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Species Diversity of Trees with Traditional Medicinal Uses: A Core-Buffer Zone Comparison in a Biosphere Reserve

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Abstract

Giam Siak Kecil-Bukit Batu, a UNESCO Biosphere Reserve, uses a zoned management approach, including core, buffer, and transition zones. The core zone prioritizes biodiversity conservation, buffer zones mitigate human impacts, and transition zones focus on sustainable development. The diversity and density of medicinal tree species in the core and buffer zones of this reserve were investigated. It was hypothesized that the core zone would support greater diversity and density of medicinal trees than the buffer zone. Standardized plot sampling was conducted using 1-ha plots, each subdivided into 25 subplots (20 m × 20 m). Trees with a diameter at breast height exceeding 10 cm were inventoried, measured, and identified, with voucher specimens collected for herbarium confirmation. A total of 52 medicinal tree species from 27 families and 36 genera were recorded. Species richness was higher in the buffer zone (39 species) than in the core zone (29 species). These findings underscore the ecological significance of buffer zones in conserving medicinal tree diversity and providing sustainable resources for local communities. The observed species richness in the buffer zone challenges the conventional assumption that core zones harbor higher biodiversity, highlighting the need for further research on sustainable resource management in buffer zones.

Keywords: *medicinal tree, diversity, core zone, buffer zone, Giam Siak Kecil-Bukit Batu, Biosphere Reserve*

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Introduction

Biosphere reserves, designated by UNESCO's Man and the Biosphere (MAB) Programme, offer a unique approach to balancing human activity with biodiversity conservation and sustainable development (Sodhi et al., 2007; Schüttler et al., 2023). These reserves prioritize the preservation of biodiversity and ecosystems while fostering sustainable economic practices (Ibrahimov & Sadullayev, 2022). Encompassing over 700 sites across 134 countries, including 22 transboundary areas (United Nations Educational, Scientific and Cultural Organization, 2024), they serve as models for integrated management of cultural and natural landscapes (Sinay, 2022). Biosphere reserves strive to create a synergistic relationship between humans and nature, promoting sustainable social and economic development within these territories (United Nations Educational, Scientific and Cultural Organization, 2016).

Indonesia is home to nineteen UNESCO-designated biosphere reserves, including the Giam Siak Kecil-Bukit Batu (GSKBB) Biosphere Reserve in Riau Province, Sumatra (United Nations Educational, Scientific and Cultural Organization, 2024). Established in 2009, GSKBB Biosphere Reserve covers an area of 705,271 ha and encompasses diverse ecosystems, including peat swamp forests, lowland rainforests, and coastal mangroves (Priatna, 2023). This biosphere reserve serves as a critical habitat for a multitude of endangered species (Priatna, 2023), including the Sumatran tiger (*Panthera tigris sumatrae*), Sumatran elephant (*Elephas maximus sumatranus*), and *sunbear* (*Helarctos malayanus*) (Simanjuntak et al., 2021).

The GSKBB Biosphere Reserve adheres to the zoned management approach common amongst biosphere reserves, encompassing core, buffer, and transition zones (United Nations Educational, Scientific and Cultural Organization, 2016; Priatna, 2023). The core zone prioritizes strict conservation efforts to safeguard biodiversity. The buffer zone acts as a protective shield, mitigating human impacts on the core area. Finally, the transition zone focuses on achieving sustainable development in collaboration with local communities. Effective management of buffer zones is crucial due to the potential for anthropogenic pressures within these areas. Buffer zones play a critical role in maintaining the integrity of the core zone and offer alternative livelihood opportunities for local communities (Sodhi et al., 2007). Medicinal plants have played a fundamental role in healthcare throughout human history.

They contain a diverse array of bioactive compounds that contribute to disease prevention, diagnosis, and treatment. Traditional medical systems, such as Ayurveda in India, Kampo in Japan, and Jamu in Indonesia, demonstrate the longstanding use of plant-based remedies in healthcare (Yuan et al., 2016; Zaki et al., 2019). These therapies have been practiced for centuries by various ethnic groups and remain essential in treating numerous ailments. Globally, an estimated 70–80% of the population continues to depend on medicinal plants as a primary source of complementary and alternative medicine (Haida & Hakiman, 2019). In the GSKBB Biosphere Reserve, local communities actively use various plant species for traditional healing. This highlights the reserve's critical role in preserving biodiversity while supporting the well-being of surrounding populations (Simanjuntak et al., 2021; Priatna et al., 2024). There is evidence that the people who live in the communities surrounding the GSKBB Biosphere Reserve utilize a variety of plant species as traditional medicine (Simanjuntak et al., 2021; Priatna et al., 2024). This is adequate proof that the GSKBB Biosphere Reserve plays a significant role in the inhabitants' lives in the surroundings.

