also influence plant diversity in the study area (Sihombing et al. 2024). Generally, a higher diversity index corresponds to greater stability within the tree community. However, high species diversity does not necessarily correlate with increased carbon storage potential (Ananda and Sutrisno 2022). This is because carbon sequestration values are not directly influenced by vegetation diversity (Salina 2019).

Diversity index (H') in the community forest area

The calculation of tree diversity shows different results in each research location (Table 3).

Table 2. Composition of tree vegetation in the forest area of Plumbon, Nglebak, and Sepanjang Villages, Tawangmangu, Karanganyar, Indonesia

Scientific name	Local name	Family	Amount of vegetation		
			Plumbon	Nglebak	Sepanjang
Pinus merkusii Jungh. & de Vriese	*Pinus*	Pinaceae	11	168	13
Swietenia mahagoni (L.) Jacq.	*Mahoni*	Meliaceae	90	17	0
Toona sureni (Blume) Merr.	*Suren*	Meliaceae	46	15	47
Durio zibethinus L.	*Durian*	Malvaceae	3	7	9
Acacia decurrens (J.C.Wendl.) Willd.	*Akasia Gunung*	Fabaceae	0	5	0
Artocarpus heterophyllus Lam.	*Nangka*	Moraceae	8	2	10
Tectona grandis L.f.	*Jati*	Lamiaceae	11	0	12
Cocos nucifera L.	*Kelapa*	Arecaceae	3	3	5
Acer laurinum Hassk.	*Huru bodas*	Sapindaceae	6	0	10
Mangifera indica L.	*Mangga*	Anacardiaceae	3	0	1
Carica papaya L.	*Pepaya*	Caricaceae	1	0	0
Hibiscus tiliaceus L.	*Waru*	Malvaceae	7	3	32
Terminalia catappa L.	*Ketapang*	Combretaceae	1	0	10
Mangifera foetida Lour.	*Pakel*	Anacardiaceae	0	0	1
Syzygium myrtifolium Walp.	*Pucuk merah*	Myrtaceae	1	2	2
Gmelina arborea Roxb. ex Sm.	*Jati putih*	Lamiaceae	3	0	0
Parkia speciosa Hassk.	*Petai*	Fabaceae	9	0	40
Gnetum gnemon L.	*Melinjo*	Gnetaceae	2	0	0
Myristica magnifica Bedd.	*Pala hutan*	Myristicaceae	27	0	3
Dalbergia latifolia Roxb.	*Sonokeling*	Fabaceae	2	0	0
Alstonia scholaris (L.) R.Br.	*Pulai*	Apocynaceae	1	1	1
Schima wallichii (DC.) Korth.	*Puspa*	Theaceae	0	15	0
Leucaena leucocephala (Lam.) de Wit	*Petai cina*	Fabaceae	0	1	0
Acacia mangium Willd.	*Akasia*	Fabaceae	58	5	0
Breynia androgyna (L.) Chakrab. & N.P.Balakr.	*Katuk*	Phyllanthaceae	0	0	1
Persea americana Mill.	*Alpukat*	Lauraceae	0	0	1
Syzygium aromaticum (L.) Merr. & L.M.Perry	*Cengkeh*	Myrtaceae	0	0	16
Archidendron pauciflorum (Benth.) I.C.Nielsen	*Jengkol*	Fabaceae	0	0	2
Artocarpus camansi Blanco	*Kluwih*	Moraceae	0	0	2
Syzygium jambos (L.) Alston	*Jambu mawar*	Myrtaceae	0	0	6

Table 3. The results of the calculation of the Shannon-Wiener diversity index (H')

Location	Diversity index value (H')	Description
Plumbon Village	2.147456643	Medium
Nglebak Village	1.278676037	Medium
Sepanjang Village	2.456086473	Medium

Table 4. The result of biomass calculation

Location	Biomass value (kg)	Biomass per unit area (kg/ha)
Plumbon Village	212844.91	462.81
Nglebak Village	221541.01	807.28
Sepanjang Village	83768.67	145.13

Table 5. The results of the calculation of the carbon stock value

Location	Carbon storage (kg/ha)
Plumbon Village	212.8926
Nglebak Village	371.3488
Sepanjang Village	66.7598

Biomass estimation in the community forest area

Based on the biomass calculations presented in Table 4, Nglebak Village exhibited the highest total biomass, amounting to 221,541.01 kg. The biomass per unit area in Nglebak Village was 807.28 kg/ha, nearly double that of Plumbon Village, despite the total biomass values not differing significantly. This indicates that Plumbon Village has a larger overall area than Nglebak Village. Conversely, the lowest biomass and biomass per unit area were recorded in Sepanjang Village, where the number of trees per plot was lower than in the other villages. Additionally, Sepanjang Village exhibited greater plant species diversity within plots, as evidenced by Table 3, which shows the highest diversity index among the three villages. Tree diameter is a key factor influencing biomass values, with larger diameters corresponding to higher biomass. The average tree diameters in the study locations were 28.02 cm in Plumbon Village, 20.85 cm in Nglebak Village, and 24.6 cm in Sepanjang Village. Biomass is defined as the total mass of living organisms within a given area or species, typically expressed in dry weight and encompassing both above- and below-ground biomass (Konstantinavičienė and Vitunskienė 2023). In the context of trees, biomass includes the dry weight of wood, leaves, and roots. The greater the biomass of a tree, the higher its carbon storage potential (Darmawan et al. 2022). Thus, biomass directly influences a tree's capacity for carbon sequestration. Biomass per unit area represents the amount of biomass contained within a one-hectare area and is calculated by dividing the total biomass by the total area of the study site (Danarto 2020). The study sites covered the following areas: Plumbon Village (459.9 ha), Nglebak Village (274.43 ha), and Sepanjang Village (577.21 ha).

Estimation of carbon storage potential in the community forest area

Based on the calculation of the carbon storage across the three research locations, presented in Table 5, Nglebak Village had the highest carbon storage value, while Sepanjang Village had the lowest carbon storage value. The carbon storage in Nglebak Village was 371.35 kg/ha, followed by Plumbon Village with 212.89 kg/ha, and Sepanjang Village with 66.76 kg/ha. These differences in carbon storage values correspond to variations in biomass per unit area among the three villages. Since Nglebak Village exhibited the highest biomass per unit area, its carbon storage value was also the highest. Conversely, Sepanjang Village had the lowest carbon storage value due to its lower biomass per unit area. Carbon storage represents the absolute amount of carbon contained in plant biomass (Roziaty and Suparti 2022). The amount of carbon stored in an area is influenced by multiple factors, including plant species diversity, land cover density, plant height, soil type, tree diameter, and effective land management (Karuru et al. 2021). Differences in carbon storage values among the three locations can be attributed to variations in these factors, which impact the extent of carbon uptake by different plant species. Carbon sequestration within plant biomass plays an important role in mitigating atmospheric carbon levels, thereby contributing to air regulation and pollution reduction. Furthermore, carbon storage in plants serves as an ecological indicator of ecosystem stability and functionality. In addition to its environmental benefits, stored carbon also acts as an energy reserve for trees, supporting their growth and physiological processes.

Based on the research and data analysis conducted, it was determined that across 20 plots in each village, a total of 30 species from 18 different families were recorded, with the Fabaceae family being the most dominant. The Shannon-Wiener diversity index (H') values for each village were 2.147 in Plumbon Village, 1.278 in Nglebak Village, and 2.456 in Sepanjang Village. These values indicate moderate species diversity, signifying sufficient productivity and a relatively stable ecosystem. The biomass values, calculated based on tree diameter measurements, were 462.81 kg/ha in Plumbon Village, 807.28 kg/ha in Nglebak Village, and 145.13 kg/ha in Sepanjang Village. Correspondingly, the carbon stock values were 212,892 kg in Plumbon Village, 371,348 kg in Nglebak Village, and 66,759 kg in Sepanjang Village. The data indicate a positive correlation between biomass and carbon stock values. However, no significant correlation was observed between species diversity (H') and carbon stock. The variations in carbon storage across the three locations may be attributed to differences in vegetation cover and density in each village. These findings highlight the influence of structural forest attributes on carbon sequestration potential, emphasizing the importance of biomass accumulation in determining carbon storage capacity.

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Estimating forest above ground biomass in Dak Lak Province, Vietnam

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Abstract. *Bao HD, Huong NTT. 2025. Estimating forest above ground biomass in Dak Lak Province, Vietnam. Asian J For 9: 115-123.* Accurately estimating forest Above Ground Biomass (AGB) is essential for assessing carbon stocks, monitoring forest health, and guiding sustainable management practices. This study examined the potential of Landsat 8 satellite imagery for AGB estimation in Dak Lak Province, located in Vietnam's Central Highlands. Field data collected from 415 sample plots across diverse forest types including evergreen broadleaf, semi-deciduous, and dry dipterocarp forests revealed AGB values ranging from 15.16 to 299.33 tons/ha. Multivariate linear regression (MLR) and random forest (RF) models were applied to predict AGB using spectral bands and vegetation indices derived from Landsat 8 imagery. The MLR model demonstrated limited predictive capability ($R^2 = 0.131$), indicating that linear relationships between spectral data and AGB were insufficient to capture the system's complexity. In contrast, the RF model exhibited superior predictive performance, achieving an R^2 of 0.653 and a concordance R^2 of 0.571 when using spectral bands alone. Incorporating vegetation indices alongside spectral bands further improved the RF model's accuracy ($R^2 = 0.671$, concordance $R^2 = 0.586$). Spatial analysis revealed considerable variability in AGB across forest types, with evergreen broadleaf forests exhibiting the highest biomass values. These findings highlight the effectiveness of satellite remote sensing and machine learning for cost-effective biomass estimation. Moreover, they highlight the urgent need for such approaches in forest management and climate change mitigation efforts in tropical regions, including Vietnam.

Keywords: Carbon stock, google earth engine, Landsat 8, linear regression, random forest

INTRODUCTION

Forest ecosystems serve as the primary terrestrial carbon reservoirs, storing approximately 80% of the biosphere's carbon and playing a crucial role in climate change mitigation (Duchelle et al. 2018). Forest biomass is a key metric for assessing carbon sequestration and the overall carbon balance of ecosystems. Accurate estimation of forest biomass is essential for understanding the carbon cycle across large terrestrial landscapes (Li et al. 2015). Forest Above Ground Biomass (AGB) is traditionally assessed through either field measurements (West 2015) or remote sensing techniques (Yang et al. 2020). While field-based methods provide the most precise AGB estimates, their large-scale application is constrained by high costs, labor intensity, and time requirements. Estimating AGB over extensive areas using traditional methods is impractical due to the need for frequent updates to capture real-time biomass values. To address these challenges, remote sensing has emerged as a powerful tool for AGB estimation, enabling the development of regional and national biomass maps (Xiao et al. 2019; Tian et al. 2023; Sa et al. 2024).

The use of remote sensing for AGB estimation has gained prominence across various ecosystems globally, with previous studies demonstrating its effectiveness in biomass assessment and monitoring. A range of remote sensing technologies, including passive and active sensors, have been applied to estimate AGB (Deng et al. 2014; Cao et al. 2016; Shen et al. 2016; Sa et al. 2024). Among available satellite platforms, Landsat 8 offers several advantages for biomass estimation, including free access to time-series data, high spatial and temporal resolution, and consistent radiometric quality (Li et al. 2020; Nguyen et al. 2020). Vegetation indices derived from Landsat spectral bands such as the Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Moisture Stress Index (MSI), and Enhanced Vegetation Index (EVI) are widely employed to enhance biomass estimation accuracy (Zhang et al. 2019).

Selecting an appropriate modeling approach is essential for reliable AGB estimation. Traditional statistical models, particularly Linear Regression (LR), have been extensively applied in biomass studies (Li et al. 2019). However, classical regression techniques often fail to capture the complex, nonlinear relationships between AGB and remote sensing variables (Zhao et al. 2018). To overcome this limitation, machine learning algorithms such as decision trees, K-Nearest Neighbors (KNN), Artificial Neural Networks (ANN), and Support Vector Machines (SVM)—are increasingly used for biomass estimation (Gao et al. 2018; Liu et al. 2018). Decision-tree-based models, particularly Random Forest (RF) and Gradient Boosting (GB), have demonstrated superior predictive accuracy in biomass modeling (Belgiu and Drăgu 2016; Zhang et al. 2019; Hu and Sun 2022; Tian et al. 2024). Additionally, machine learning algorithms involve numerous adjustable parameters that significantly influence model performance, highlighting the importance of parameter tuning in optimizing predictive accuracy (Freeman et al. 2016; Probst and Boulesteix 2018).

Given the urgent need for efficient, large-scale monitoring of forest biomass, satellite remote sensing remains a

cornerstone of forest management and carbon stock assessment strategies (Camarretta et al. 2023). Since the launch of the Landsat mission in the 1970s, remote sensing has played a pivotal role in forest monitoring and mapping. Among machine learning approaches, the Random Forest algorithm has gained prominence due to its high accuracy, computational efficiency, and robustness against noise and overfitting (Wang et al. 2016; Gao et al. 2018; Tian et al. 2024). Numerous studies have employed RF for satellite-based biomass estimation, demonstrating its effectiveness for large datasets.

This study evaluates the utility of Landsat 8 imagery in predicting forest aboveground biomass using the RF algorithm. The objectives were to (i) model the relationship between field-measured AGB and Landsat reflectance; (ii) compare the predictive performance of the RF model with Multiple Linear Regression; and (iii) identify the most suitable model for AGB estimation in the study area.

MATERIALS AND METHODS

Study area

Dak Lak Province is situated in the Central Highlands of Vietnam, spanning approximately 13,085 km², which constitutes 3.9% of the country's total land area. The province lies between 107°28'57" to 108°59'37" E longitude and 12°09'45" to 13°25'06" N latitude (Figure 1). The terrain is predominantly mountainous, with elevations ranging from 400 to 2,442 meters above sea level, the highest point being Chu Yang Sin Mountain. A relatively flat highland region, covering about 50% of the province, extends across its central portion. Dak Lak experiences a distinct seasonal climate, with a rainy season from May to October, driven by prevailing southwest winds. Peak rainfall occurs in July, August, and September, contributing 80-90% of the annual total. In the eastern region, influenced by the Eastern Truong Son Range, the rainy season extends until November, while the dry season lasts from November to April of the following year. The province encompasses a total natural area of 1,312,537 hectares. According to the Provincial Forest Protection Department, as of late 2022, forested land covered 497,018 hectares, including 413,845 hectares of natural forests and 83,173 hectares of plantations, resulting in a forest coverage rate of 38.03%.

Materials

Satellite data

This study utilized Landsat 8 satellite imagery, selected based on its temporal correlation with forest inventory data. Landsat 8 was launched on 11 February 2013 from Vandenberg Air Force Base, California, and is equipped with two scientific instruments: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These instruments provide seasonal imagery of Earth's surface at spatial resolutions of 30 m (visible, near-infrared, and shortwave infrared), 100 m (thermal infrared), and 15 m (panchromatic band). Landsat 8 was developed through a collaboration between the United States Geological Survey (USGS 2023) and NASA. The OLI represents a significant technological advancement over previous Landsat sensors, incorporating innovations demonstrated by NASA's EO-1 test satellite. It features a quad-mirror telescope and 12-bit quantization, enhancing image quality and data accuracy. Additionally, the OLI includes two new spectral bands-one designed for detecting thin clouds and another for coastal observations (NASA 2024).

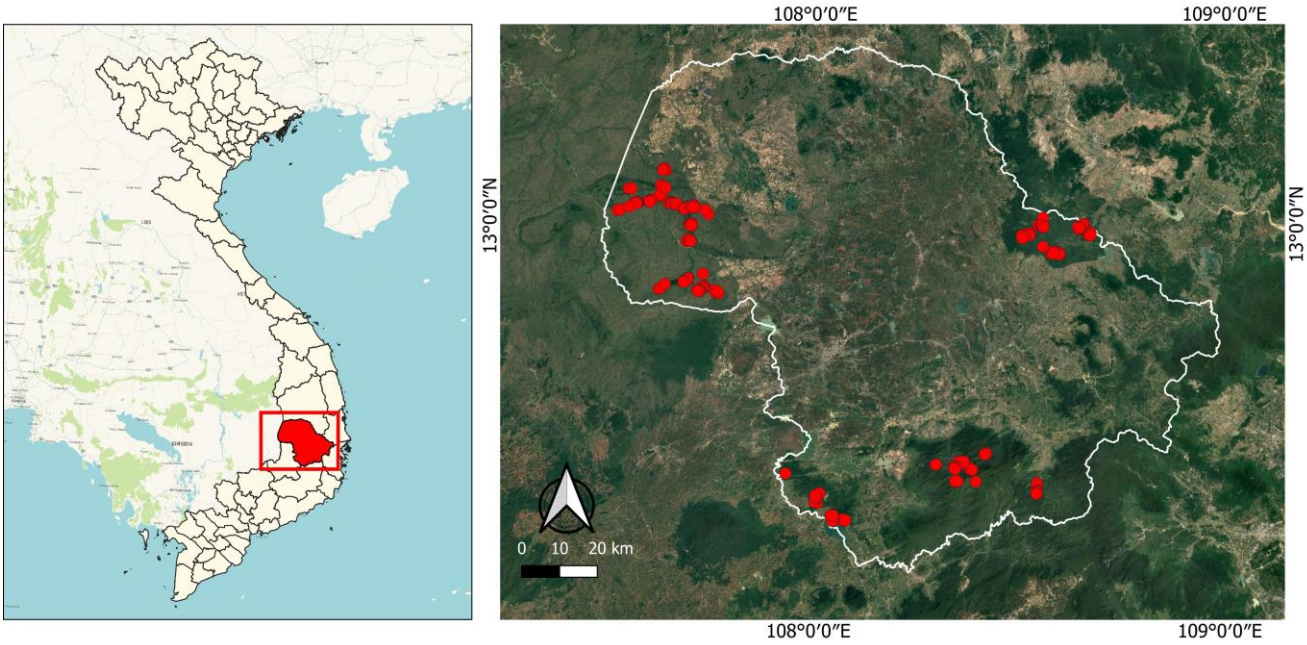


Figure 1. Location of the study area and ground plots at sites in Dak Lak Province, Central Highlands of Vietnam

Field data

Forest data for this study were collected from various natural forest types in Dak Lak Province, including dry deciduous forests, semi-deciduous forests, and evergreen broadleaf forests. Sampling was conducted using 30 × 30 m (900 m²) plots. Within each plot, tree parameters such as height, diameter at breast height, and species composition were recorded. Above Ground Biomass (AGB) for each tree was estimated using biometric equations developed by Bao et al. (2012), specifically calibrated for natural forests in the study area. Plot-level AGB values were then obtained by summing the individual tree biomass estimates.

Methods

Satellite image processing

Landsat 8 images, pre-calibrated for atmospheric conditions and free of cloud interference, were obtained from the Google Earth Engine (GEE) platform. Vegetation indices, which characterize plant spectral properties, were derived based on strong chlorophyll absorption at 0.65 μm, using a combination of infrared and near-infrared bands. Mathematical transformations, either linear or nonlinear, were applied to multiband reflectance data to enhance vegetation-related information while minimizing interference from non-vegetation elements. This approach effectively captured vegetation conditions (Hao et al. 2024).

All primary spectral bands and derived vegetation indices were extracted and aligned with field sample plots, enabling integration with statistical analyses. Seven vegetation indices were computed to support the study: Normalized Difference Vegetation Index (NDVI) = Measures vegetation health; Enhanced Vegetation Index (EVI) = Reduces atmospheric influences for improved vegetation monitoring; Soil-Adjusted Vegetation Index (SAVI) = Adjusts for soil brightness to enhance vegetation signals; Green Normalized Difference Vegetation Index (GNDVI) = Reflects vegetation health by assessing chlorophyll concentration; Moisture Stress Index (MSI) = Estimates vegetation water content; Red Edge NDVI (RENDVI) = Utilizes red-edge spectral bands to refine NDVI measurements; Simple Ratio (SR) = Computes the ratio between near-infrared and red spectral bands.

The coordinates of sample plot centers were used to extract satellite-derived predictor variables, including spectral and vegetation indices. These variables, along with Above Ground Biomass (AGB) estimates from field data, were processed using GEE's sample raster value tool. A stratified approach was applied, allocating 80% of the dataset for model training, while the remaining 20% was reserved for accuracy assessment (Ouchra et al. 2023).

Correlation analysis

To develop a forest Above Ground Biomass (AGB) estimation model, Multiple Linear Regression (MLR) was employed for regression analysis. MLR assumes a linear relationship between the dependent variable (AGB) and a set of independent predictor variables derived from remote sensing data (Wang et al. 2015). Initially, the correlation between AGB and each spectral band and vegetation index was analyzed, and only variables exhibiting a significant correlation with AGB were selected for further analysis. Stepwise linear regression, implemented in RStudio, was used to establish the relationship between observed AGB and predictor variables extracted from Landsat imagery.

In addition to MLR, the Random Forest (RF) algorithm, a robust machine learning technique, was applied for AGB estimation. RF is widely used for both classification and regression tasks due to its ability to handle large datasets efficiently and assess the relative importance of predictor variables (Blackard et al. 2008; Belgiu and Drăgu 2016). The algorithm extends conventional decision tree models by aggregating multiple decision trees, thereby enhancing predictive accuracy and robustness against outliers (Carreiras et al. 2012). In this study, the bagging (bootstrap aggregating) algorithm was employed to generate multiple subsets of the training dataset, known as bootstrap datasets, from which decision trees were constructed and subsequently combined to form the RF model. Typically, 70% of the training samples were included in the bootstrap datasets (in-bag data), while the remaining 30% (out-of-bag or OOB data) were used for model validation. All analyses were performed using RStudio and the Google Earth Engine (GEE) platform.

Model performance was evaluated using the coefficient of determination (R^2), which measures the proportion of variance in AGB explained by the model, with higher values indicating better model performance. Additionally, the Root Mean Square Error (RMSE) was used to assess the standard deviation of residuals, where lower values indicate higher model accuracy. These metrics were used to compare the accuracy of the MLR and RF models in estimating AGB.

RESULTS AND DISCUSSION

Above ground biomass field data

A total of 415 sample plots were surveyed to collect essential forest parameters, including diameter at breast height and tree height. These parameters were used to calculate AGB for each plot, which was then converted into tons per hectare. The estimated AGB values ranged from a minimum of 15.16 tons/ha to a maximum of 299.33 tons/ha, with an average value of 96.95 tons/ha.

When analyzed by forest type, 54 plots classified as broadleaf evergreen forests exhibited AGB values ranging from 19.33 to 299.33 tons/ha. Similarly, semi-deciduous forests displayed a minimum AGB of 19.33 tons/ha. However, dry dipterocarp forests recorded a lower minimum AGB value of 15.56 tons/ha. The distribution of AGB values across different forest types is illustrated in Figure 2.

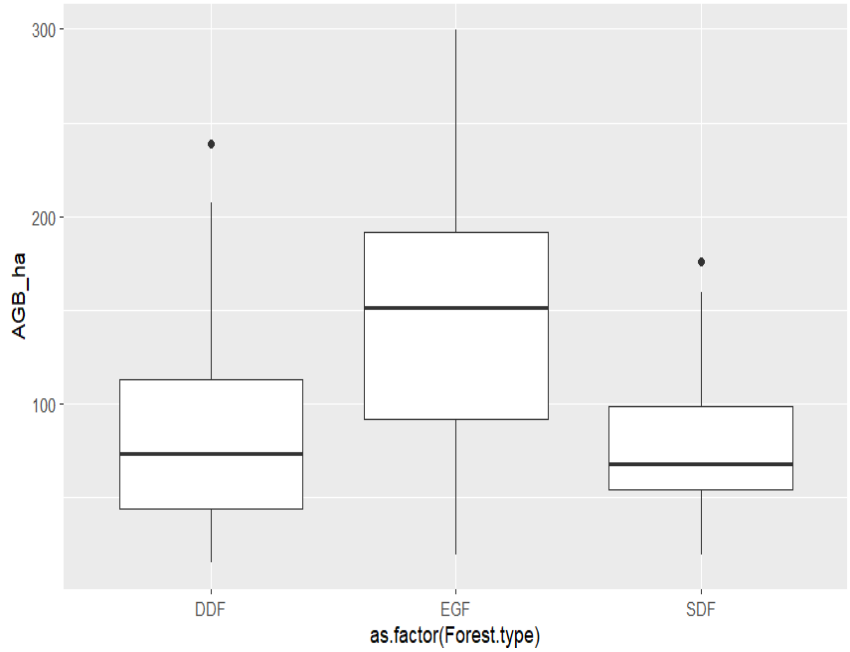
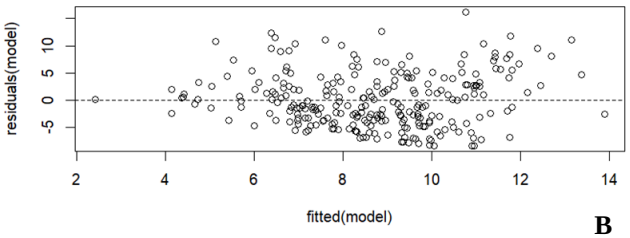


Figure 2. Distribution of calculated AGB values from survey data across different forest types. DDF = Dry Deciduous Forests; EGF = Evergreen Broadleaf Forests; SDF = Semi-Deciduous Forests