Detailed inventories of plant communities within buffer zones are critical for optimizing management strategies and ensuring sustainable resource utilization (McNeely & Scherr, 2003). Such inventories, mainly focused on commercially or ecologically valuable species, provide valuable data for policy makers and local communities. This information can inform conservation efforts and identify opportunities for sustainable resource use within the buffer zone framework, ultimately contributing to the success of biosphere reserve management (McNeely & Scherr, 2003).

Despite the well-documented role of biosphere reserves in biodiversity conservation, medicinal tree species remain an understudied component of these ecosystems. Previous research has primarily focused on overall forest composition, timber resources, or flagship species, often neglecting the ecological and cultural significance of medicinal trees (Kaur et al., 2022). In this study, the diversity and density of medicinal tree species within the core and buffer zones of the GSKBB Biosphere Reserve were assessed to address this gap.

While buffer zones are typically considered transitional areas with lower biodiversity than core zones, this study challenges that assumption by comparing medicinal tree diversity across these zones. Understanding these patterns is essential for developing conservation strategies that integrate biodiversity protection with sustainable resource use (Zhang et al., 2024), particularly for local communities that rely on medicinal plants for traditional healthcare (Pidigam et al., 2023).

Despite the ecological and cultural importance of medicinal trees, research on their diversity within buffer zones remains limited. Most studies have focused on core zones, overlooking the role of buffer areas in sustaining biodiversity and supporting sustainable resource use. Additionally, traditional ecological knowledge regarding medicinal plants is often underutilized in conservation planning (Sharma & Pandey, 2012). In this study, the diversity of medicinal tree species in both the core and buffer zones of the GSKBB Biosphere Reserve was examined to assess the potential of the buffer zone for sustainable utilization by local communities.

Methods

Description of the study site The GSKBB Biosphere Reserve, encompassing 705,271 ha in Riau Province, Sumatra, is a unique example of a public-private partnership in conservation. The reserve was designated in 2009 by the Man and Biosphere Programme (MAB) of UNESCO as a model for balancing biodiversity conservation, sustainable development, and research within a vast peatland ecosystem (Zulkarnaini et al., 2022).

The GSKBB Biosphere Reserve follows a zoned management approach, dividing the area into core, buffer, and transition zones. The core zone prioritizes biodiversity conservation, while the buffer zone serves as a protective barrier, incorporating managed forests and conservation efforts. The transition zone integrates sustainable land uses such as agriculture and fisheries, supporting both conservation and community livelihoods. The study sites were located in the Bukit Batu Sub-district, Bengkalis Regency, within the GSKBB Biosphere Reserve. Humus and Makmur resorts were selected as representative sampling sites for the core and buffer zones, respectively, based on their ecological characteristics, accessibility, and land-use patterns. Humus represents a relatively undisturbed primary peat swamp forest within the core zone, while Makmur is a buffer zone with a mix of secondary forest and managed land-use activities. These sites were chosen to capture variations in medicinal tree diversity under differing conservation and anthropogenic pressures. The geographical coordinates, determined using GPS, are S01°19'07.4", E101°51'26.7" for Humus and S01°23'76", E101°43'45" for Makmur (Figure 1).

The study sites were situated within a peat swamp tropical rainforest at an elevation of 6 meters above sea level. The terrain is characterized by flat topography with a slope ranging from 0 to 8%. Soil composition across the sites comprised three distinct types: (1) Organosols, characterized by a high organic matter content (peat); (2) Tropofibrists, with constituent materials including clay, gravel, plant residues, and sand, exhibiting a dark brown to black colour and a fiber content exceeding 15% when crushed; and (3) Sapric peats, similar to Tropofibrists but with a fiber content less than 15% (Soil Survey Staff, 2003; Ferdinan et al., 2013; Priatna, 2023).

The study sites experience a tropical climate classified as type A according to Schmidt and Ferguson (Schmidt & Ferguson, 1952). This classification is characterized by annual rainfall ranging from 809 to 4,078 mm and a Q value (proportion of dry months) between 0 and 14.3%. The region experiences a distinct wet season with less than six months exceeding 200 mm of monthly rainfall (Priatna, 2023). Conversely, the dry season is characterized by six to seven months of receiving less than 100 mm of monthly rainfall. Typically, the wet season occurs from September to January, while the dry season spans from February to August.