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  16.4357     2.0244   8.119 5.57e-15 ***
b4           35.6421    24.7990   1.437  0.15141
b5            0.4355    10.1106   0.043  0.96566
b6          -74.2318    24.6767  -3.008  0.00279 **
b7           17.1850    26.9139   0.639  0.52349
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.852 on 410 degrees of freedom
Multiple R-squared:  0.131,     Adjusted R-squared:  0.1226
F-statistic: 15.46 on 4 and 410 DF,  p-value: 8.717e-12
```

A



B

Figure 3. Results: A. Linear regression output summary; B. Residuals vs fitted values plot

Relationship between AGB and Landsat 8 data

Multiple linear regression analysis

A Multiple Linear Regression (MLR) model was applied to predict Above Ground Biomass (AGB) using Landsat 8 spectral bands. The model identified relationships between AGB and four spectral bands: Band 4, Band 5, Band 6, and Band 7. While the intercept (16.44, $p < 0.001$) indicated a significant baseline level of AGB, the p-values for Band 4, Band 5, and Band 7 (0.151, 0.966, and 0.523, respectively) suggested that these bands did not have statistically significant effects on AGB at the 0.05 level.

Interestingly, Band 6 exhibited a statistically significant negative coefficient (-74.23, $p = 0.003$), indicating a negative relationship between Band 6 and AGB. However, the overall explanatory power of the model was limited, with an R^2 value of only 0.131. This suggests that additional predictor variables, interactions between spectral bands, or environmental factors should be incorporated to enhance prediction accuracy. Figure 3 illustrates the regression analysis results and the residual patterns.

Random forest regression model using spectral data

The performance of the Random Forest (RF) regression model for estimating Above Ground Biomass (AGB) using Landsat spectral bands was evaluated across different numbers of decision trees (ntree). Results indicated a consistent improvement in model accuracy with increasing ntree values. For ntree = 100, the model achieved an R^2 of 0.647, and the concordance between estimated and actual AGB was strong, with a concordance R^2 of 0.549.

Increasing ntree to 200 slightly improved the R^2 to 0.650, with a concordance R^2 of 0.557. Further increases to ntree = 500 and 1000 resulted in marginal gains, with R^2 values of 0.652 and 0.653, respectively, and concordance R^2 values improving to 0.569 and 0.571. These results suggest that while increasing ntree enhances the model's ability to capture the relationship between spectral data and AGB, the improvements plateau beyond 500 trees, indicating diminishing returns. Figure 4 illustrates the concordance between actual and estimated AGB for different ntree values.

Random forest regression model using vegetation indices

The performance of the Random Forest (RF) regression model in estimating Above Ground Biomass (AGB) using vegetation indices was assessed across varying numbers of decision trees (ntree). At ntree = 100, the model achieved an R^2 of 0.663, with a concordance R^2 of 0.532. Increasing ntree to 200 resulted in a slight decrease in R^2 to 0.661, while the concordance R^2 remained stable at 0.533.

For ntree = 500, the model's R^2 improved again to 0.663, with a concordance R^2 of 0.534. However, at ntree = 1000, the R^2 slightly decreased to 0.661, with the concordance R^2 remaining at 0.533. These results indicate that while ntree influences model performance, the improvements plateau beyond 500 trees, suggesting limited additional benefits from further increasing decision trees. Figure 5 illustrates the concordance between actual and estimated AGB for different ntree values using vegetation indices.

Random forest regression model using both spectral bands and vegetation indices

The Random Forest (RF) regression model's performance in estimating Above Ground Biomass (AGB) was further analyzed using a combination of spectral bands and vegetation indices. At ntree = 100, the model achieved an R^2 of 0.675, with a concordance R^2 of 0.597. However, as ntree increased to 200, the R^2 slightly decreased to 0.668, while the concordance R^2 dropped to 0.580.

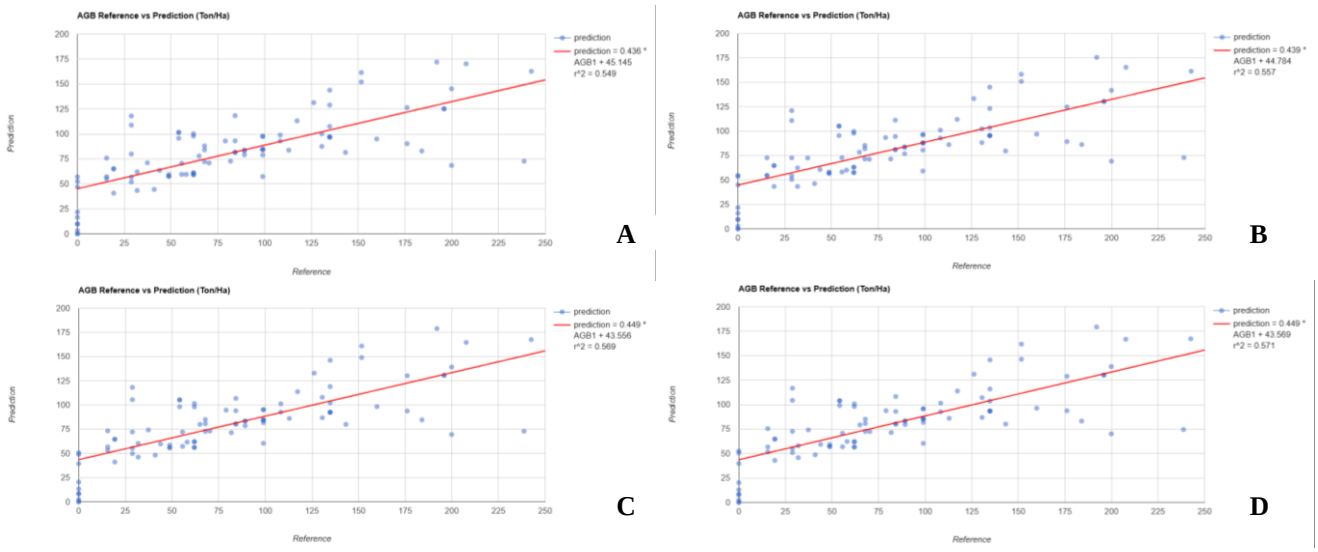


Figure 4. Correlation of actual AGB and estimates using spectral bands with different ntree: A. ntree = 100; B. ntree = 200; C. ntree = 500; D. ntree = 1000

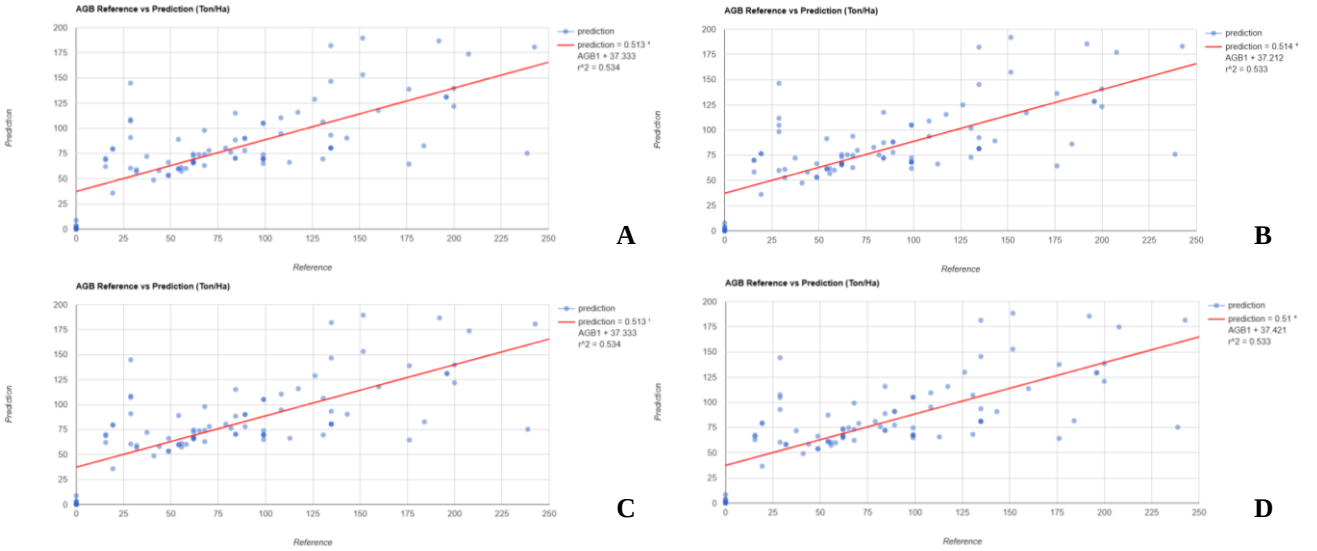


Figure 5. Correlation of actual AGB and estimates using VIs with different ntree: A. ntree = 100; B. ntree = 200; C. ntree = 500; D. ntree = 1000

Increasing ntree to 500 resulted in an R^2 of 0.670, with a concordance R^2 of 0.584. For ntree = 1000, the model's R^2 marginally improved to 0.671, with a concordance R^2 of 0.586. These results suggest that integrating both spectral bands and vegetation indices enhances the model's predictive performance compared to using either dataset alone. However, the improvements stabilize at higher ntree values, indicating diminishing returns beyond 500 trees. Figure 6 illustrates the concordance between actual and estimated AGB for different ntree values.

Estimating AGB map

Figure 7 illustrates the distribution of the estimated AGB values derived from the combination of spectral bands and vegetation indices for Dak Lak Province.

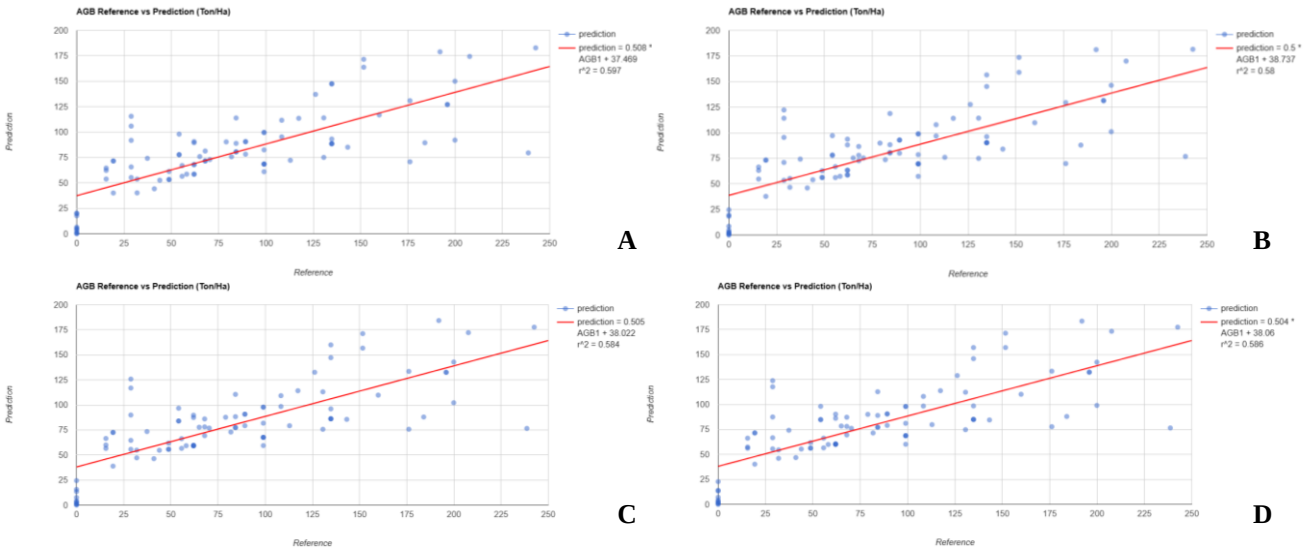


Figure 6. Correlation of actual AGB and estimates using VIs with different ntree: A. ntree = 100, B. ntree = 200, C. ntree = 500, and D. ntree = 1000

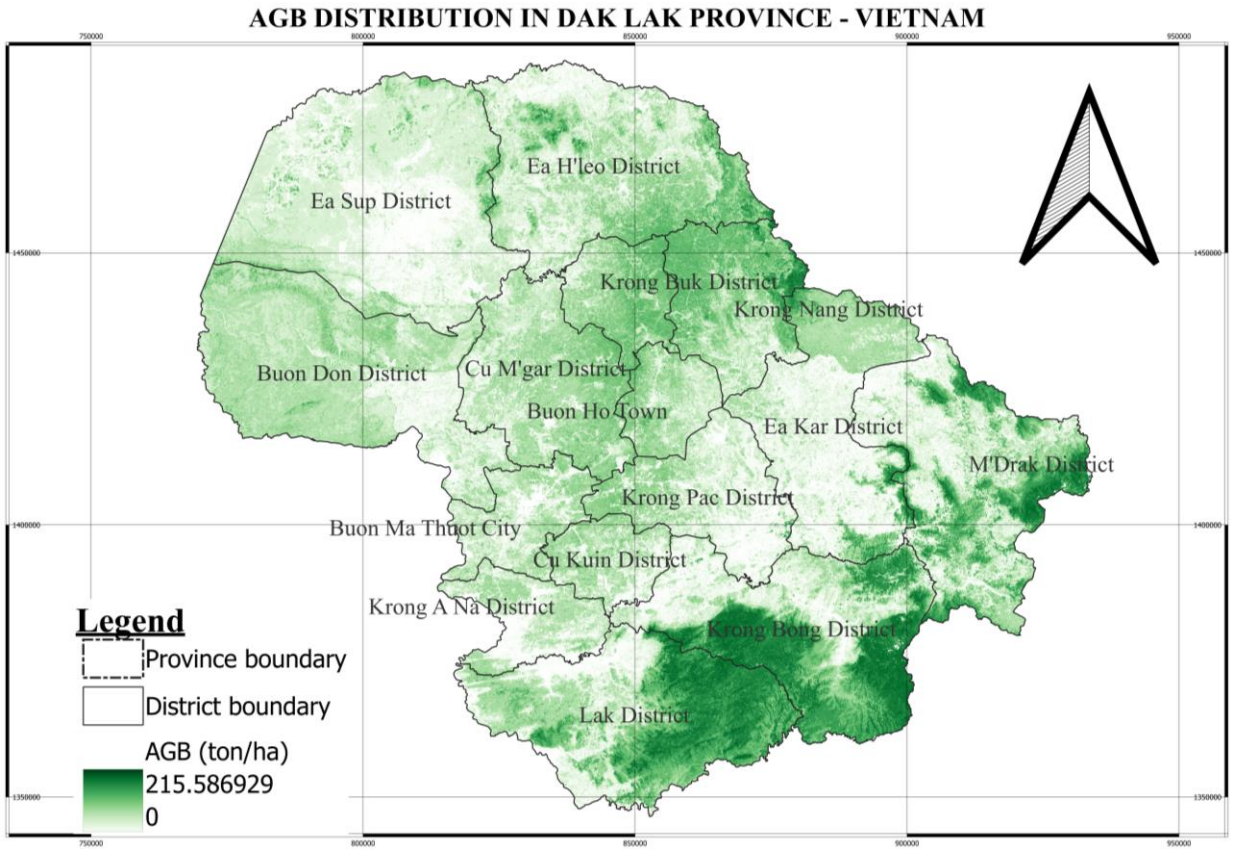


Figure 7. Estimated AGB value from the RF model in Dak Lak Province, Vietnam

The areas with the highest AGB storage in forests are predominantly located in the southern and eastern parts of the province, specifically in the districts of Lak, Krong Bong, M'Drak, and Ea Kar. These districts contain extensive natural broadleaf evergreen forests, which contribute significantly to their high biomass storage compared to other regions in the province.

Discussion

This study assessed the relationship between Above Ground Biomass (AGB) and Landsat 8 spectral bands, vegetation indices, and their combined application in predictive modeling. The findings provide significant insights into the performance of multiple linear regression and random forest regression models, as well as the spatial distribution of AGB across Dak Lak Province.

The multiple linear regression model identified a significant negative correlation between AGB and Band 6 ($p = 0.003$). However, its explanatory power was low ($R^2 = 0.131$), indicating that spectral bands alone may not sufficiently capture AGB variability. The nonsignificant contributions of Bands 4, 5, and 7 further suggest the necessity of incorporating additional variables, such as vegetation indices or environmental factors, to enhance prediction accuracy.

The random forest regression model outperformed the linear regression model, highlighting the efficacy of machine learning techniques in AGB estimation. Model accuracy improved with an increasing number of decision trees (ntree), with R^2 rising from 0.647 (ntree = 100) to 0.653 (ntree = 1000). Similarly, concordance between estimated and actual AGB consistently improved, plateauing at $R^2 = 0.571$ for ntree = 1000. These results indicate that while spectral data are valuable, their predictive capacity is limited when used in isolation.

The inclusion of vegetation indices further enhanced the model's predictive performance, reflecting their strong association with vegetation structure and biomass. The R^2 values ranged from 0.663 (ntree = 100) to 0.661 (ntree = 1000), while concordance between estimated and actual AGB exhibited slight improvement, stabilizing at $R^2 = 0.534$. Despite these gains, the marginal benefits observed with increasing ntree suggest a saturation point in the explanatory power of vegetation indices. The combination of spectral bands and vegetation indices yielded the most accurate AGB predictions, with R^2 values ranging from 0.675 (ntree = 100) to 0.671 (ntree = 1000), and concordance R^2 stabilizing at 0.586 for ntree = 1000. These findings emphasize the complementary nature of spectral and index-based data in capturing vegetation and forest structure characteristics. However, diminishing returns beyond ntree = 500 suggest an optimal tree number for balancing computational efficiency and model performance.

The spatial distribution of AGB, as estimated by the RF model, revealed distinct biomass variations across different forest types in Dak Lak Province. Evergreen broadleaf forests exhibited the highest AGB values, reflecting their dense vegetation structure and substantial carbon storage potential. In contrast, semi-evergreen and dry forests had lower AGB values, aligning with their less dense canopy cover and reduced biomass storage capacity.

The RF model demonstrated improved accuracy compared to previous studies in the Central Highlands. For instance, Bao et al. (2012) reported an R^2 of 0.53 when using only spectral bands, consistent with the lower predictive power observed in this study when relying solely on Landsat data (concordance $R^2 = 0.571$ for ntree = 1000). In contrast, combining spectral bands and vegetation indices in the present study enhanced RF model accuracy, achieving an R^2 of 0.671 and a concordance R^2 of 0.586 for ntree = 1000. These results reinforce the advantages of integrating vegetation indices, which capture additional information on vegetation structure and health, with spectral data for AGB estimation.

Moreover, these findings align with those of Dang et al. (2019), who reported an R^2 of 0.81 and RMSE of 36.67 Mg/ha using an RF model with combined spectral bands in dry dipterocarp forests. Although the R^2 achieved in this study was slightly lower, the results validate the applicability of RF algorithms for biomass estimation and demonstrate their effectiveness in capturing the spatial variability of AGB across diverse forest types. The spatial distribution analysis indicated high AGB concentrations in the southern and eastern districts, particularly in Lak, Krong Bong, M'Drak, and Ea Kar, where extensive broadleaf evergreen forests serve as significant carbon sinks. These results are consistent with previous studies highlighting the role of natural forest cover in biomass storage and climate change mitigation.

This study highlights the importance of integrating spectral data and vegetation indices for accurate AGB estimation. The superior performance of the RF model highlights the potential of machine learning approaches in modeling complex variable relationships. However, limitations include reliance on Landsat 8 data, which has moderate spatial resolution, and the exclusion of additional environmental variables, such as topography, soil characteristics, and climate data, that may influence AGB distribution. Future research should incorporate higher-resolution satellite imagery, such as Sentinel-2 or UAV-derived data, to improve spatial accuracy. Additionally, integrating environmental variables and testing alternative machine learning algorithms, such as gradient boosting or support vector regression, may further enhance AGB predictions. Expanding the study to other provinces with diverse forest types could also validate the model's applicability and generalizability.

In conclusion, this study evaluated the potential of random forest regression models in estimating aboveground biomass in Dak Lak Province, Vietnam, using Landsat 8 spectral bands, vegetation indices, and their combination. The results demonstrated that integrating spectral bands with vegetation indices yielded the most accurate AGB predictions, achieving an R^2 of 0.671 and a concordance R^2 of 0.586 with 1000 decision trees. These findings highlight the complementary role of spectral and index-based data in capturing vegetation structure and biomass. The spatial analysis indicated that evergreen broadleaf forests in the southern and eastern districts, including Lak, Krong Bong,

M'Drak, and Ea Kar, had the highest AGB values. These forests serve as crucial carbon sinks, emphasizing their ecological significance and the necessity for conservation efforts. The RF model demonstrated superior performance compared to traditional linear regression and improved upon previous studies relying solely on spectral data. However, further accuracy improvements could be achieved by incorporating additional variables such as topography, soil properties, and climate factors, as well as utilizing higher-resolution satellite imagery. This study highlights the effectiveness of RF regression models in AGB estimation, offering a robust framework for forest biomass monitoring. These findings support sustainable forest management and climate change mitigation strategies in the Central Highlands Region of Vietnam.

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Distribution and habitat mapping of key fauna species in other land use for biodiversity offset

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Abstract. *Hernawan E, Rosmiati M, Lastini T, Kandar M. 2024. Distribution and habitat mapping of key fauna species in other land use for biodiversity offset. Asian J For 9: 124-136.* Despite their status as non-forest and non-conservation areas, other land use areas (APL), especially those adjacent to forests, are still habitats for wildlife, including key animals or essential ecosystems that are ecologically important for biological conservation as animal boundaries or as protectors of conservation areas. The existence of key animal habitats or essential ecosystems underscores the urgent need for a comprehensive biodiversity action plan (BAP) for APLs. The APLs are geographically dispersed nationwide to address diverse external needs beyond forestry. Some APLs are situated on Mount Tenggamus in Lampung Province, Sumatra Island, and on Mount Latimojong in South Sulawesi Province, Sulawesi Island, Indonesia. This research aims to find out the distribution of key animals in other land uses as a basis for controlling land use for sustainability. The research method used is vegetation analysis based on elevation, presence of animals, and distribution mapping using Weighted Linear Combination (WLC). The results showed that degraded and deforested ecosystems dominated both APLs. Some key species are confined to APLs, where their habitats have been fragmented by agricultural land use. This results in limited home ranges and the possibility of inbreeding, which will reduce the survivability of offspring. In addition, due to human pressure, including hunting, key animals in OLs are at risk of extinction. Immediate protection measures are essential to prevent this.

Keywords: Degraded, distribution mapping, essential ecosystem, flora endemic, key animal habitat

INTRODUCTION

Lampung Province is located within the Ring of Fire of Sumatra Island in the South (Utama et al. 2021). In addition to its notable biodiversity, the region is home to numerous endangered species of flora and fauna. The International Union for Conservation of Nature (IUCN) has classified the Sumatran rhino (*Dicerorhinus sumatrensis* (G.Fischer, 1814), tiger (*Panthera tigris* subsp. *sumatrae* Pocock, 1929), and elephants (*Elephas maximus* subsp. *sumatranus* Temminck, 1847) as critically endangered species due to their dwindling populations (IUCN SSC Cat Specialist Group 2015; IUCN SSC Asian Rhino Specialist Group 2020; Williams et al. 2020; Winarno et al. 2024). In comparison, South Sulawesi Province is situated along the Wallace Line, which delineates the boundary between the Asian and Australian continents. Maps showing old water levels during the Pleistocene demonstrate that Sulawesi is just east of the old Sunda land shelf. This persistent water gap, even during the Pleistocene, has prevented many plant and animal groups from colonizing Sulawesi. The species that did get to Sulawesi have developed at least subspecies differences from the mainland population in most cases. Thus, diversity is less in Sulawesi, but endemic species and subspecies are much higher than in Sundaland (Metcalfe 2017).

The origins of APLs in Tenggamus Mountain and Latimojong Mountain are rooted in converting a protected forest into a site conducive to cultivation activities and human settlements, resulting in a diminution of suitable habitat for flora and fauna (Muhaimin et al. 2018). Road construction also hurts animals in Lampung Province. Highways can greatly impact where animals live and how they live, especially near the highways. The highways can make it hard for animals to move around, harming their health. More and more accidents occur when animals try to cross highways, which can mean more traffic. The noise from vehicles can also bother animals and force them to move to a smaller area. At the start of road construction, wildlife was monitored. This showed more threats to wildlife, especially tigers, Sumatran elephants, and Sumatran rhinos (Winarno et al. 2024). Operations of mining have significant effects on biodiversity over the level of spatial scales, from the local site to the larger landscape, regional, and even global levels, and have effects both from direct mining processes as well as indirect ones like occupancy to places rich in biodiversity (Shanmukha et al. 2024). In addition, mining activities and micro hydro development can accelerate habitat loss for flora and fauna. The biodiversity in Wallace's line of great interest in world science has declined, which was triggered by forest degradation and deforestation driven by Indonesian government policies. One of the policies of the government of Indonesia is to release state forest areas as the habitat of endemic species for other uses such as agricultural land, plantation land, transmigration, and mining concessions. In reducing the impact of these releases on decreasing biodiversity, the Government of Indonesia is also developing conservation