The marine environment strongly influences the regional climate, resulting in temperature fluctuations between 26.0 °C and 32.0 °C. This unique combination of soil types, topography, hydrological features, and diverse lifeforms contributes to the high biodiversity observed within the study

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area (Badan Pusat Statistik, 2022). Furthermore, Simanjuntak et al. (2021) highlighted the potential of this ecosystem's plant life for medicinal applications.

Materials The field research was carried out in the swamp forest area of the GSKBB Biosphere Reserve and required ropes, tally sheets, twig scissors, machetes, measuring tape, and a global positioning system (GPS) to support activities in the field.

Primary data collection comprised initial surveying of the research locations in the Humus and Makmur resorts, followed by inventories. A 1 ha (100 m × 100 m) plot was established at each site and subdivided into 25 subplots measuring 20 m × 20 m (Figure 2). Within each subplot, all trees with a diameter at breast height (dbh) exceeding 10 cm were included in the inventory. These trees were then measured for dbh (1.3 m from the ground level at the base of the tree) and identified by local names, and voucher specimens were collected for further scientific identification in the herbarium.

The collected voucher herbaria from the field were identified using a modified and updated expert system for identifying tree species in peat swamp forests originally developed by Denny and Wardani (2019). This enhanced system was installed on a local workstation. Following expert system identification, results were validated through comparative analysis with voucher specimen identifications from established reference herbarium collections. The scientific names of all trees obtained from the identification were standardized based on the accepted names from the World Flora Online database using the *R* package "WorldFlora" (Kindt, 2020). To analyze species richness and phylogenetic diversity, we constructed phylogenetic dendrograms using the *R* packages 'V.PhyloMaker2' and 'phytools' (Jin & Qian, 2022; Revell, 2024). In this study, medicinal trees are defined as species that contain bioactive compounds and are documented in traditional or scientific literature as being used for treating, preventing, or managing health conditions. To ensure a systematic approach, a comprehensive literature review was conducted to identify medicinal tree species. This process involved searching major scientific databases, including Web of Science, Scopus, and Google Scholar, using keywords such as 'medicinal trees,' 'bioactive compounds,' 'traditional medicine,' and 'ethnobotany.' Inclusion criteria required that studies provide clear documentation of medicinal use, either in pharmacological research or ethnobotanical surveys.

In this study the following hypotheses are tested: (H_1) medicinal tree diversity, as measured by the Shannon-Wiener diversity index (H'), is lower in the buffer zone compared to the core zone, and (H_2) medicinal tree density is lower in the buffer zone. To test these hypotheses, the identified trees were categorized as medicinal or non-medicinal trees based on a comprehensive review of available literature, including 'Useful Indonesian Plants' (Heyne, 1987).

The Shannon-Wiener diversity index (H') and density (tree ha^{-1}) of medicinal tree species were calculated for each 20 m × 20 m subplot. The 1-ha plot design, subdivided into 25 subplots, was chosen to ensure representative sampling of tree diversity and structure. In tropical rainforests, the addition of new species beyond a one-hectare plot is negligible. A 1-ha plot is considered sufficient to capture the variation in tree species composition and structure within an area. Moreover, a 1-ha plot is widely recognized as a standard size in tropical forest research (Kartawinata et al., 2006; Davis et al., 2024). The Shannon-Wiener diversity index was then calculated using the Equation *[1]*.

$$H' = \Sigma (pi*\ln(pi) \qquad [1]$$

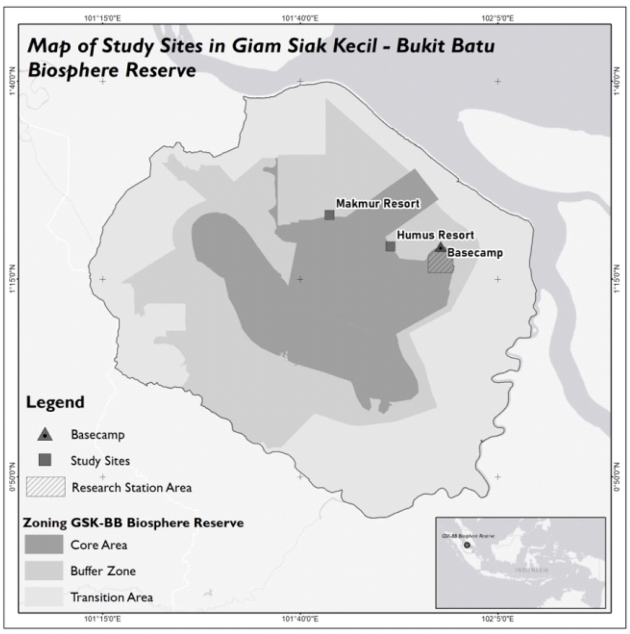

Figure 1 The study sites of the buffer and core zone of the Giam Siak Kecil-Bukit Batu Biosphere Reserve.

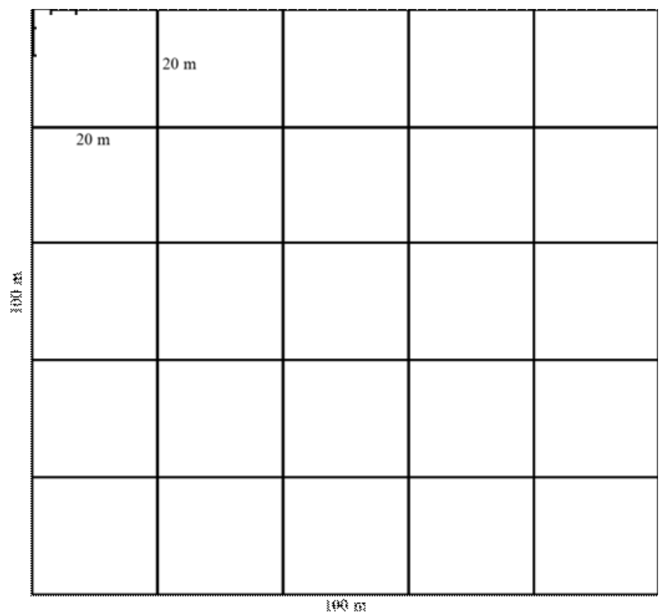

Figure 2 Plot measurement and data collection of tree species.

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note: *pi* represents the proportion of each species in the subplot (Begon et al., 2009; Magurran, 2021). Finally, a *t*-test was conducted to compare the medicinal tree diversity and density between the buffer and core zones. Statistical significance was set at a p-value < 0.05.

Results

Tree identification and species composition Our research employed an expert system for the identification of tree species within a peat swamp forest. The system achieved genus-level identification for 27 genera, but species-level identification was only successful for 15 species (Figure 3). The accuracy of identification reached 79% at the genus level and 29% at the species level. Despite its efficiency in rapidly categorizing species, expert systems often struggle with closely related taxa due to overlapping morphological traits. Species within the same family often share similar traits, complicating automated identification systems (Seeland et al., 2019). Therefore, post-identification validation using herbarium specimens remains essential to ensure taxonomic accuracy. These findings highlight significant challenges in the application of expert systems for tree identification in taxonomically complex environments such as peat swamp forests.

The validation process confirmed the accurate identification of all samples, underscoring the reliability of traditional taxonomic methods compared to the expert system. The expert system achieved 79% accuracy at the genus level but only 29% at the species level, likely due to taxonomic complexity and morphological similarities among related species. In contrast, the traditional methodherbarium specimen validationrelies on direct morphological comparison with reference specimens, ensuring a higher degree of accuracy (Nanni et al., 2025). This approach is widely recognized as the gold standard in plant identification due to its ability to verify ambiguous species classifications, particularly in highly diverse and taxonomically complex environments such as peat swamp forests (Botello, 2024). The standardized identification of medicinal plant species in Humus and Makmur, using the World Flora Online (WFO) database, recorded a total of 52 tree species from 36 genera and 27 families, reinforcing the effectiveness of traditional validation methods (Figure 4).

The species composition was clustered based on the families with the highest number of species (Figure 4). The clustering of species based on their family affiliation revealed that Annonaceae and Myrtaceae were the dominant families in both locations. When data from both locations were combined, Myrtaceae emerged as the family with the highest number of species, followed by Annonaceae. The dominance of certain tree species in tropical ecosystems is shaped by a combination of ecological, morphological, and evolutionary factors (Yulisma et al., 2018). Species with traits such as rapid growth rates, high shade tolerance, and efficient nutrient uptake tend to outcompete others, allowing them to establish dominance within specific forest strata (Leigh et al., 2004). Moreover, differences in seed dispersal mechanisms and adaptation to varying microclimatic conditions influence species distribution and community structure (Medina, 2007). In peat swamp forests, dominant species often exhibit specialized root structures and waterlogging resistance, further contributing to their ecological success (Leigh et al., 2004).