in an ex-situ manner, namely in essential ecosystems. It requires a BAP in the management of former forest areas to protect key animal habitats that are included in the IUCN red list criteria for species threatened with extinction. According to Iskandar (2021), for this work, as usual, we must be aware of the presence of plants and animals that meet the criteria of Indonesian Law, CITES, and IUCN. As a rule, the IUCN criterion is the highest, but traded species might meet the CITES regulation but not the IUCN criteria. For this reason, we must check every species observed and/or reported against all the three main regulations mentioned above. Then, to find out the distribution of the remains of unique species on the island of Sumatra and the island of Sulawesi, especially outside the conservation area, it is necessary to know their distribution. The objective of this paper is to map the distribution of key species in the Tenggamus Mountains of Lampung Province and the Latimojong Mountains of South Sulawesi Province, specifically in other land use areas.

MATERIALS AND METHODS

Study area

In Lampung Province, the research area is situated near the protected forest area of Mount Tenggamus, with a focus on identifying potential micro hydro development sites. Administratively, the research site is in Way Panas Village, Wonosobo Sub-district, Tanggamus District, Lampung, Indonesia (Figure 1). Way Panas village is situated in the northern portion of Wonosobo Sub-district, forming a border between Wonosobo Sub-district and Ulubelu Sub-district. Wonosobo Sub-district, the largest sub-district in Tanggamus District, is home to 28 pekon, or villages, making it the most pekon-rich sub-district. The administrative center of Wonosobo Sub-district is situated in Tanjung Kurung, 12.8 km southwest of Way Panas Village. The area of Way Panas Village encompasses 11.48 km^2, with a population of 2,926 inhabitants. Way Panas Village is the largest village in Wonosobo Sub-district, accounting for 5.05% of the total area of Wonosobo Sub-district.

In South Sulawesi, the research location was in Rante Balla Village and Boneposi Village, Latimojong Sub-district, Luwu District, South Sulawesi Province, Indonesia, where PT MDA's gold mining CoW is physically located. The Tana Toraja, Makassar, Bugis, and Javanese tribes, Rante Balla, Salubulo, Boneposi, Tolajuk, and Ulu Salu Villages are the nearest to the project site (mine) (Figure 1).

Procedures

The focus of the research was on APL areas that have the potential to be used for micro hydro and mining activities that have the potential to cause loss of flora and fauna. AOI has identified based on literature review, data and information land use for development planning of micro hydro or mining activities. Secondary and primary data were collected after the AOI (Area of Interest) was identified and delineated. Based on technical considerations in the field and differences in tree habitat based on height above sea level, the observation points for tree vegetation are based on altitude. Meanwhile, observation points for animals and animal habitats are carried out based on information from local communities and field workers. In addition, observation points are based on presence-absence. The research flow chart can be seen in Figure 2.

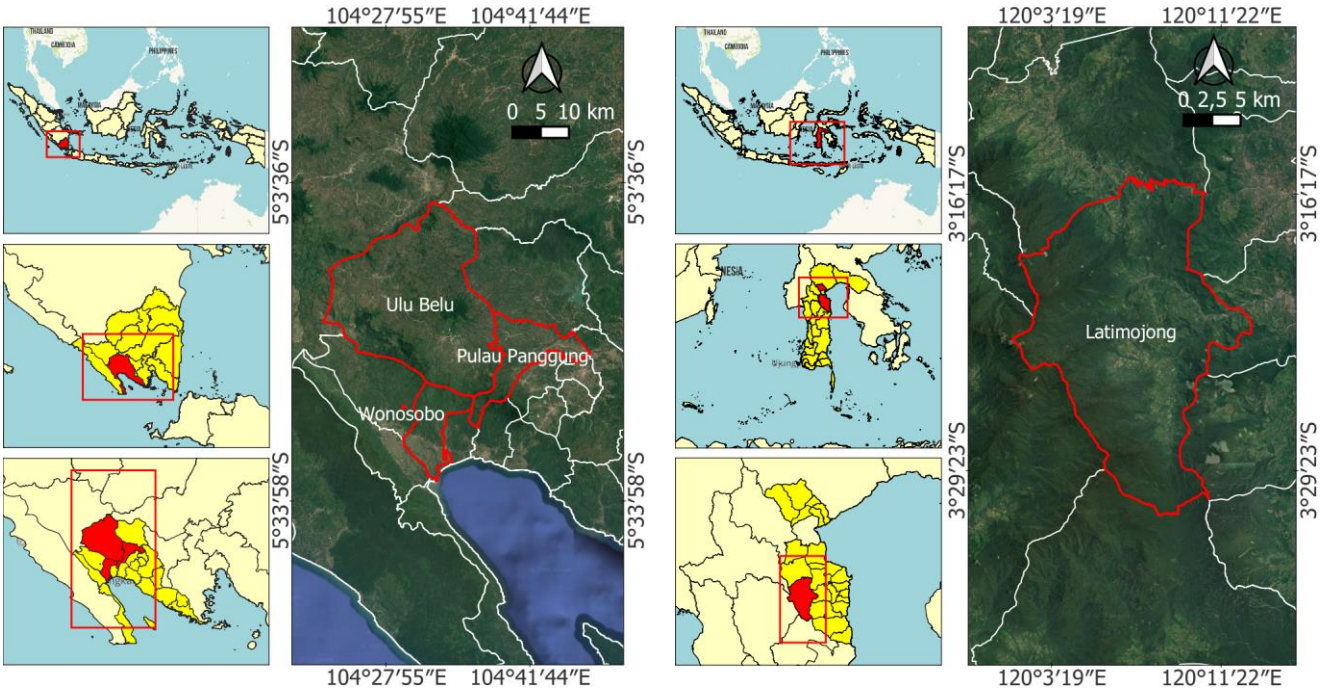

Figure 1. A. Research location in Wonosobo, Tanggamus, Lampung, Indonesia; B. Research location in Latimojong, Luwu, South Sulawesi, Indonesia

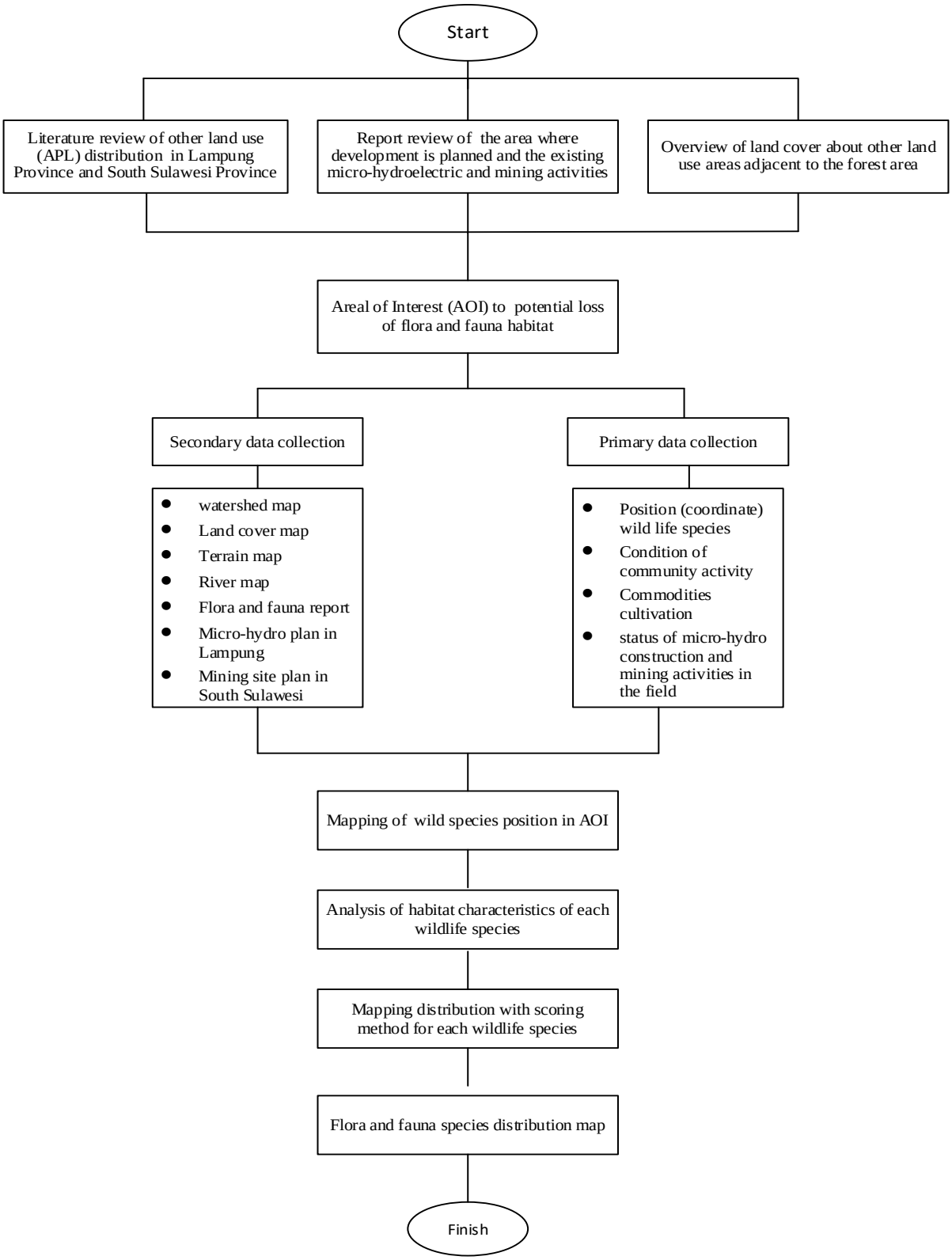

Figure 2. Flow chart diagram of research

Data analysis

The species mapping method used by using the scoring method, namely by using data on animal presence, land cover, and water presence, then scoring each variable. Scoring of potential animal presence is done by scoring a score for areas where animals are found, a score of 100, and for those where no animals are found, a score of 20. Scoring of land cover is divided into natural forest cover with a score of 100, secondary forest cover with a score of 60, and other land uses with a score of 20. While scoring

the availability of water is based on the proportion of animal presence. The weight for animal presence is 50, the weight for land cover is 30, and the weight for water availability is 20. The distribution value is the sum of the multiplication between the weight and score of each variable. To determine the distribution level, the low distribution value, if the value is < 40; the medium distribution value, if the value is between 40 - 60; and the high distribution value if the value is > 60.

RESULTS AND DISCUSSION

Mapping of key flora and fauna species habitat in Lampung

AOI determination

Referring to the results of the gap analysis by the Ministry of Forestry and the Ministry of Marine Affairs and Fisheries in 2010, there are still endangered wildlife habitats; it is estimated that around 80% are still outside the conservation area system (Chrismiawati et al. 2022), one of which is in the essential ecosystem as ex-situ conservation of wildlife. Essential ecosystem areas are regions with significant ecosystem values, not classified as nature conservation areas, nature reserves, or hunting parks. These areas are crucial for supporting ecological survival through biodiversity conservation efforts (Qomariah et al. 2021), while ex-situ conservation can have the function of providing an additional layer of protection for species that are critically endangered or whose habitats are severely threatened (Mahanayak 2024). In accordance with prevailing legislation and regulatory frameworks, designated essential ecosystem areas encompass parks, wildlife corridors, and high conservation value areas. However, areas with potential as essential ecosystems are not limited to those within forest or conservation areas (in-situ) but also include those outside these areas (ex-situ). These areas are vulnerable to human pressures, such as converting forest land into cultivation areas, including micro-hydro development. The range of electricity produced by micro hydro is 5kW-100 kW, usually providing power for a small community or rural industry in remote areas away from the grid. The basic concepts considered in the design of micro-hydropower plants are: topography and geomorphology of the site, evaluation of water resources and their generation potential, site selection and basic layout, hydraulic turbines and generators and their controls, environmental impact assessment and mitigation measures, economic evaluation of the project and financing potential, institutional framework and administrative procedures for obtaining necessary permits (Anaza et al. 2017). One possible impact is the reduction of land cover for the construction of micro-hydro facilities and equipment and changes in water temperature due to the generator process, leading to the loss of terrestrial flora and fauna and aquatic biota such as fish. It is, therefore, necessary to assess the state of biodiversity as a basis for mitigation. The area of interest research in Lampung Province is the area that has the potential for the development of micro hydro around Tenggamus Mountain (Figure 3).

Mapping of key flora and fauna species habitat in the Tenggamus Mountain, Lampung

The condition of the existing land cover in the AOI for micro hydro plant area shows that it is dominated by dry land mixed with shrubs is 84.27%, followed by 6.66% wetland agriculture land cover, 5% pure dryland agriculture, 3.12% settlements, and the rest are secondary dryland forest and open land; above this AOI is directly adjacent to the protected forest area. Thus, the function of this AOI is an area of spillover of flora and fauna from the protected forest areas (Figure 4; Table 1).

The data presented in the table above indicates the existence of two distinct flora and fauna habitats within the study site: natural habitats in primary dryland forest land cover and modified habitats in other land cover types. The natural habitats in this AOI are characterized by their location along riverbanks, where the steep slopes make the area unsuitable for agricultural use. These habitats within the study site have significant conservation value, providing essential food sources for fauna and flora. This is evidenced by notable conservation vegetation species such as *dao* (*Dracontomelon dao* (Blanco) Merr. & Rolfe) and figs (*Ficus* spp.) within the area. The urgency of preserving these habitats is underscored by the presence of endangered or threatened species such as *Anguilla bicolor* McClelland, 1844 or *pelus pita* (NT), *Spilornis cheela* (Latham, 1790) or Crested serpent eagle (LC), *Helarctos malayanus* (Raffles, 1822) or sun bear (VU), *Symphalangus syndactylus* (Raffles, 1821) or siamang (EN), and *Macaca nemestrina* (Linnaeus, 1766) or *beruk* (EN).

The proximity of agricultural areas to natural habitats often leads to human-wildlife conflicts (Rifaie et al. 2021). A survey of the modified habitat indicated the absence of protected tree species. The only three species identified were those with high economic value, including durian (*Durio zibethinus* Murray), *duku* (*Lansium domesticum* Corrêa), cacao (*Theobroma cacao* L.), and coffee (*Coffea arabica* L.). Based on observation interviews with the locals, we observe several moderate to high-risk IUCN status species; there are siamang (*S. syndactylus*), pig tailed monkey (*M. nemestrina*), and Malayan sun bear (*H. malayanus*).

Table 1. Land coverage in AOI in Lampung

Land coverage	Area (ha)	Percentage (%)
Secondary dryland forest	118.62	0.90
Settlement	411.91	3.12
Dryland agriculture	659.74	5.00
Dryland mixed agriculture	11129.08	84.27
Wetland farming	879.71	6.66
Open Land	6.91	0.05
Grand total	13205.97	100.00

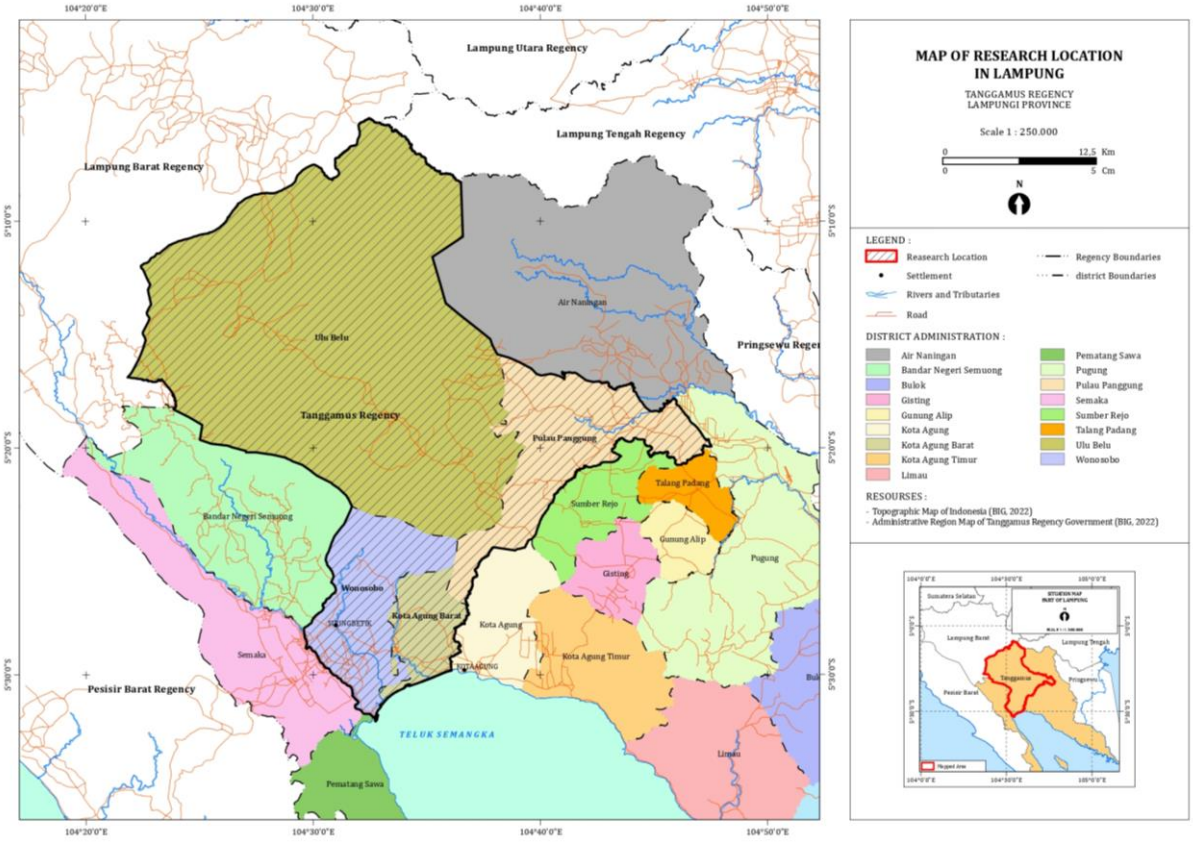

Figure 3. An area of interest for research is APL. There is the potential for micro-hydro development in Mt. Tenggamus, Indonesia

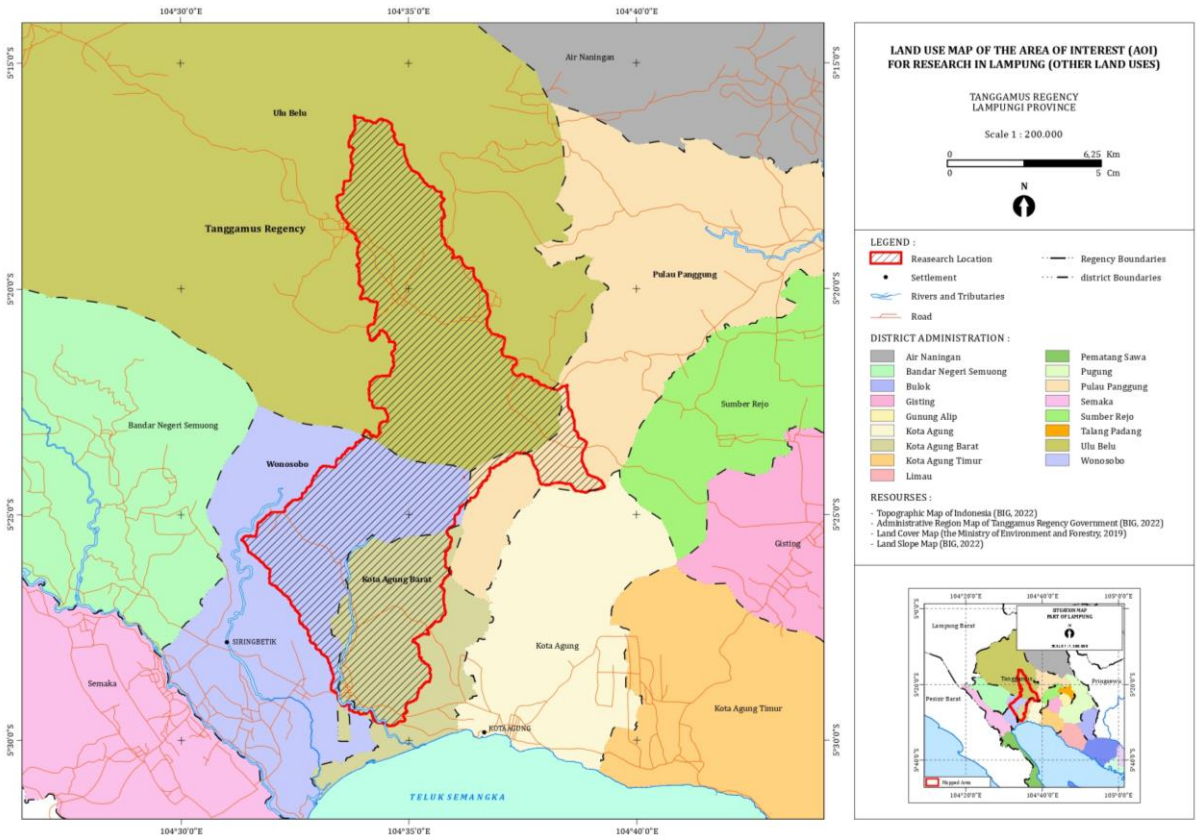

Figure 4. Map of land coverage in AOI in Lampung, Indonesia

Threatened species of birds can be spotted within modified habitats, with no sightings of Endangered (EN) species. Coffee plantations and mixed orchards sustain diverse species of birds. Thus, modified habitats have become important to many birds livelihoods. Notable species in modified habitat are the collared kingfisher (*Todiramphus chloris* (Boddaert, 1783)), ruby-throated bulbul (*Rubigula dispar*), and tailed drongo-cuckoo (*Surniculus lugubris* (Horsfield, 1821)). The results of the incidental observation nocturnal visual encounter survey indicated the presence of a few low-risk IUCN status species. These species included the Asian common toad (*Duttaphrynus melanostictus* (Schneider, 1799)), the Asian giant toad (*Phrynoidis asper* (Gravenhorst, 1829)), and the crab-eating frog (*Fejervarya cancrivora* (Gravenhorst, 1829)). No threatened species of amphibians were encountered within the modified habitat. The species observed demonstrated tolerance to pollution disturbance. Residents rarely observed or knew indicator species due to their cryptic morphology and low population size. The reptiles documented in modified habitats are classified as "Least Concern" (LC) by the IUCN. The lizards have been observed primarily in proximity to orchards. The Asian box turtle (*Cuora amboinensis* (Daudin, 1801)) is frequently encountered in the downstream area of the Way Belu River and has been introduced into local captivity. The Malayan softshell turtle (*Dogania subplana* (Geoffroy Saint-Hilaire, 1809)) is found near Way Panas Village, where the local populace consumes it. Based on the findings of flora species and animal encounters and overlaid with the land cover map, a distribution map of endemic flora distribution, bird distribution, amphibian distribution, and fish distribution was obtained as shown in Figure 5.

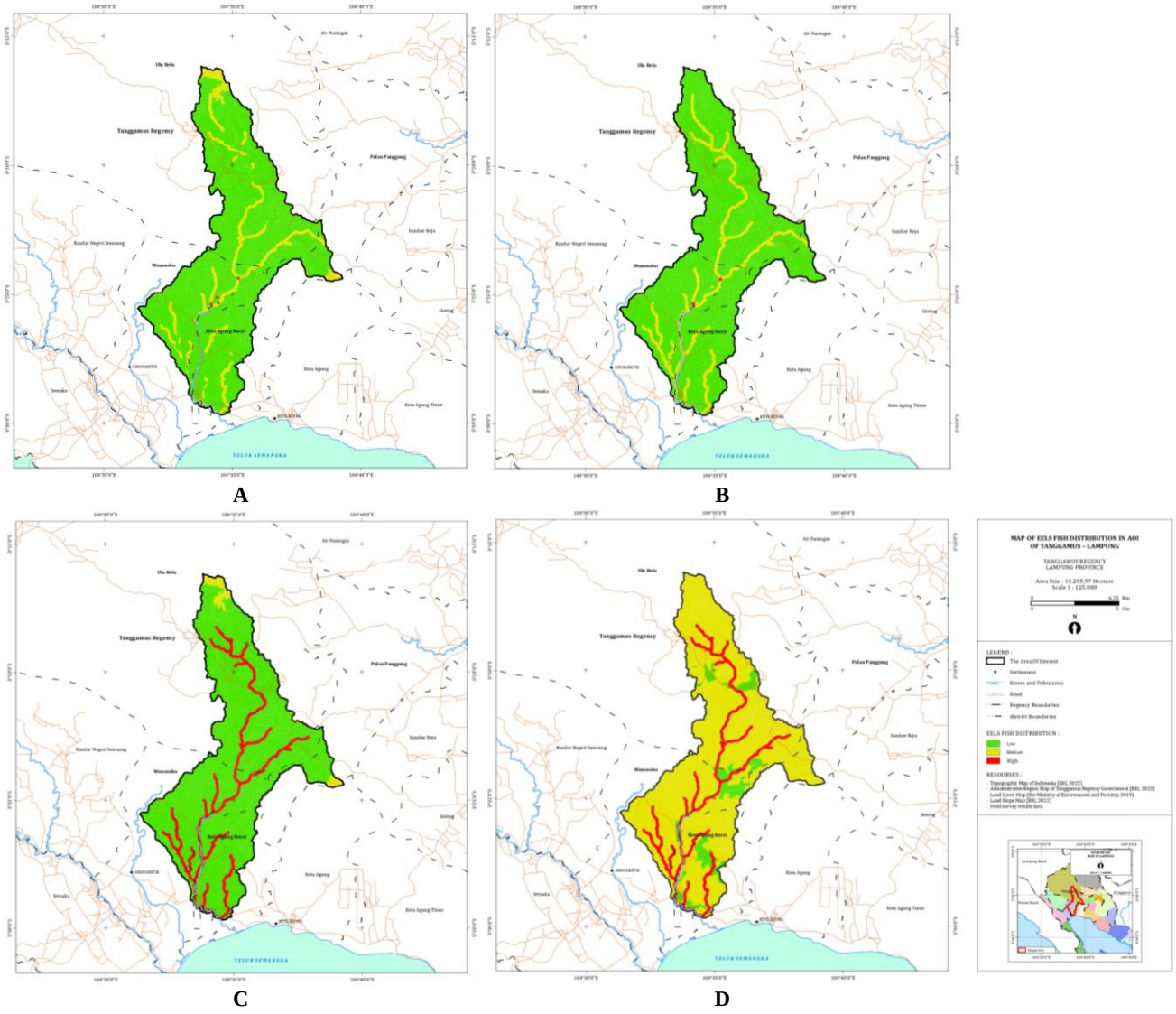

Figure 5. Distribution map of some plants and animals in Tenggamus Mountain, Lampung, Indonesia: A. Endemic vegetation; B. Birds; C. Amphibians; D. Fish

Mapping of key flora and fauna species habitat in South Sulawesi

APL of Latimojong Mountain, South Sulawesi

Conservation efforts at mining sites should focus on preserving biodiversity. This is because mining activities will disrupt vegetation establishment, and the basal area of shrubs and fragmented and open forests will be higher than before mining activities (Kpangui et al. 2021). Therefore, the APLs as the AOI that will be examined for flora and fauna distribution is the APL of Mount Latimojong, an area indicated to have the potential for mining material deposits (Figure 6). This is the main basis for assessing the impact of mining activities as the basis for mining mitigation strategies.

Despite the designation of this area as forest and its subsequent categorization as APL in the Latimojong Mountains of South Sulawesi, the ecosystem remains classified as a forest ecosystem that has undergone degradation due to land clearing, which was then followed by the cultivation of garden crops, including cloves, coffee, and cocoa. The condition of the existing land cover in the AOI for micro hydro plant area shows that it is dominated by most of the area is dry land mixed with shrubs (84.27%), followed by 6.66% wetland agriculture land cover, 5% pure dryland agriculture, 3.12% settlements, and the rest is secondary dryland forest and open land. Above this AOI is directly adjacent to the protected forest area. In contrast to the situation in Lampung AOI, the South Sulawesi AOI exhibits a distinguishing characteristic (Figure 7; Table 2). The presence of natural flora and plants in this region cannot be distinguished between natural and modified habitats. This is since some modified habitats, such as those found in mixed agricultural drylands, have been left by cultivators and have experienced natural succession. Consequently, these habitats already possess endemic flora resulting from the natural succession process and the results of planting (Figure 8). The presence of notable conservation vegetation species, such as (i) the banyan (*Ficus* sp.), which provides a nesting place for tarsiers and a food source for various birds and short-tailed monkeys; (ii) *dao* (*D. dao*), whose fruit is food for hornbills; (iii) kalopiso trees (local name, indeterminate), whose fruit for short-tailed macaques (tonkean); and (iv) *aren* (*Arenga pinnata*): the trunk is a nesting place for tarsiers; the fruit is food for tonkean monkeys, tarsiers, and cuscus. Wood from various types of trees is economically valuable to the community. These include various *bakan* trees (*Actinodaphne* sp.), *mara* (*Macaranga tanarius* (L.) Müll.Arg.), *dao* (*D. dao*), *rengas* (*Gluta renghas* L.), *kani* or *dadap* (*Erythrina fusca* Lour.), and *nyatoh* (*Palaquium* sp.). A notable tree, the *pulai* (*Alstonia scholaris* (L.) R.Br.), is used for its medicinal properties, with its bark and trunk used in traditional remedies. A comprehensive review of the existing literature reveals the diverse therapeutic applications of *pulai* wood and bark, including the treatment of prolonged fever, obesity, elevated cholesterol, dandruff and lice, toothaches, diarrhea, nausea, and malaria. At the same time, the fauna found in Mount Latimojong AOI is included in Table 3.

Based on the habitat characteristics of several species of animals found, they have been mapped as described in Figure 8.

Table 2. Land coverage in AOI in South Sulawesi

Land coverage	Area (ha)	Percentage (%)
Secondary dryland forest	551.11	30.57
Dryland agriculture	377.98	20.97
Dryland mixed agriculture	681.13	37.78
Shrubs	192.49	10.68
Grand total	1802.71	100.00

Table 3. Land coverage in AOI in Mt. Latimojong, South Sulawesi, Indonesia

Species	Family	2013	2017	2019	2022	IUCN	Note
Ailurops ursinus (Temminck, 1824)	Phalangeridae	1	1			VU	Endemic Sulawesi
Strigocuscus celebensis (Gray, 1858)	Phalangeridae	1	1			NT	Endemic Sulawesi
Macaca tonkeana (Meyer, 1899)	Cercopithecidae	1			1	VU	Endemic Sulawesi
Tarsius fuscus	Tarsiidae	1	1			VU	-
Sus celebensis Müller & Schlegel, 1843	Suidae	1	1		1	NT	Widespread
Babyrousa bolabatuensis Hoojer, 1950	Suidae	1				EN	-
Rusa timorensis (Blainville, 1822)	Cervidae	1	1			VU	Widespread
Bubalus depressicornis (C.H.Smith, 1827)	Bovidae	1				EN	Doubtful, see
Bubalus quarlesi (Ouwens, 1910)	Bovidae	1				EN	Burton et al. 2005
Macrogalidia musschenbroekii (Schlegel, 1877)	Viverridae	1	1			VU	Not yet recorded from S. Sulawesi
Acerodon celebensis (Peters, 1867)	Pteropodidae					VU	Endemic Sulawesi
Pteropus griseus (E.Geoffroy, 1810)	Pteropodidae					VU	Sulawesi & East Nusa Tenggara
Rousettus bidens (Jentink, 1879)	Pteropodidae	1				VU	Endemic Sulawesi
Accipiter nanus (W.Blasius, 1897)	Accipitridae	1				NT	Endemic
Ichthyophaga humilis (S.Muller & Schlegel, 1841)	Accipitridae	1				NT	Widespread SE Asia
Lophotriorchis kienerii (Sparre, 1835)	Accipitridae	1				NT	-
Macrocephalon maleo S.Müller, 1846	Megapodiidae					EN	Nesting ground not in this area
Megapodius cumingii Dillwyn, 1853	Megapodiidae	1				NT	Nesting ground not in this area
Ficedula rufigula (Wallace, 1865)	Muscicapidae	1				NT	Habitat loss
Rhyticeros cassidix (Temminck, 1823)	Bucerotidae	1	1		1	VU	Endemic
Penelopides exarhatus (Temminck, 1823)	Bucerotidae				1	VU	Endemic
Hydrosaurus microlophus (Bleeker, 1860)	Agamidae				1	DD	In CITES list
Malayopython reticulatus (Schneider, 1801)	Pythonidae	1	1		1	LC	In CITES list
Macaranga tanarius (L.) Müll.Arg.	Euphorbiaceae	1	1		1	LC	In CITES list
Erythrina fusca Lour.	Fabaceae	1	1		1	LC	In CITES list
Palaquium sp.	Sapotaceae	1	1		1	VU	In CITES list
Total		21	11	0	9		

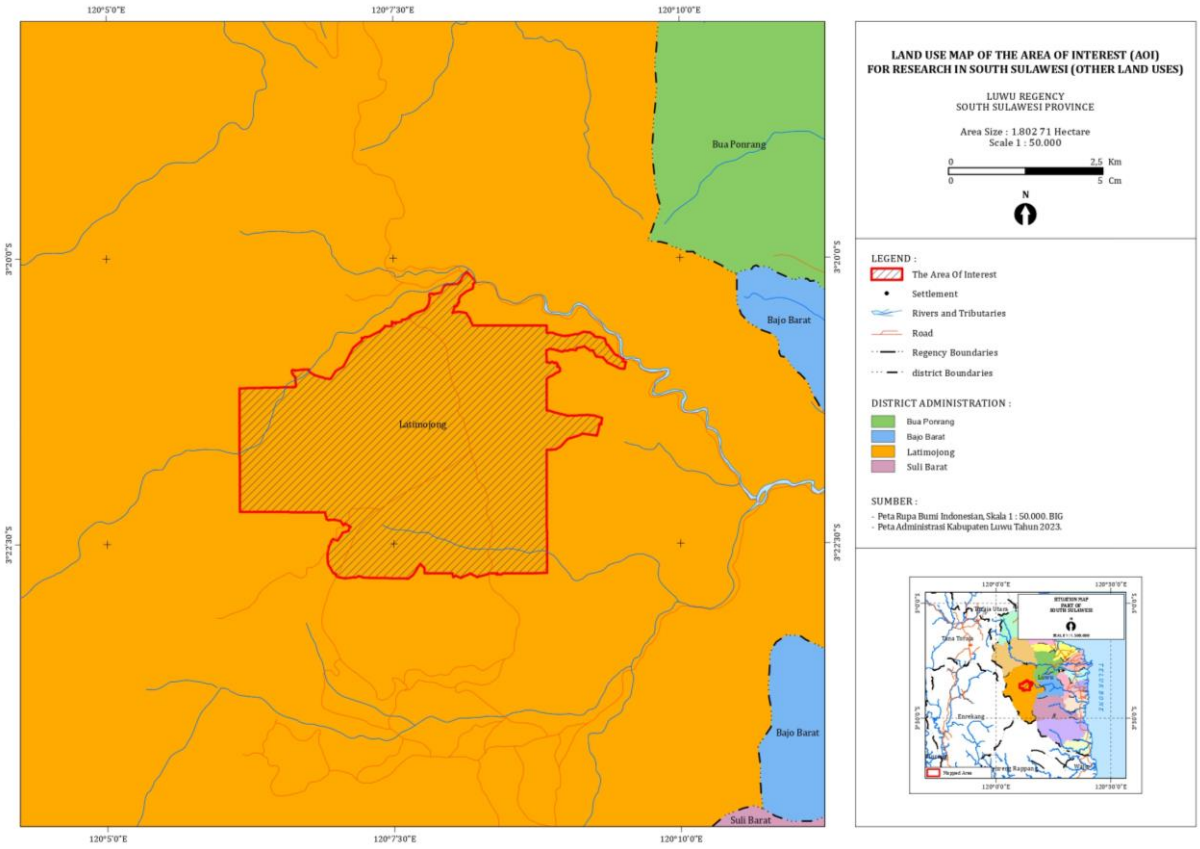

Figure 6. An area of interest for research is APL. There is the potential for gold mining in Mt. Latimojong, South Sulawesi, Indonesia

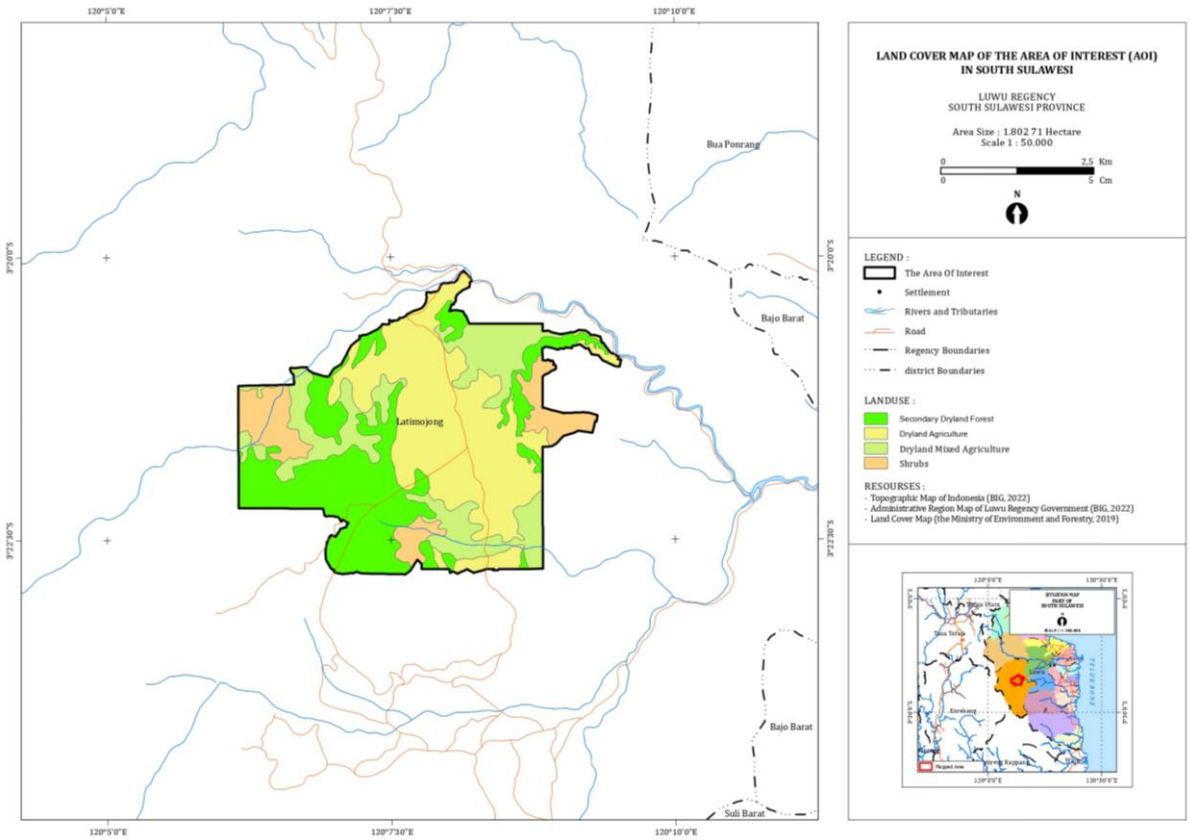

Figure 7. Land coverage in AOI in Mt. Latimojong, South Sulawesi, Indonesia

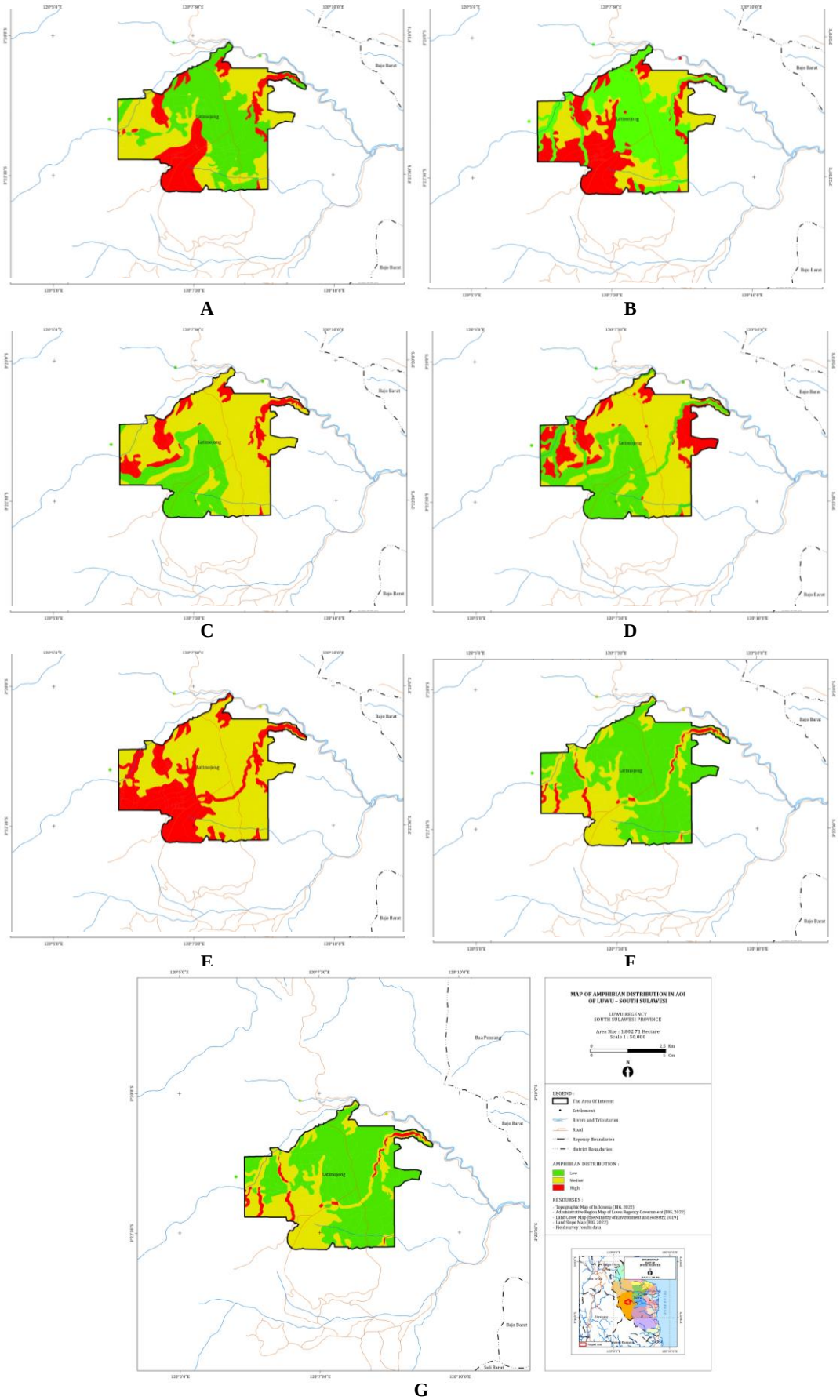

Figure 8. Distribution map of some plants and animals in Tenggamus Mountain, Lampung, Indonesia: A. Endemic vegetation; B. Black eagle; C. Hornbill's; D. Tarsius; E. Sulawesi pig; F. Amphibia; G. Eel

Discussion