As illustrated in Figure 5, the species density data highlighted that *Palaquium dasyphyllum* and *Diospyros venosa* were the most densely populated species in the Humus and Makmur districts, respectively. *P. dasyphyllum* had a density of 411 trees ha^{-1} in Humus, while *D. venosa* showed a density of 439 trees ha^{-1} in Makmur. The high densities of *P. dasyphyllum* and *D. venosa* suggest that these species are well-suited to the local environmental conditions and could play a crucial role in the ecosystem's structure and function. Despite their abundance, the medicinal potential of these species appears limited, as indicated by the scarce literature on their medicinal uses. Cunningham (2001) emphasized the importance of continued ethnobotanical research to explore and potentially reveal undocumented medicinal properties. In contrast, *Mangifera indica*, widely recognized for its significant medicinal value (Berry et al., 2010), was found at lower densities in both districts, with 178 trees ha^{-1} in Humus. The distribution and dominance of medicinal tree species are influenced by a combination of climatic, edaphic, and ecological factors. Species that thrive in tropical forests often exhibit specific physiological adaptations, such as drought resistance, shade tolerance, and efficient nutrient uptake, enabling them to outcompete others (Shanley & Luz, 2003). Additionally, soil properties, including pH, organic matter content, and water retention capacity, play a crucial role in determining species composition (Arshad et al., 2024).

Human-induced environmental changes, such as habitat fragmentation and natural resources extraction, also affect the availability and distribution of medicinal tree species, altering forest structure and resource accessibility (García-

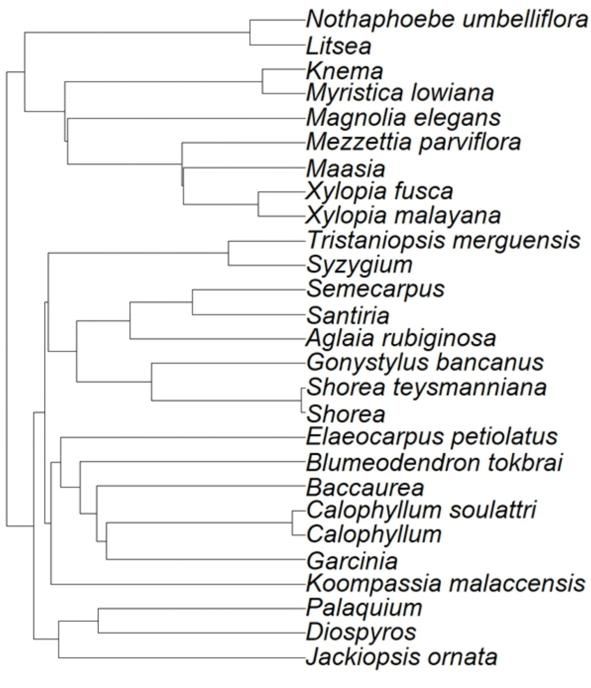

Figure 3 Results of tree species identification using the peat swamp forest tree identification expert system.

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Flores et al., 2019). Understanding these ecological dynamics is essential for developing conservation strategies that maintain both biodiversity and sustainable resource use.

Comparative analysis of core and buffer zones Our study aimed to compare the diversity and density of medicinal trees in the buffer and core zones of the forest. Contrary to our hypothesis that the core zone would exhibit a higher diversity and density of medicinal trees due to presumed lower anthropogenic pressures and more favorable ecological conditions, our results indicated otherwise. The buffer zone harbored greater species diversity, with 39 species compared

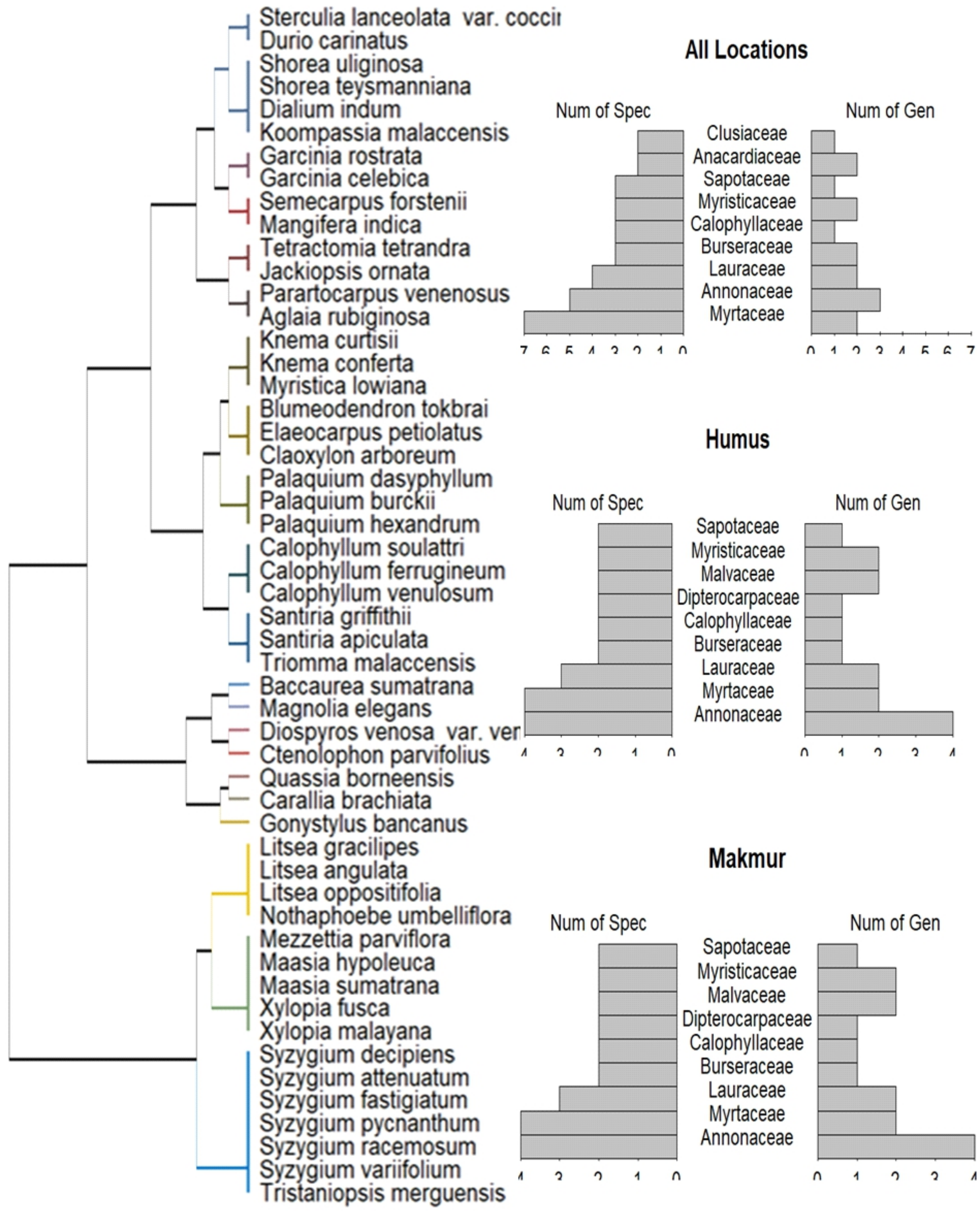

Figure 4 Species composition is presented in (A) a phylogram of 52 species recorded across all locations; and bar charts representing the number of species and genera from the nine largest families in: (B) all locations, (C) Humus, and (D) Makmur.