Dracontomelon dao is an endemic species of lowland forests, capable of thriving in diverse soil conditions, particularly in alluvial soils and swampy (Putri et al. 2022); this species is distributed in Sumatra, Kalimantan and Sulawesi Islands (Kurniawan et al. 2008). In degraded habitats in Sulawesi, *D. dao* was one of the dominating species compositions in these sites alongside *Diospyros celebica* Bakh., *Canangium odoratum* (Lam.) King, *Ficus benjamina* L., *Pterospermum celebicum* Miq, *Kleinhovia hospita* L., and *Vitex cofassus* Reinw. ex Blume. BB, CS, FP, and PB (Nessi et al. 2023). In remnant forests throughout Visayas, Philippines, *D. dao* has to be only encountered as singletons (Peque and Hölscher 2014). In the two study sites, the APL on Tenggamus Mountain and Latimojong Mountain, *D. dao* was also found in singletons.

The primate species in Indonesia exhibit considerable diversity, ranging from the smallest to the largest. A total of 59 primate species from 11 genera inhabit Indonesian forest habitats. These include *M. nemestrina*, which is found on the islands of Kalimantan and Sumatra; *S. syndactylus*, which is found on the island of Sumatra; and *Tarsius fuscus* Fischer, 1804 (Ruskhanidar et al. 2017). In addition to natural conditions, various primates are found in modified habitats, such as farmland (Utari et al. 2023). *M. nemestrina* is classified as Endangered due to a 50% population decline in the last three generations (approximately 33 years), which is expected to continue to decline without intervention. Some of the factors leading to the decline are the conversion of prime habitat to agricultural land (e.g., oil palm, durian, rubber), mining, and habitat degradation due to deforestation, road building, and infrastructure development, as well as draining of peat swamps and seasonal forest burning (Rupert et al. 2022). In Philippines, seventeen threats to tarsiers are involved, ranging from high, medium, or low. Then, 11 threats caused and/or exacerbated fragmentation were involved. Two were assessed as serious threats, four as medium, and four as low. Those 11 of the threats identified may result from fragmentation or habitat destruction. The direct threats to tarsiers include incidental hunting for pets, sometimes with dogs. Excessive noises can sometimes be heard in the area while harvesting trees, forest fires, and typhoons. These could also cause an open canopy, allowing excessive light to penetrate the forest. The presence of houses near the forests, farms, and recreational areas in the forest would likely threaten the species in the future, possibly by exacerbating habitat loss (Torrefiel et al. 2023). The population of siamang is threatened due to the reduced quantity and quality of habitat and hunting of wild animals. Siamang has a category of endangered based on the IUCN (The International Union for Conservation of Nature) Red List (2019). Based on the threat to the wildlife trade, siamang is classified on Appendix I CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora), where their population is declining in natural habitat, so their trade is very strict by the government. In Indonesia, siamang is protected by the state based on the Regulation of the Minister of Environmental and Forestry Number P.106 of 201 (Rasyid et al. 2024).

Tarsier habitats typically include secondary forests, garden forests, the edges of secondary forests adjacent to plantations or farms, and areas surrounding human settlement (Mustari et al. 2013), with resting places or nests generally in bamboo clumps, especially thorny bamboo (*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f.). There are 52 plant species from 30 families in tarsier habitat and are dominated by Euphorbiaceae and Bambusaceae (Wirdateti and Dahrudin 2008), while in Central Kalimantan, it was found in 43 vegetation types (Octavianus 2020). At the research site, the APLs of Mount Tenggamus, *M. nemestrina*, and *S. syndactylus* were found to inhabit hilltops within fragmented ecosystems. Due to their dispersed distribution, these species cannot be mapped. In contrast, the APLs of Mount Latimojong, *T. fuscus*, have been observed to reside within *Ficus* sp., allowing for their mapping. The presence of tarsius and cuscus has been documented in a secondary forest that has experienced minimal disturbance. The area is also home to forage trees and human habitation, including banyan and sugar palm trees.

Sulawesi forest pig (*Sus celebensis* Müller & Schlegel, 1843) lives in various habitats, including primary forests and swamps, open grasslands, and agricultural areas. The species is found at all altitudes up to moss forests >2,500 masl, although it is less common above 1,500 masl. (Melletti and Meijaard 2018).The Sulawesi forest pig, also known as the Sulawesi warty pig (*S. celebensis*), is an extant wild pig endemic to the Indonesian island of Sulawesi. However, there is a theory that *S. celebensis* was domesticated and/or deliberately introduced to other islands in Indonesia before the advent of the Neolithic agricultural transition in the region. According to this theory, the long-standing practice of hunter-gatherers intensively rearing wild-caught *S. celebensis* piglets for adoption into human society as pets may have altered the predator-prey dynamic brought aspects of wild pig behavior and reproduction under indirect human selection and control and caused changes that differentiated pigs in contact with humans from those living in the wild (Brumm 2023). On the other island, for example, West Java, the fact that hunters frame their pig hunts as partly public service for pest control while enjoying the esoteric aspects of it as a thrill and a hobby shows that this activity has a strong psychological and moral footing for its sustainability (Mulyanto et al. 2021). The continued hunting is because wild pigs are considered a pest and as part of the survival of agriculture.

The presence of hornbills in given is closely associated with food availability. An increase in food sources leads to corresponding rise in the hornbill population. The primary food source of hornbills is fruit-bearing; therefore, their population dynamics are influenced by the fruiting seasons of these trees (Fitriansyah et al. 2022). Apart from fruiting trees, hornbills also have different trees for nesting. Mount Ungaran, Central Java, Indonesia, the trees that were used for nests were *salam klontong* (*Syzygium glabratum* (DC.) Veldkamp), *nagasari* (*Syzygium antisepticum* Blume) Merr. & L.M.Perry), and *marong* (*Cratoxylum formosum* (Jack) Benth. & Hook.fil. ex Dyer). *Syzygium glabratum* and *S. antisepticum* belong to family of Myrtaceae. The height of these trees ranged between 24-35 m with a diameter of

0.83-1.75 m (Rahayuningsih et al. 2017). The black eagle (*Ictinaetus malayensis* (Temminck, 1822)), as a raptor or bird of prey, is a top predator in the food chain as a counterweight and indicator of ecosystem health in forest areas and presence in Java Island at Bromo Tengger Semeru National Park (TNBTS) as habitat (Ningtyas et al. 2021). In India, *I. malayensis* is a major predator in the evergreen mountain forests of Mizoram, mainly preying on rodents, thus playing a very important role in controlling rodent populations (Sailo et al. 2020). The black eagle (*I. malayensis*) distribution in China was historically restricted to the Fujian, Taiwan, and Yunnan regions. However, in the last two decades, there has been an increase in the number of sightings across China, indicating an expansion of the habitat of the black eagle in suitable forests (Lei et al. 2014). Whereas in the research locations, namely on Mount Tenggamus and Mount Latimojong, hornbills were found. The food tree was *D. dao*, and the food source and nest were *Ficus* sp. However, black eagles are only found and can be mapped on Mount Latimojong, South Sulawesi Province.

The productive and physiological amphibians, ectothermic reptiles, are strongly influenced by rainfall, water availability, and temperature. So, amphibians depend on external heat sources for the thermoregulation process of distribution underlying speciation, dispersal, and local extinction vary according to climate factors (Cruz et al. 2024). In Italy, abiotic river features mainly affected the amphibian community, while otters or fish as predators did not seem to have a detrimental effect on the amphibian community (Nessi et al. 2023). The environmental categories of amphibians in Lombok were classified into three categories. Category 1 has a high influence, consisting of humidity, canopy, and tree species richness. Category 2 has a moderate influence: altitude, air temperature, and water temperature. Category 3 has a low influence, consisting of river length, river width, left and right river width explored, and river slope (Syazali et al. 2017). Likewise, in the study site, Amphibians were found in streams on various land covers in the APLs of Mount Tenggamus and Mount Latimojong. The habitat of Amphibians is located in small streams as part of larger river systems, particularly areas with forest vegetation cover and spring water. The distribution of amphibian's presence along the riverbank with widths up to 50 cm on both the right and left sides of rivers is influenced by the condition of the vegetation. By overlaying maps of tributary streams and analysing the condition of the land cover, we can gain insights into the distribution patterns of amphibians in a given region. The following map and table illustrate the results of this analysis.

The eel life cycle consists of five stages: leptocephalus, glass eel, elver, yellow eel, and silver eel. Leptocephalus stages occur in the marine environment, where it undergoes metamorphoses into glass eels stage. Glass eel then migrate from seawater to freshwater, where they grow and mature into silver eels. Upon reaching maturity, silver eels return to the sea to spawn (Rachmawati et al. 2023). The quantity of young eel immigrating to freshwater habitats has been monitored in some river mouths, using eel traps often connected to eel passes, while growing yellow eel in freshwater habitats has been paid less attention. Eel habitat is in large rivers or springs with the most natural vegetation cover, assuming that human activity is minimal (Degerman et al. 2019). The eel fish is a catadromous, so its initial habitat starts from the deep sea. After hatching will follow the flow of ocean currents to migrate to the mouth of the river. From the mouth of the river, the eel (*A. bicolor)* will live in river bodies, swamps, rice field irrigation channels, canals, waterways connected to sea waters, and up to the lake (Romadhi et al. 2022), with water quality conditions, namely, sufficient water salinity, and the river mouth remains connected to the sea even during the dry season (Sugianti et al. 2020). Because of a complex life cycle, catadromous fish species face any level threats of multiple anthropogenic activities that have resulted in worldwide decline since the beginning of the 20th century (Podda et al. 2021). Referring to information from the Ministry of Fisheries and Maritime Affairs of the Republic of Indonesia, the existence of this fish is recorded to be spread across several countries in Africa, Oceania, and Asia. This fish is found in Indonesia, Myanmar, the Philippines, Vietnam, and Thailand in Southeast Asia. In Indonesia itself, the distribution area is along the west coast of Sumatra, the south coast of Java, Bali, NTB, NTT, along the east coast of Kalimantan, Sulawesi Waters, Maluku, to Waters in Papua. At the research site, the eel distribution presence indication can be mapped both in the APL of Mount Tenggamus and in the APL of Mount Latimojong, that is, in streams of various land covers.

Management implications

Biodiversity offsets are conservation strategy designed to compensate for biodiversity losses while ensuring the protection and maintenance of biodiversity values in alternative locations. Offsets generally can be applied where biodiversity loss cannot be avoided, mitigated, or minimized from development proposals (Fallding 2014). It functions as a planning and decision-making instrument that acknowledges and assigns value to biodiversity, facilitating the mitigation of impacts as part of land-use planning processes. Offsetting enables the preservation and management of biodiversity in areas where onsite protection is infeasible or impracticable biodiversity offsets companies have voluntarily implemented to achieve no net loss or net gain of biodiversity to compensate for residual biodiversity loss from their activities. Mining industries have implemented these in Madagascar (Ta and Campbell 2023). Although biodiversity offsets are applied in many countries to compensate for environmental impacts, research on regulatory frameworks and implementation enabling effective offsets is lacking. Some aspects concern as well as the consideration is of trade-off when regulations focus only on the biodiversity aspect of ecosystems. This aspect can assess offsets of any land and support the reform of programs that balance development and conservation. Consequently, these scholars have called for a moratorium on their application. Nevertheless, it is imperative to undertake an empirical evaluation of existing programs, such as conservation banking, before arriving at a definitive conclusion regarding the merits or shortcomings

of any policy instrument (Grimm and Köppel 2019). The location that can be used as a biodiversity offset area to save wildlife on APLs is by ex-situ conservation, namely the cultivation and protection of plants and animals outside their natural habitat with several methods, namely handing over management to zoos, botanical gardens, aquaria, seed banks, pollen banks, semen banks, tissue culture banks, or through genetic engineering (Mahanayak 2024). But the most important thing is to minimize anthropogenic threats to wildlife in agricultural landscapes by establishing environmentally friendly farming practices that can sustain wildlife populations in the long term (Holzner et al. 2024). Furthermore, stringent stipulations imposed by the funding entity are poised to substantially influence the execution of biodiversity offset mechanisms.

Policies of conversion forestland to other land use (APLs) for activities not associated with the forestry sector, such as agriculture, plantations, transmigration, mining, and power generation development, should be concerned with key vegetation and animals that are stuck in APLs. If this is not a concern, these key plants and animals will soon become extinct due to habitat fragmentation, changing the ecosystem in which key plants grow and the home range of key animals. Therefore, when planning land use for agriculture, plantations, mining, or micro-hydro development, it is necessary to require biodiversity offsets if key plants and animals are found in the area to be used. To ensure their presence, mapping the distribution of key wildlife is necessary.

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Empowering women for biodiversity conservation in Mt. Lantoy Key Biodiversity Area Argao, Cebu, Philippines

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[1]Department of Forestry, College of Agriculture, Forestry and Environment, Cebu Technological University. Ed Kintanar Street, Argao 6021, Cebu, Philippines. Tel.: +63-32-401-0737 Ext. 1700, ♥email: lillo.edgardo1@gmail.com
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Abstract. *Lillo EP, Alcazar SM, Malaki AB, Cutillas AL, Chavez MLM, Abejo III MR, Cañarijo III DM, Redoblado BR, Margate MA, Diaz JL, Mago JE, Belanizo J, Beceril R, Revillas MJ, Davirao C, Obando ME, Diaz GGG, Gonzaga CF, Cagara BN, Dano VL. 2025. Empowering women for biodiversity conservation in Mt. Lantoy Key Biodiversity Area Argao, Cebu, Philippines. Asian J For 9: 137-143.* Women play a vital role in agricultural production and natural resource management. However, they often face barriers that limit their decision-making power and leadership in environmental initiatives. This study investigates the role of gender in biodiversity conservation, focusing on women's participation, practices, challenges, and perceptions in the Mt. Lantoy Key Biodiversity Area (KBA) in Argao, Cebu, Philippines. Using a mixed-methods approach, the research employed structured surveys, Key Informant Interviews (KIIs), and Focus Group Discussions (FGDs) with the same respondents to cross-check results. The findings reveal that while women are actively involved in daily resource use such as household provisioning and small-scale farming, only 36.7% have participated in formal conservation activities like tree planting and community cleanups. Societal expectations, including caregiving and household responsibilities, significantly constrain their involvement, alongside a lack of specialized training and limited access to decision-making platforms. Despite these challenges, respondents expressed strong support for women's leadership in conservation, recognizing its potential to improve ecological outcomes and community resilience. The study emphasizes the need for gender-responsive strategies in local and national policies, such as flexible participation schedules, capacity-building programs, and mechanisms to recognize women's contributions to conservation. Empowering women through targeted reforms and inclusive governance can enhance biodiversity conservation in the Mt. Lantoy KBA, contributing to goals like food security, climate adaptation, and poverty reduction.

Keywords: Biodiversity conservation, climate resilience, community participation, conservation policy, women's leadership

INTRODUCTION

Women play a critical yet often under-recognized role in biodiversity conservation, particularly in rural and marginalized communities. Broeckhoven and Cliquet (2015) emphasizes that gender minorities, particularly women, face discrimination that contributes to biodiversity loss. Despite these challenges, women are increasingly assuming leadership positions to enhance their families' and communities' resilience against climate-related impacts and disaster risks (Broeckhoven and Cliquet 2015). In addition, women have traditionally been responsible for meeting their families' food, medicinal, and nutritional needs and play an essential role in households. Women are involved in almost all aspects of farming, from seed selection, planting, weeding, winnowing, harvesting to storing seeds (Pradhan et al. 2021).

The development sector has made significant strides in addressing gender disparities, aiming to engage and empower women through targeted interventions in both policy and practice. Empowering women and promoting gender equality is critical in achieving the Sustainable Development Goals (SDGs) and is at the core of efforts to eradicate poverty and hunger, improve education and health, combat climate change, and addressing environmental challenges (Pradhan et al. 2021). Addressing gender inequality in biodiversity conservation is fundamental in attaining goals and targets under the Global Biodiversity Framework 2030 by Convention on Biological Diversity's and aligning them with the Sustainable Development Goals (SDG) (Pradhan et al. 2021). Evidence supports the notion that gender equity leads to more effective, inclusive, and sustainable conservation efforts (Alvarez and Lovera 2016; Lau 2020). Increased participation of women in conservation science, gives multiple benefits to societies at local and national level (Alvarez and Lovera 2016; Cook et al. 2019). A study by Widiastuti (2024) demonstrates that natural resource conditions improve when women are actively involved in management, and environmental policies are strengthened when women participate in decision-making processes.

Intentionally including women in conservation efforts leads to positive social and environmental outcomes

(Taukobong et al. 2016). Nevertheless, globalization, climate change, land degradation, and biodiversity loss present new challenges and opportunities for women. In mountainous and upland areas, rapid depletion of natural resources results in declining agricultural productivity and ecosystem health (Pradhan et al. 2021). In the Philippines, karst landscapes, which cover 11.7% of the nation's landmass, significantly impact endemic flora and fauna (BMB-DENR 2019). Mount Lantoy in Cebu Island Philippines is identified as a Key Biodiversity Area (KBA) and home to several endemic species of flora and fauna (Lillo et al. 2019). The area harbors 112 plant species, classified into 64 families and 84 genera, including 88 native tree species, with 17 classified as threatened. Of these, two species are critically endangered, three are endangered, nine are vulnerable, and three are categorized as other threatened species. The high species diversity index in the area proves the ecological significance of Mount Lantoy and its potential for conservation initiatives (Lillo et al. 2019).

Mount Lantoy faces significant threats, including illegal logging, hunting, and the conversion of forests to agricultural land, leading to moderate ecological disturbances (Lillo et al. 2019). Despite their critical ecological roles, local communities, including women, have limited participation in conservation efforts, as observed in the area. This study aims to explore the role of empowering women for leadership in biodiversity conservation within the Mt. Lantoy Key Biodiversity Area (KBA) in Argao, Cebu, Philippines. This investigation seeks to examine the intersection of gender and conservation leadership, emphasizing the role of women in achieving long-term, sustainable biodiversity outcomes in the region (Pascual et al. 2014; Broeckhoven and Cliquet 2015; Kariuki and Birner 2016; Yang et al. 2018).

This study specifically focuses on the role of women in biodiversity conservation within the Mt. Lantoy KBA, exploring their participation, challenges, and perceptions regarding conservation practices in the area. It aims to highlight the significance of fostering women's leadership in conservation efforts to enhance not only the ecological resilience of Mt. Lantoy but also to promote broader societal benefits. These benefits include advancing gender equity, improving sustainable livelihoods, and ultimately contributing to the realization of national and global biodiversity conservation goals. By empowering women, particularly in leadership roles, this research seeks to promote inclusive conservation practices that recognize and leverage the invaluable contributions women can make to protect our natural heritage. Through this study, we emphasize the importance of gender in achieving effective and sustainable conservation outcomes, particularly in areas with rich but vulnerable biodiversity like Mt. Lantoy.

MATERIALS AND METHODS

Study area

This study was conducted in the vicinity of Mount Lantoy (9°54′9″N, 123°32′9″E), a designated Key Biodiversity Area (KBA) in Cebu, Philippines (CI, DENR, and Haribon 2006). Six barangays, including Butong, Conalum, Cansuje, Catang, Tabayag, and Usmad, comprise the surrounding community (Lillo et al. 2019) (Figure 1). Mount Lantoy is one of 117 terrestrial KBAs in the Philippines, identified based on criteria of vulnerability and irreplaceability, and is part of a larger KBA of Mount Lantoy and Nug-as which covers 10,457 hectares. These areas serve as habitat to a number of threatened species, including two that are critically endangered, two endangered, four vulnerable, and sixteen classified as restricted-range (CI, DENR-PAWB, and Haribon 2006). Consequently, the conservation and protection of Mount Lantoy as KBA depend largely on the management and supervision of local communities.

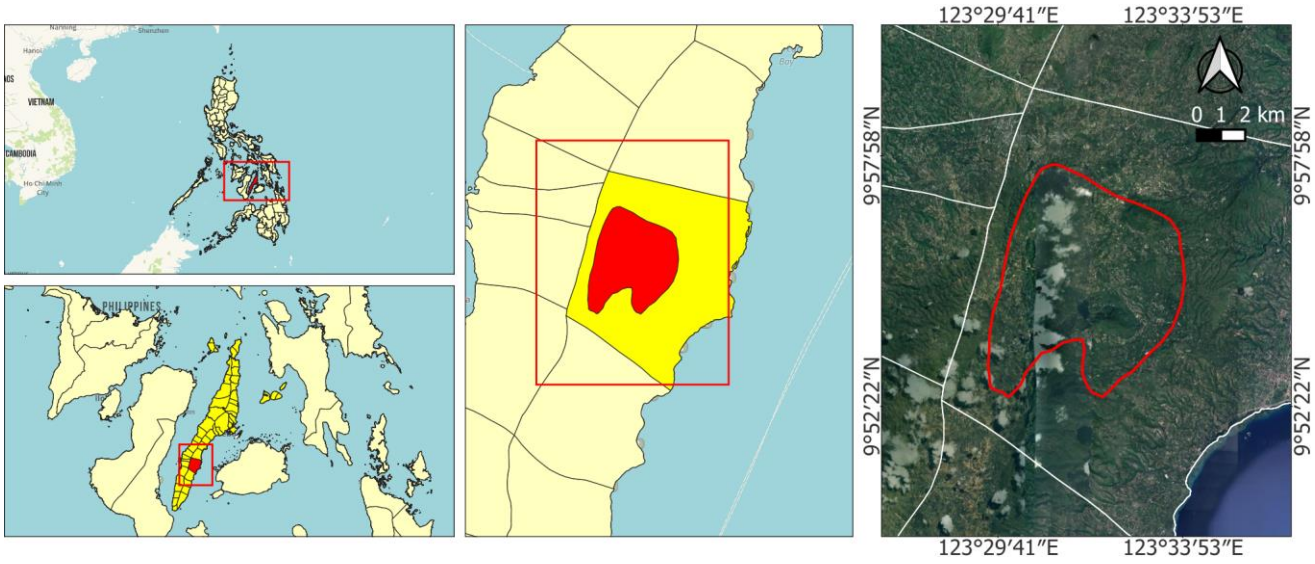

Figure 1. Map of study area in the Mt. Lantoy Key Biodiversity Area (KBA) in Argao, Cebu, Philippines

Data collection

In this study, data collection was focused on assessing the pivotal role of women in biodiversity conservation within six barangays adjacent to Mount Lantoy Key Biodiversity Area (KBA). A representative sample comprising 10% of the total female population in these barangays was selected using simple random sampling, resulting in 89 participants. A structured questionnaire served as the primary data collection tool, and included questions on demographic profiles, participation in biodiversity conservation activities, problems and issues encountered in conservation efforts, perceptions of gender equity's impact on conservation, and views on incorporating gender-responsive approaches in conservation policies.

To enrich and validate the quantitative data collected, qualitative data were gathered through Key Informant Interviews, and Focus Group Discussions (FGDs) with the same respondents to cross-check results. This mixed-methods approach enabled a more comprehensive understanding of women's involvement in conservation initiatives in the Mount Lantoy KBA.

Data analysis

The data were initially encoded in an Excel spreadsheet for analysis of frequency and percentage distributions. These encoded data were subsequently imported into IBM SPSS version 20.0 software for verification. The use of SPSS for verification allows for rigorous checks, minimizing errors related to data entry and ensuring that the results are reliable and consistent.

RESULTS AND DISCUSSION

Demographic profile of the respondents and its correlation with conservation

Marital status

As presented in Table 1, the majority of respondents (75.3%) are married, while only 7.9% are widowed. During the focus group discussions, the research team asked participants how their current civil status influenced their potential involvement in biodiversity conservation efforts in Mount Lantoy Key Biodiversity Area (KBA). The married respondents expressed their willingness to participate in environmental conservation activities, provided these efforts do not conflict with their household responsibilities. Married women, in particular, highlighted that they often take on the primary role in managing household tasks, especially when their husbands are away for work. They indicated that they would be more likely to engage in environmental activities, particularly those funded by the government. This aligns with their belief that government-supported initiatives would be more feasible for participation, as such programs are often seen as beneficial to their families and communities. According to Van Aelst and Holvoet (2016) married women in Tanzania were more likely to access external projects and resources, thereby enhancing their ability to participate in conservation initiatives.

Furthermore, under the Philippine government's Pantawid Pamilyang Pilipino Program (4P's), households that are members of the program are required to participate in activities related to environmental conservation, especially if they reside within areas like the KBA. Many respondents, particularly those in the 4P's program, emphasized that their participation in conservation activities would be dependent on the alignment of these activities with their household duties.

On the other hand, widows expressed challenges in consistently participating in such initiatives. They explained that their primary focus is on livelihood activities that sustain their families, particularly their children. For many widows, the time and resources required for regular engagement in biodiversity conservation activities are limited, as they prioritize securing their family's immediate needs. These findings underscore the broader point that women are not a homogeneous group; varying social identities, including marital status, shape different lived experiences and power asymmetries (Murali et al. 2021). The varying levels of participation based on marital status highlight the importance of designing biodiversity conservation programs that consider the different roles and time commitments of community members. Policies that integrate family responsibilities, particularly for women and widows, will likely lead to higher and more sustained participation in conservation efforts. This approach ensures that everyone, regardless of marital status or social standing, has the chance to contribute to and benefit from the sustainable management and protection of natural resources, particularly in the Mount Lantoy Key Biodiversity Area.

Educational attainment

The majority of respondents (69%) have completed their high school education and enrolled college degree but failed to graduate, while 30% have graduated college and some (2%) pursued postgraduate studies (Table 1). Notably, all respondents who graduated college with postgraduate degrees are teachers working at the elementary and high school levels (Table 1). These individuals have earned Master's and Doctoral degrees in education and currently hold leadership positions within the Department of Education.

Table 1. Demographic profile of the respondents in the Mt. Lantoy Key Biodiversity Area (KBA) in Argao, Cebu, Philippines

Profile of the respondents	Attributes	Frequency	Percentage
Marital status	Live-in	7	7.9
	Married	67	75.3
	Widow	7	7.9
	Single	8	9.0
	Total		100
Educational attainment	Post graduate	1	2
	College graduate	13	28
	College undergraduate	6	13
	Vocational	1	2
	High school graduate	25	54
	Total		100

The Focus Group Discussion (FGD) further underscored distinct perspectives on biodiversity conservation across different educational groups. Respondents with high school and undergraduate education expressed a willingness to engage in conservation activities, though they highlighted concerns that such efforts must not interfere with their household responsibilities, particularly for married women or their livelihood activities, especially among widowed participants. This suggests that, for individuals with lower educational attainment, practical constraints related to daily life and livelihood often shape their ability and willingness to engage in biodiversity conservation activities (Oldekop et al. 2022).

Conversely, respondents with college degree and have postgraduate degrees, particularly those employed as teachers, focused predominantly on educating their students about the importance of biodiversity, the diverse species within the environment, and conservation strategies. Their role in conservation was more indirect, emphasizing raising awareness and fostering environmental responsibility among the younger generation, especially in relation to Mount Lantoy's Key Biodiversity Area (KBA). This aligns with the findings of Oldekop et al. (2022), which suggest that individuals with higher levels of education, particularly educators, are more inclined to prioritize environmental education and awareness-raising efforts.

The educational background of respondents also has significant implications for the effectiveness of biodiversity conservation initiatives. Those with higher educational attainment are more likely to engage with scientific discussions and contribute to strategies aimed at preserving biodiversity. However, their involvement is typically more focused on educational activities rather than direct fieldwork or community-based conservation efforts. On the other hand, respondents with lower levels of education may benefit from conservation programs that are tailored to their specific realities. Such programs should account for the practical challenges they face, including time constraints and household duties, which can limit their participation in conservation activities (Oldekop et al. 2022; Xu et al. 2022). Additionally, Børresen et al. (2022) highlights the importance of local knowledge of ecosystem services and their relationship with livelihoods in the sustainability of natural resources, which directly affects community well-being.

This study further illustrates that educational attainment plays a crucial role in shaping how individuals contribute to biodiversity conservation. As Majumder (2018) points out, education enhances personal capacity, helps individuals overcome obstacles, and expands opportunities for well-being. Emayavaramban et al. (2020) also notes that while men tend to travel far for work, women often remain on farms, working within their communities. These gendered roles may influence how individuals approach conservation, with women more likely to stay within the local context and engage in community-based activities.

Given these findings, it is clear that future conservation initiatives in the Mount Lantoy KBA should consider the varying educational levels and the specific needs of different groups. Programs should be designed to accommodate the practical constraints faced by individuals with lower educational attainment, while also leveraging the specialized knowledge and advocacy skills of those with higher levels of education. Such tailored approaches will enhance the inclusivity and effectiveness of biodiversity conservation efforts.

Participation of women in biodiversity conservation activities

The result of the study reveals that only 36.7% of the respondents in Mount Lantoy KBA reported involvement in biodiversity conservation activities, with the majority focusing on tree-planting and community cleanup initiatives. In contrast, 60.7% of women did not participate at all. This limited engagement raises concerns about the overall inclusivity and effectiveness of biodiversity conservation programs in Mount Lantoy KBA. According to Widiastuti (2024), meaningful representation of women in decision-making processes is crucial for achieving equitable conservation outcomes. Guha (2025) similarly emphasizes that environmental justice and gender equality are interconnected, necessitating inclusive strategies to address environmental challenges and foster social equity.

Norms and attitudes about women's roles in environmental management can be achieved by working closely with community leaders to champion women's participation and share success stories of female-led conservation projects (Staples and Natcher 2015). When women's voices and experiences are integrated into conservation planning, programs are more likely to be responsive to the needs of local communities, fostering both ecological integrity and social well-being (Staples and Natcher 2015; Baynes et al. 2019).

By considering and increasing women's participation in biodiversity conservation efforts, Mount Lantoy KBA and other KBA's in Cebu Island can develop more equitable, innovative, and durable solutions. Bridging gender gaps in biodiversity conservation decision-making, not only enhances the effectiveness of ecological initiatives but also contributes to broader social and economic development. The current high percentage of non-participation suggests potential barriers in the long run, such as cultural norms, limited awareness of conservation issues, unequal access to resources or education, and inadequate policy support that will restrict women's engagement. Identifying and addressing these obstacles can yield significant benefits.

Ensuring greater female representation in decision-making forums not only strengthens the legitimacy of conservation policies but also enriches the diversity of perspectives and skills brought to bear on biodiversity conservation issues. Staples and Natcher (2015), as well as Baynes et al. (2019), emphasize that promoting gender equity in conservation extends beyond simply inviting women to attend meetings; it requires active engagement, leadership opportunities, and support from the broader community. Training and awareness-raising sessions for women can enhance their leadership skills, technical knowledge, and confidence, enabling them to play more substantive roles in conservation initiatives (Widiastuti 2024). Local governments and non-governmental organizations should implement policies and funding mechanisms that encourage and facilitate women's

involvement, ensuring they have a seat at the table and a voice in key decisions (Guha 2025). In Mount Lantoy KBA, these steps are especially critical for the long-term sustainability of biodiversity conservation efforts.

Respondent's perception towards impacts of gender equity in biodiversity conservation

The majority of the respondents (60%) agreed that promoting gender equity can lead to more effective and sustainable biodiversity conservation outcomes, while 40% remain neutral or disagree. These results are consistent with Silvestri et al. (2012) who argue that both men and women are integral to the stewardship of landscapes and resources. The inclusion of women in conservation efforts is not just a matter of gender equality, but a strategic approach to harness diverse skills, knowledge, and perspectives, which enhances the effectiveness of these initiatives.