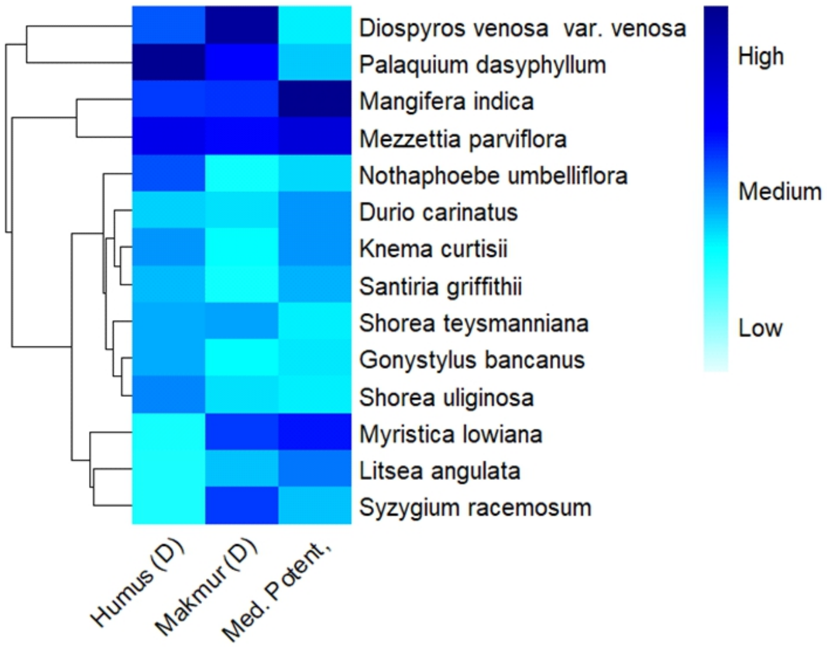

Figure 5 The correlation between species composition and the medicinal plant potential.

to 29 in the core zone. However, despite the apparent difference in species richness, the Shannon-Wiener diversity index (*H'*) did not reveal a statistically significant difference in medicinal tree diversity between the zones ($t = 0.7389$, p-value > 0.05). Similarly, the buffer zone had a higher density of medicinal trees (528 trees ha^{-1}) than the core zone (498 trees ha^{-1}). However, a *t*-test again revealed no significant difference between the zones ($t = 0.431$, p-value > 0.05).

The diversity and density of medicinal tree species observed in the buffer zone highlight its ecological importance in biodiversity conservation (Putz et al., 2012). Although statistical differences between the core and buffer zones may not be significant, research suggests that low-intensity disturbances in buffer zones promote habitat heterogeneity, enhancing species richness and ecosystem resilience (Mishra et al., 2008). Such disturbances, including low-impact traditional practices, create a mosaic of microhabitats that support a diverse assemblage of medicinal tree species (Sahu et al., 2008; Harvey et al., 2010; Pardini et al., 2010). These activities can result in a mosaic of different successional stages, providing niches for a broader range of species. This finding aligns with previous research. For example, in the Nokrek Biosphere Reserve in Meghalaya, buffer zone sites exhibited a higher number of plant species and greater plant density compared to core region sites (Sangma & Lyngdoh, 2014). Similarly, studies in the Mediterranean region and the Vologda Region (the southern taiga area of the European part of the Russian Federation) have shown that buffer zones possess higher biodiversity than core zones (Lecina-Diaz et al., 2019; Belyakov et al., 2024).

The higher diversity and density of medicinal trees in the buffer zone highlight its ecological and socio-economic role in reducing resource extraction pressure on the core zone. A well-managed buffer zone provides an alternative resource base, enabling the sustainable harvesting of medicinal plants while minimizing dependence on core forest resources (Endress et al., 2006). The key mechanisms include regulated harvesting and agroforestry (Boukeng et al., 2024).

Furthermore, the buffer zone's accessibility might lead to more active management and conservation efforts. Local communities often engage in sustainable practices that include the protection and cultivation of medicinal plants (Schroth et al., 2013). These practices can contribute to the higher diversity and density observed in the buffer zone.

Our initial hypothesis posited that the core zone, being less disturbed, would harbor higher species richness and density of medicinal trees. This assumption is based on the traditional view that undisturbed areas provide optimal conditions for biodiversity (Dao et al., 2016; DeFries et al., 2004; Jeong et al., 2023). However, our findings challenge this view and suggest that controlled disturbances in the buffer zone might create conditions that are equally, if not more, favorable for certain medicinal tree species (Connell, 1978).

Species composition of medicinal trees and the properties
As presented in Table 1, the identified medicinal trees exhibited a variety of potential therapeutic properties, including antioxidant activity, antibacterial, anti-inflammatory properties, antimicrobial, antiviral, antifungal, antidiabetic, cytotoxic, antiplatelet, antidegenerative, anticoagulant, anti-rachitic, gutta-percha, secondary metabolite, psychoactive, and essential oils. This highlights the potential of the GSKBB Biosphere Reserve as a source of natural products with diverse medicinal applications.