In addition, over half of the participants (55%) agreed that gender equity positively impacts biodiversity conservation, while 27% disagreed and not perceiving a direct link between gender equity and improved conservation outcomes. The majority of the respondents' agreement to the concept reflects a growing awareness that diverse perspectives, particularly those contributed by women, are essential to the success and sustainability of conservation efforts. Study by Ben-Amar et al. (2017) emphasizes the critical role that women, especially in leadership positions, play in advancing environmental strategies within organizations. In addition, studies by Bravo and Reguera-Alvarado (2019) and Carvajal et al. (2022) also highlight the benefits of female representation in decision-making processes, noting that women's involvement leads to better social and environmental outcomes.

In this study, the positive perception of gender equity's role in biodiversity conservation underscores the idea that inclusive and diverse decision-making processes are essential in addressing the complex challenges of biodiversity loss. Women's participation contributes not only to more comprehensive conservation strategies but also to a more equitable resource management, leading to more resilient ecosystems and communities. Furthermore, local knowledge and experiences often possessed by women are crucial for understanding and managing natural resources sustainably.

The 40% of the respondents who remained skeptical or neutral regarding the positive impact of women's participation may reflect deep-seated traditional gender norms or biases that undervalue women's roles in natural resource management. This reluctance of the respondents could be linked to societal structures that have historically placed men in positions of authority, particularly in environmental decision-making. Challenging these perceptions requires targeted educational and outreach programs that highlight the empirical evidence supporting gender equity's benefits in conservation. Studies by Pascual et al. (2014), Broeckhoven and Cliquet (2015), Kariuki and Birner (2016), and Yang et al. (2018) emphasizing the crucial importance of gender equity in achieving successful biodiversity conservation outcomes. Ensuring equal participation of women in conservation initiatives is not just a matter of social justice, but a key to creating more inclusive, comprehensive, and ultimately more successful conservation strategies. However, these efforts will require ongoing advocacy, education, and the dismantling of gender-based barriers that limit women's roles in environmental stewardship, particularly in the conservation of Mount Lantoy KBA's.

Incorporating gender-responsive approaches in biodiversity conservation policies

The majority (62%) of the respondents believe prioritizing women's involvement in biodiversity conservation could lead to positive outcomes and project success. This strong endorsement underscores the importance of gender inclusion and reflects a growing awareness of the significant roles' women play in community-based conservation, resource management, and environmental stewardship (Elias et al. 2017). However, 28% of respondents expressed skepticism or hesitation, which could stem from traditional gender roles, cultural norms, or limited exposure to gender-inclusive initiatives. Meanwhile, the 10.1% who remained neutral likely represent those who are either uninformed or uncertain about how gender dynamics influence conservation outcomes. These findings highlight the critical need for education and awareness campaigns to build a deeper understanding of the benefits of women's participation in environmental management (Widiastuti 2024).

To fully harness the potential of gender-responsive strategies, policymakers must prioritize the development of inclusive conservation frameworks. These frameworks should not only acknowledge and celebrate women's contributions but also actively address barriers that hinder their participation (Guha 2025). Conducting gender impact assessments is essential to identify gender-specific challenges and opportunities. These assessments will guide the equitable allocation of resources and empower women to participate more fully in conservation initiatives.

Engaging local communities is also critical to fostering support for gender equity in biodiversity conservation. Community participation is a key determinant of the success of such policies, as it creates a sense of ownership and shared responsibility. Policymakers and conservation organizations should work collaboratively with communities to raise awareness of the value of gender equity and to break down cultural and structural barriers that limit women's involvement. Encouraging examples exist in places like Tost, Mongolia, where women are increasingly taking on key roles in snow leopard conservation efforts (Mijiddorj et al. 2019). In such contexts, improvements in women's status through enhanced education and greater participation in governance structures have created opportunities for their involvement in community conservation initiatives. These examples demonstrate that empowering women can lead to tangible conservation successes.

To ensure long-term effectiveness, continuous monitoring and evaluation of gender-responsive policies must be institutionalized. This will help track progress, identify gaps, and make necessary adjustments to ensure conservation efforts remain inclusive and impactful over time. By

addressing gender equity, fostering local participation, and ensuring adaptive management, biodiversity conservation policies can be more effective and sustainable, with broader benefits for communities and ecosystems alike.

In conclusion, women play a crucial role in the daily use and management of natural resources in Mt. Lantoy Key Biodiversity Area, Argao, Cebu, Philippines. However, their formal participation in biodiversity conservation activities remains limited. Only 36.7% of women have engaged in activities such as tree planting or community cleanups, highlighting a gap between their everyday contributions to environmental management and their involvement in organized conservation efforts. Several barriers hinder women's full engagement in formal conservation activities. Societal expectations around caregiving and household responsibilities place significant limitations on their time and mobility, preventing their active participation. Furthermore, a lack of specialized training, along with limited access to decision-making platforms, restricts their capacity to contribute meaningfully to conservation initiatives. Despite these challenges, the study found strong support for women's leadership in conservation efforts. Respondents recognized that women's leadership could enhance ecological outcomes and strengthen community resilience, reflecting a growing appreciation for gender-inclusive approaches in biodiversity conservation. To bridge the gap in women's participation, the study underscores the importance of integrating gender-responsive strategies into both local and national policies. Key recommendations include providing flexible participation schedules, establishing capacity-building programs, and creating mechanisms to formally recognize and value women's contributions to conservation. By addressing these challenges, women can take on more leadership roles in environmental initiatives, ultimately improving biodiversity conservation, food security, climate adaptation, and poverty reduction.

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Analysis of productivity from four stingless bees (Apidae: Meliponini) and forages in urban forest, South Sulawesi, Indonesia

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Abstract. *Budiaman, Rahman AF, Nurhayati, Jumadi NH, Khatima K, Prastiyo A. 2025. Analysis of productivity from four stingless bees (Apidae: Meliponini) and forages in urban forest, South Sulawesi, Indonesia. Asian J For 9: 144-151.* Non-timber forest products that are widely used by the community as additional income and are easy to do are stingless bee cultivation (meliponiculture). The productivity of stingless bees in several species is still not widely studied, and it is important to know the potential of stingless bee species that can be used for honey production and other products. This study aimed to compare the productivity of four stingless bees in the urban forest (Awani Bee Garden), South Sulawesi. The analysis used in this study was One-Way Analysis of Variance (ANOVA), Pearson correlation analysis, Principal Component Analysis (PCA), and descriptive analysis. The results showed that *Tetragonula sapiens* (Cockerell, 1911) had the highest productivity in the number of honey pots (50.50±6.97), number of brood cells (601.22±59.71), honey production (15.72±1.35 g), and propolis production (29.01±1.99 g). In contrast, *Tetragonula sarawakensis* (Schwarz, 1937) had the lowest productivity. Nest temperature was strongly related to productivity parameters, namely, the number of honey pots (0.853), the number of brood cells (0.857), honey production (0.942), and propolis production (0.956), while nest humidity had a weak relationship. PCA analysis showed that nest temperature, honey production, propolis production, and number of brood cells dominated PC1 (74.1%), with *T. sapiens* close to optimal productivity. The availability of 27 species of forage plants, which are important sources of nectar, pollen, and resin for the bees, supported these results, such as *Mangifera indica* L. and *Artocarpus altilis* (Parkinson) Fosberg. Of the four types of stingless bees studied, the best cultivated in the urban forest area was *T. sapiens* species, with almost all the highest production. These results emphasize the importance of managing nest conditions and feed diversity in supporting stingless bee productivity.

Keywords: Bee ecology, bee product yield, forage diversity, meliponiculture, nest microclimate

INTRODUCTION

Urban forests, as green urban areas with ecological functions, serve as potential habitats for honey bees, including stingless bees (Apidae: Meliponini). Despite the environmental pressure from urbanization, these bees have shown remarkable adaptability to urban environments (Souza et al. 2025). Their tolerance to disturbances and ability to utilize various feed sources, such as wild and cultivated plants (Vazhacharickal et al. 2024), is truly impressive. The vegetation in urban forests provides primary feed in the form of nectar, pollen, and resin, which are needed to maintain colony activity and produce products such as honey, bee bread, and propolis (Hristov et al. 2020). Variations in plant composition in a location greatly affect bee productivity because each bee species prefers certain types and qualities of feed sources (Kaluza et al. 2016). Importantly, the existence of urban forests in South Sulawesi plays a significant role in biodiversity conservation, serving as a place for stingless bee cultivation, as well as a biodiversity conservation area and the utilization of ecosystem services in urban areas.

Stingless bees are social insects that produce honey and other products, such as propolis and bee bread, with high economic and ecological value, especially in tropical areas such as Indonesia. These bees are widely distributed in tropical and subtropical regions, with more than 500 species identified globally (Bueno et al. 2023). The presence of stingless bees in Indonesia has begun to be considered an alternative to honey bee cultivation because of their ability to adapt to the environment and not being at risk of stinging (Prastiyo et al. 2024). Honey from these bees also has high bioactive value, including antibacterial and antioxidant activity (Martinello and Mutinelli 2021). This unique feature makes their honey a treasure trove of health benefits, intriguing researchers and health enthusiasts alike. In addition to honey, other products such as propolis and bee bread also have commercial potential. Stingless bees also play a role in plant pollination, which supports biodiversity and ecosystem sustainability (Toledo-Hernández et al. 2022). This role benefits urban forest ecosystems rich in species and depend on pollinator interactions. Differences influence stingless bee productivity in species, environment, and availability of feed sources (Flo et al. 2018). Environmental factors such as temperature and humidity also significantly determine colony activity and production (Abou-Shaara et al. 2017).

Awani Bee Garden is one of the stingless bee cultivation locations developing in South Sulawesi, with agroecosystem conditions in urban forests. Urban forest has diverse

potential, thus supporting the sustainability of stingless bee colonies and educational spaces (Vazhacharickal et al. 2020). Local studies on the relationship between environmental conditions and bee productivity are still limited, so this study will also play a role in supporting the development of sustainable bee cultivation. A vegetation-based approach with mapping of superior feed sources can be used to conserve and enrich bee feed plants (Ignatieva et al. 2023). Stingless bee cultivation management can support the existence of forests as buffer ecosystems (Wayo et al. 2025).

The four stingless bee species studied were *Tetragonula laeviceps* Smith (1857), *Tetragonula drescheri* (Schwarz, 1939), *Tetragonula sapiens* (Cockerell, 1911), and *Tetragonula sarawakensis* (Schwarz, 1937). Each stingless bee species shows different variations in productivity depending on environmental conditions and available feed sources (Suhri et al. 2021). Productivity differences may be influenced by preferences for feed types and the effectiveness of converting feed sources into bee products (Abrahamczyk and Kessler 2015). Bee feed sources are the main factors determining stingless bee colonies. Types of plants that flower throughout the year are the main determinants in maintaining the production of bee colonies (Al-Ghamdi et al. 2016). Natural and urban forests provide a diversity of plant species that produce feed that cultivated plants cannot replace. The existence and preservation of the surrounding forest are crucial for the sustainability of stingless bee cultivation. Research on stingless bee productivity has been widely eyed amidst the increasing public interest in sustainable bee cultivation. In addition to the economic potential of honey products and derivatives, stingless bee cultivation also supports biodiversity conservation (Harianja et al. 2023). The development of stingless bee cultivation in Indonesia can empower rural communities and diversify the local economy. Forested, well-maintained, and managed areas can be a natural resource for stingless bee cultivation. The challenges in this cultivation are low technical understanding, lack of data on cultivation conditions, and changes in land use around the cultivation area.

This study aims to analyze the productivity of four stingless bee species and their relationship to feed sources and nest conditions. The parameters observed include the number of honey pots, the number of bee bread pots, the number of brood cells, the weight of honey, the weight of bee bread, and the weight of propolis produced. In addition, flowering feed sources were identified during the research period around the research location, as well as temperature and humidity conditions in the nest, to see the relationship between nest conditions and productivity. The results of this study are expected to provide an overview of the most productive bee species at the research location. Thus, this study contributes to sustainable stingless bee cultivation based on urban forest ecosystems.

MATERIALS AND METHODS

Research location

The research location was Awani Bee Garden, Faculty of Forestry, Universitas Hasanuddin, Makassar, South Sulawesi, Indonesia (Figure 1). Located at coordinates 5°7'48.339"S 119°29'0.38"E, the stingless bee cultivation and education site lies within an urban forest and occupies gently sloping terrain at an elevation of 9 meters above sea level. Established on September 8, 2021, the site is managed by the Faculty of Forestry. It serves as an open-air laboratory for research as well as a learning space for students and the wider community. The area is surrounded by green space and designed to support interactions between stingless bees and vegetation, providing forage sources such as trees and shrubs.

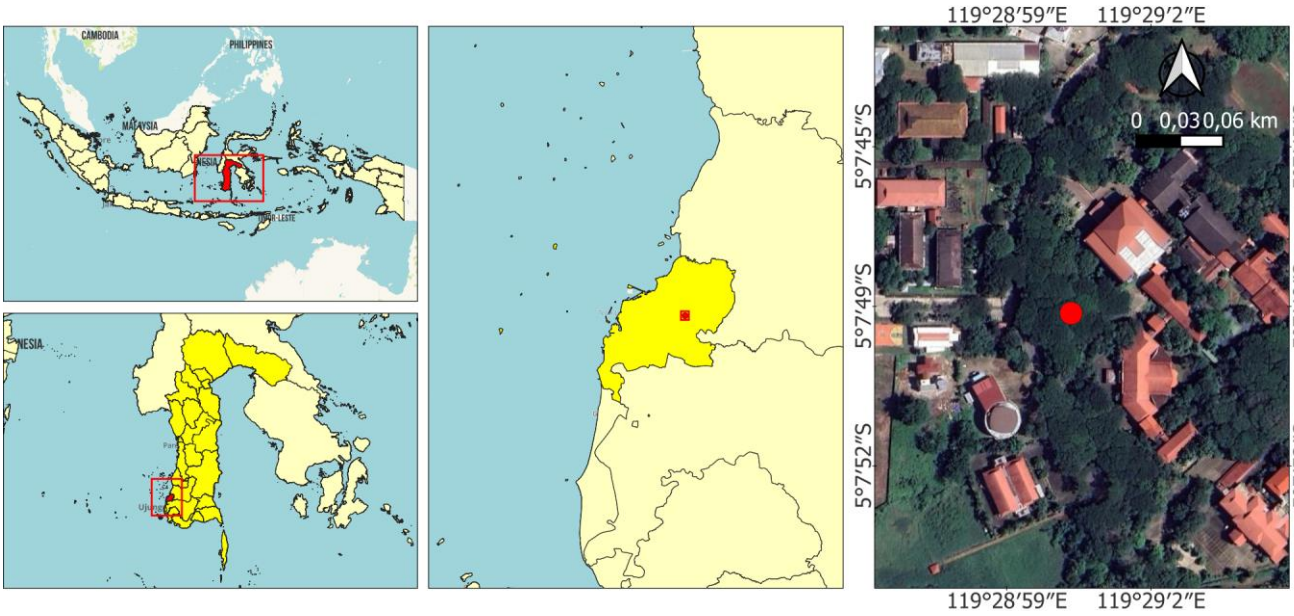

Figure 1. Map of research location at Awani Bee Garden, Makassar, South Sulawesi, Indonesia

Procedures

This study was conducted over three months (12 weeks), specifically from October to December 2024. The collection was carried out in a wet tropical climate, as Makassar falls within a humid equatorial zone. A total of 12 colonies were used as samples, with three colonies for each species. The bee boxes used measured 15×25×15 cm. All colonies were of the same age (1 month) post-transfer. The procedures in this study were adapted from Erwan et al. (2023) and further developed by incorporating correlation analysis between colony productivity and internal nest conditions, including temperature and humidity.

Number of honey pots, bee bread, and brood cells

Observations of the number of honey pots, bee bread pots, and brood cell counts in the four stingless bee species were conducted directly. Calculation of all parameters is done using counters. The four stingless bee species have nest structures that are quite similar (Figure 2).

Production of honey, bee bread, and propolis

The production of honey, bee bread, and propolis was obtained at the end of the study. The honey pot in each hive was taken with a knife and collected, then squeezed and weighed with a digital scale (Radwag AS 220/C/2) with an accuracy of 0.0001 g. Likewise, the bee bread that had been separated from the pot was weighed. Propolis was cleaned with honey, and bee bread was collected and weighed.

Measurement of nest temperature and humidity

Measurement of nest temperature and humidity was carried out every week of observation in the morning (07:00-09:00), afternoon (11:00-13:00), and evening (15:00-17:00). Measurements were carried out for 12 weeks of observation using a thermohygrometer (HTC-2).

Identification of bee forage sources

Feed sources for stingless bees were identified within a radius of 150 m from the nest for the Genus *Tetragonula*, with the most visits below that radius (Erwan et al. 2023). Observations were made during the research period, and flowering feed sources were recorded. Identification of nectar and pollen was carried out directly by taking flower samples, where nectar can be seen in the sweet liquid found at the base of the petals, and pollen on the flower pistil.

Data analysis

Analysis of honey pots, bee bread pots, brood cells, honey production, bee bread production, propolis production, nest temperature, and nest humidity was conducted using One-Way Analysis of Variance (ANOVA) (Aleme et al. 2017) in SPSS version 22. Pearson correlation analysis (Negera et al. 2024) examined the relationship between nest temperature and humidity and the productivity of the four stingless bee species. Principal Component Analysis (PCA) was performed to interpret (Wan et al. 2017) the effects of nest temperature and humidity on stingless bee productivity. Bee forages were analyzed descriptively (Agussalim et al. 2018).

RESULTS AND DISCUSSION

Productivity of four stingless bees and nest conditions

Observation results of four stingless bee species showed significant variations in the productivity of honey pots, bee bread pots, brood cells, and propolis production (Table 1). *Tetragonula sapiens* bees obtained the highest results in almost all productivity parameters, including honey pots (50.50±6.97), brood cells (601.22±59.71), honey production (15.72±1.35 g), and propolis (29.01±1.99 g). In contrast, *T. sarawakensis* showed the lowest productivity, especially in producing bee bread (2.58±1.28 g) and bee bread pots (4.95±0.86). Nest conditions, such as temperature and humidity, were relatively stable between species, with an average temperature of 28.3°C and humidity of 76.4%. Various species show different productivity characteristics in honey production, propolis, and brood cells (Erwan et al. 2023).

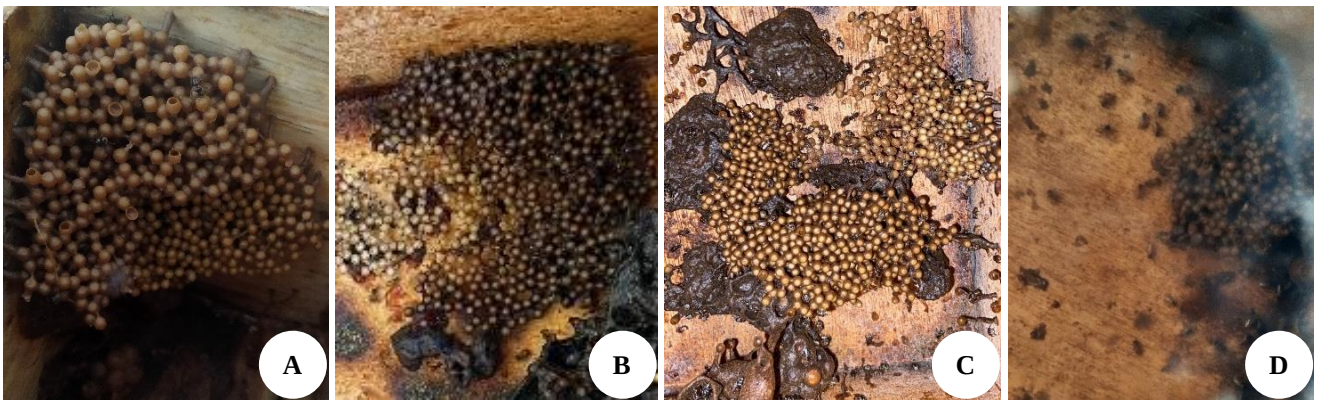

Figure 2. Nests of the four stingless bees in Awani Bee Garden, Makassar, South Sulawesi, Indonesia. A. *Tetragonula laeviceps*; B. *Tetragonula drescheri*; C. *Tetragonula sapiens*; and D. *Tetragonula sarawakensis*

The results indicate that *T. sapiens* species has a higher productivity potential than other species in the same environmental conditions. This advantage is related to adapting the species' behavior in obtaining feed sources and colony management in producing products (Erwan et al. 2023). The productivity of stingless bees is influenced by the colony's structure and the collecting feed (Agus et al. 2019). The study by Simone-Finstrom et al. (2017) also explained that the productivity of propolis and honey is related to the colony's size and nest management.

Tetragonula laeviceps and *T. drescheri* bees showed moderate production characteristics with their respective potentials. The *T. laeviceps* bee colony produced the highest number of pot bee bread (25.72±11.83), while *T. drescheri* had fairly good propolis production (16.57±3.13 g). However, the number of brood cells and honey produced was still below that of *T. sapiens* bees. This difference explains bees' ecological interaction and foraging behavior, which differ among species. The productivity conditions of the bee colony are closely related to the conditions of the surrounding environment (Neov et al. 2019).

The temperature and humidity conditions of the nest did not differ significantly between the four species. This factor plays a more significant role in maintaining the stability of the nest and can indirectly determine the variation in productivity between species. Microclimate stability plays a role in supporting the development of larvae and bee production (Nganso et al. 2024). Therefore, *T. sapiens* showed the best productivity in Awani Bee Garden as an area in the middle of an urban area with many anthropogenic disturbances. This success in an urban environment offers hope for bee conservation in such areas. The condition of the meliponiculture area is the key to the success of stingless bee cultivation (May-Itzá et al. 2022).

Correlation of productivity from four stingless bee species and nest temperature and humidity

Correlation analysis showed a very strong relationship between several stingless bee productivity parameters and nest temperature, and conversely, nest humidity did not show a significant correlation (Table 2). Nest temperature showed a positive and very strong correlation with the number of honey pots (0.853), number of brood cells (0.857), honey production (0.942), and propolis production (0.956). These results are in line with the results of the one-way ANOVA analysis (Table 1), where *T. sapiens* had the highest nest temperature (28.36±0.94°C) and showed the highest productivity in several parameters, including the number of honey pots, number of brood cells, and honey and propolis production.

Tetragonula sapiens bees that live at the highest nest temperature produce the most honey compared to other species, indicating that a nest temperature of around 28.3°C is ideal for the colony. Temperature conditions in beekeeping are around 28°C for maintaining colony activity in collecting and processing nectar (Razanova et al. 2021). Nest humidity shows a weak correlation with all productivity parameters, including correlations with honey production (0.208), propolis production (0.077), and number of brood cells (0.290). Although the humidity value between species is almost uniform (76%), no strong relationship was found with production results. Humidity can be influenced by surrounding conditions, including the design of the beehive (Prastiyo et al. 2023).

Table 1. Productivity of four stingless bee species (*Tetragonula* spp.) and nest conditions

Parameters	*T. laeviceps*	*T. drescheri*	*T. sapiens*	*T. sarawakensis*
Honey pot number (pots)	21.44±12.47[a]	13.16±0.63[a]	50.50±6.97[b]	15.70±3.01[a]
Bee bread pot number (pots)	25.72±11.83[b]	10.14±2.21[a]	15.42±1.83[ab]	4.95±0.86[a]
Brood cell number (eggs)	304±140.79[a]	285.58±43.60[a]	601.22±59.71[b]	245.72±35.16[a]
Production of honey (g/3 months)	6.97±10.72	8.69±2.40	15.72±1.35	8.60±4.57
Production of bee bread (g/3 months)	12.18±10.67	12.42±2.75	7.31±2.16	2.58±1.28
Production of propolis (g/3 months)	13.27±3.56[a]	16.57±3.13[a]	29.01±1.99[b]	15.47±3.96[a]
Nest temperature (°C)	28.25±0.98	28.28±0.92	28.36±0.94	28.30±0.06
Nest humidity (%)	76.50±4.26	76.39±4.04	76.47±4.02	76.45±0.06

Note: Values followed by different letters in each row indicate significant differences at $p<0.05$

Table 2. Correlation of productivity from four stingless bee species with nest temperature and humidity

Parameters	Honey pot number (pots)	Bee bread pot number (pots)	Brood cell number (eggs)	Production of honey (g/3 months)	Production of bee bread (g/3 months)	Production of propolis (g/3 months)	Nest temperature (°C)	Nest humidity (%)
Honey pot number	1							
Bee bread pot number	0.264	1						
Brood cell number	0.985*	0.232	1					
Production of honey	0.967*	0.040	0.980*	1				
Production of bee bread	-0.146	0.644	-0.047	-0.215	1			
Production of propolis	0.926*	-0.061	0.956*	0.991*	-0.216	1		
Nest temperature	0.853*	-0.278	0.857*	0.942*	-0.489	0.956*	1	
Nest humidity	0.433	0.652	0.290	0.208	-0.159	0.077	0.074	1

Note: The (*) indicates a very strong correlation between parameters

The number of brood cells has a very strong correlation with propolis production (0.956), which indicates the growth of the colony population in increasing nest defense activity through propolis. Propolis protects the hive from pathogens and is needed in producing honey pots, bee bread, and brood cells (Borba et al. 2017). *Tetragonula sapiens* bees recorded the highest propolis production and number of brood cells. This explains that *T. sapiens* colony has the most active and productive colony. Active bee colonies produce large amounts of propolis as a response to the risk of environmental disturbances (Dequenne et al. 2022).

Effect of nest temperature and humidity on stingless bee productivity

Conducted PCA to understand the multivariate relationship between productivity parameters and nest conditions of the four stingless bee species (Figure 3). The PCA results (PC1 and PC2) showed 91.4% of the total data variation, dominated by PC1 with 74.1%. Parameters on PC1, such as honey production, propolis production, number of brood cells, and nest temperature, showed that productivity was influenced by nest temperature. These results align with previous correlation analysis, which showed that nest temperature has a strong relationship with several parameters. PCA analysis is useful in identifying and interpreting dominant environmental factors in beekeeping. PCA with a multivariate approach functions in bees' ecological and behavioral data (Sousa et al. 2016).

The PCA interpretation image shows that *T. sapiens* is located in the same quadrant as high productivity variables, such as honey and propolis production, and high nest temperature, thus reinforcing that this species is most responsive to optimal nest conditions. In contrast, *T. sarawakensis* and *T. drescheri* tend to be located far from productivity, indicating that both species have a low relationship to nest temperature conditions and production results. This strengthens the previous correlation results, where nest temperature is not strongly correlated in these species due to different adaptations. PCA emphasizes that nest temperature preferences influence productivity between species. PCA analysis is used to separate groups of bee species based on the parameters used (Kalaycıoğlu et al. 2017). The colony's success is largely determined by the suitability of the species to a particular microhabitat (Pereira et al. 2025). Therefore, the selection of species for production purposes is very important and still considers the surrounding environmental conditions.

Nest humidity has a low contribution to PC1 and PC2, which aligns with previous correlation results that showed a weak relationship to all productivity parameters. Nest humidity does not have a dominant role and is relatively small in explaining the variation in stingless bee productivity at the research location. Stingless bee cultivation management is advised to pay more attention to temperature conditions in the nest. PCA shows the effect of nest temperature on each parameter and reveals the relationship between productivity parameters. Stingless beekeepers should not only focus on the final results, such as honey or propolis, but also maintain nest conditions that support colony population growth. The colony management approach aligns with the principles of integrated ecology in meliponiculture (Barbiéri and Francoy 2020). The population of bee colonies greatly determines the capacity for foraging and production (Rodney and Purdy 2020).

Bee forage sources at Awani Bee Garden

The diversity and availability of bee feed source plants in Awani Bee Garden determine the productivity level of the four stingless bee species studied. During the study period, 27 types of plants were identified as flowering (Table 3), most of which provide nectar and pollen sources to support honey formation, bee bread, and colony growth. Plants such as *Mangifera indica* L., *Artocarpus altilis* (Parkinson) Fosberg, and *Artocarpus heterophyllus* Lam. contribute resin providers for propolis production (Putri et al. 2025).

Based on the results (Table 1), *T. sapiens* has the highest productivity in several parameters, largely due to its ability to optimize feed from various flowering plants throughout the year. The positive relationship between productivity and feed availability is further strengthened by the correlation results showing that the number of honey pots, brood cells, and propolis production have a very strong relationship to nest temperature (Table 2). Of course, the main thing is supported by the available feed sources. Abundant feed sources can increase bee production (Requier et al. 2015). The high productivity of *T. sapiens* and *T. laeviceps* depends on the presence of plants that combine nectar and pollen, such as *Lagerstroemia indica* L., *Tridax procumbens* L., *Ixora grandiflora* Zoll. & Moritzi, and other plants. In contrast, *T. sarawakensis'* productivity is relatively low (Table 1), due to its inability to compete in utilizing the variety of feed available at the research location. This is also supported by PCA (Figure 3), where *T. sapiens* is located close to optimal productivity and environmental variables.

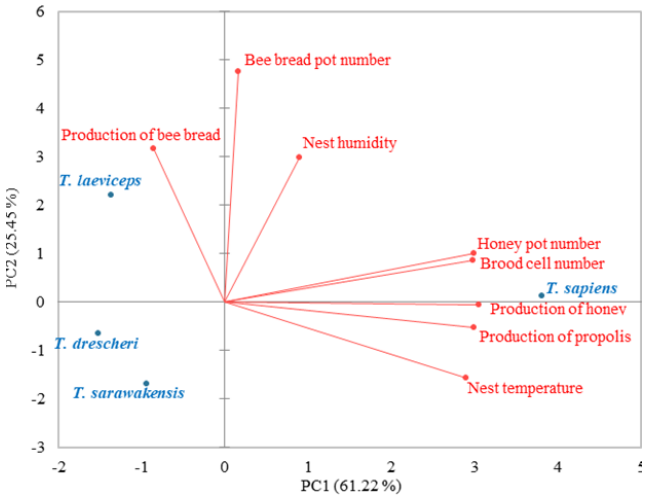

Figure 3. Biplot PCA of the relationship between the productivity of the four stingless bee species and nest conditions

Feed sources affect the quantity of yield, the quality of the nest, and the colony's health (Trinkl et al. 2020). Plants such as *Ficus septica* Burm.fil. and *Hibiscus rosa-sinensis* L., rich in nectar, help maintain the energy supply. The nectar that becomes honey is a carbohydrate bees need (Wright et al. 2018). At the same time, plants such as *Macaranga tanarius* (L.) Müll.Arg. or *Paspalum conjugatum* P.J.Bergius provide a source of pollen, as an important protein for larval development. Pollen brought by bees will be converted and processed in the nest into bee bread (Kieliszek et al. 2018). Honey and bee bread are very much needed by bees as feed reserves during the lean season (Sultana et al. 2024). The lean season for honey bees is when the environmental conditions are dry or rainy (Lavinas et al. 2025). In the dry season, the lack of flowering feed sources disrupts bee production, and in the rainy season, bees will remain in the nest. This preference for bee feed sources explains the differences in nest structure between more adaptive species, such as *T. sapiens*, compared to other species. Although the microenvironment (temperature and humidity of the nest) is relatively homogeneous (Tables 1 and 2), the ability to access and convert available feed is a major differentiating factor in the productivity of each species.

Resin plants such as *M. indica*, *A. altilis*, and *A. heterophyllus* are important for propolis production, especially for *T. sapiens*, which recorded the highest yield of 29.01 g/3 months. Bees use propolis as an antimicrobial agent in the nest and an indicator of colony health (Pusceddu et al. 2021). The availability of local resin with chemical quality that meets bees' needs also determines the colony's success in maintaining productivity amidst microenvironmental pressures. Vegetation management that maintains local resin-producing species is a strategy in stingless bee cultivation (Shanahan and Spivak 2021). Enrichment of bee feed needs to be improved to support the sustainability of bee colonies. Considering the relationship between feed sources, nest conditions, and bee productivity, it can be concluded that the selection and preservation of plant species around the cultivation location are crucial factors in developing healthy and productive colonies. Multifunctional plant species, such as *M. indica* and *A. altilis*, must be a priority in managing agroecological landscapes around urban forests. These findings also strengthen the landscape ecology approach in developing sustainable stingless bee farming (Potts et al. 2010; Williams et al. 2011; Kaluza et al. 2016).

Table 3. Plant types of bee forage plants in Awani Bee Garden

Plant types	Scientific name	Forage source
Crape myrtle	*Lagerstroemia indica* L.	Nectar and pollen
Teak	*Tectona grandis* L.f.	Nectar and pollen
Candlenut	*Aleurites moluccanus* (L.) Wild.	Nectar and pollen
Jamaican cherry	*Muntingia calabura* L.	Nectar and pollen
Mango	*Mangifera indica* L.	Nectar, pollen, and resin
White mulberry	*Morus alba* L.	Pollen
Jackfruit	*Artocarpus heterophyllus* Lam.	Pollen and resin
Papaya	*Carica papaya* L.	Nectar and pollen
Breadfruit	*Artocarpus altilis* (Parkinson) Fosberg	Nectar, pollen, and resin
Sea hibiscus	*Hibiscus tiliaceus* L.	Nectar and pollen
Chinese violet	*Asystasia gangetica* (L.) T.Anderson	Nectar and pollen
Jungle flame	*Ixora grandiflora* Zoll. & Moritzi	Nectar and pollen
Ylang-ylang	*Cananga odorata* (Lam.) Hook.f. & Thomson	nectar and pollen
Parasol leaf tree	*Macaranga tanarius* (L.) Müll.Arg.	Pollen
Coatbuttons	*Tridax procumbens* L.	Nectar and pollen
China rose	*Hibiscus rosa-sinensis* L.	Nectar and pollen
Custard apple	*Annona reticulata* L.	Nectar
Royal palm	*Roystonea regia* (Kunth) O.F.Cook	Nectar and pollen
Palm grass	*Setaria palmifolia* (J.Koenig) Stapf	Pollen
Chinese evergreen	*Aglaonema* sp.	Nectar
False daisy	*Eclipta prostrata* (L.) L.	Pollen
Hauili fig tree	*Ficus septica* Burm.fil.	Pollen
Asthma plant	*Euphorbia hirta* L.	Nectar and pollen
Sensitive plant	*Mimosa pudica* L.	Nectar and pollen
Carabao grass	*Paspalum conjugatum* P.J.Bergius	Pollen
Purple nutsedge	*Cyperus rotundus* L.	Nectar
Little ironweed	*Cyanthillium cinereum* (L.) H.Rob.	Nectar and pollen

The productivity of four stingless bee species in urban forests was significantly influenced by species variation, temperature, and micro-humidity conditions in the nest, and the availability of feed sources consisting of nectar, pollen, and resin. *Tetragonula sapiens* showed the highest productivity in terms of the number of honey pots, bee bread pots, brood cells, production of honey and propolis, which were statistically strongly correlated with optimal nest temperature (29.3°C) and high relative nest humidity (76.4%). PCA analysis confirmed that *T. sapiens* was strongly associated with environmental variables that supported productivity, especially those related to dominant feed sources such as *M. indica* and *A. altilis*, which provided a combination of nectar, pollen, and resin. The diversity and function of feed plants around the cultivation location determined the colony's success in producing honey, propolis, and bee bread while influencing nest structure and reproduction rates. Thus, sound and sustainable management of the feed landscape is key to increasing stingless bee productivity, especially through multifunctional plants and optimization of nest microclimate conditions.

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