Discussion

Tree identification and species composition Species identification in peat swamp forests remains challenging due to high biodiversity and the prevalence of morphologically similar taxa. In this study, the expert system achieved 79% accuracy at the genus level but only 29% at the species level, underscoring its limitations in resolving fine-scale taxonomic distinctions. Accurate species-level identification is crucial for biodiversity assessments, conservation planning, and sustainable resource management, as misidentifications can lead to incorrect estimates of species

Table 1 List of medicinal tree species found at the core and buffer zone

No	Scientific name	Family	Notes	Core zone	Buffer zone
1	*Aglaia rubiginosa*	Meliaceae	Anti-inflammatory, antifungal[4] [17]	√	√
2	*Baccaurea sumatrana*	Phyllanthaceae	Antioxidant[30]		√
3	*Blumeodendron tokbrai*	Euphorbiaceae	Antiviral[11]		√
4	*Calophyllum ferrugineum*	Calophyllaceae	Antibacterial[1] [38]	√	
5	*Calophyllum soulattri*	Calophyllaceae	Anti-inflammatory[1] [11] [26] [38]		√
6	*Calophyllum venulosum*	Calophyllaceae	Antioxidant[1] [7] [38]	√	√
7	*Carallia brachiata*	Rhizophoraceae	Antibacterial, antioxidant[22]	√	
8	*Claoxylon arboreum*	Euphorbiaceae	Part of a traditional concoction for supplements[33]		√
9	*Ctenolophon parvifolius*	Ctenolophonaceae	Part of a traditional concoction for supplements[8]	√	√
10	*Dialium indum*	Fabaceae	Antioxidant[25]		√
11	*Diospyros venosa var. venosa*	Ebenaceae	Part of a traditional concoction for supplements[36]	√	√
12	*Durio carinatus*	Malvaceae	Antioxidant[12]	√	√
13	*Elaeocarpus petiolatus*	Elaeocarpaceae	Antioxidant, antiviral[35]	√	
14	*Garcinia celebica*	Clusiaceae	Antimicrobial[9] [31]		√
15	*Garcinia rostrata*	Clusiaceae	Antidiabetic[9] [31]		√
16	*Gonystylus bancanus*	Thymelaeaceae	Antiviral[11] [13]	√	√
17	*Jackiopsis ornata*	Rubiaceae	Antioxidant[28]	√	
18	*Knema conferta*	Myristicaceae	Antioxidant[38]		√
19	*Knema curtisii*	Myristicaceae	Cytotoxic[31] [34]	√	√
20	*Koompassia malaccensis*	Fabaceae	Antioxidant, antiacne[6]		√
21	*Litsea angulata*	Lauraceae	Antioxidant, antibacterial[19] [38]		√
22	*Litsea gracilipes*	Lauraceae	Essential oil[19] [38]	√	
23	*Litsea oppositifolia*	Lauraceae	Antioxidant, antibacterial[19] [38]		√
24	*Maasia hypoleuca*	Annonaceae	Antibacterial[16]	√	
25	*Magnolia elegans*	Magnoliaceae	Antiplatelet[11]	√	√
26	*Mangifera laurina*	Anacardiaceae	Antidegenerative[14]	√	√
27	*Mezzettia parviflora*	Annonaceae	Antioxidant[29]	√	√
28	*Myristica lowiana*	Myristicaceae	Anticoagulant[23]	√	√
29	*Nothaphoebe umbelliflora*	Lauraceae	Anti-inflammatory[2]	√	√
30	*Palaquium burckii*	Sapotaceae	Anti-rachitic[37]	√	√
31	*Palaquium dasyphyllum*	Sapotaceae	Antioxidant[37]	√	√
32	*Palaquium hexandrum*	Sapotaceae	Gutta-percha[37]		√
33	*Parartocarpus venenosus*	Moraceae	Secondary metabolite[20]		√
34	*Polyalthia sumatrana*	Annonaceae	Antioxidant[32]	√	√
35	*Santiria apiculata*	Burseraceae	Antimicrobial, essential oil[18]	√	√
36	*Santiria griffithii*	Burseraceae	Antimicrobial, essential oil[18]	√	√
37	*Semecarpus forstenii*	Anacardiaceae	Suspected as antioxidant[21]		√
38	*Shorea teysmanniana*	Dipterocarpaceae	Antioxidant, antibacterial[11] [38]	√	√
39	*Shorea uliginosa*	Dipterocarpaceae	Antioxidant, antibacterial[38]	√	√
40	*Simaba borneensis*	Simaroubaceae	Antioxidant, anti-inflammatory[5]	√	
41	*Sterculia coccinea*	Sterculiaceae	Anti-inflammatory[24]		√
42	*Syzygium attenuatum*	Myrtaceae	Essential oil[10]		√
43	*Syzygium decipiens*	Myrtaceae	Essential oil[10]	√	√
44	*Syzygium fastigiatum*	Myrtaceae	Essential oil[10]	√	
45	*Syzygium pycnanthum*	Myrtaceae	Essential oil[10]		√
46	*Syzygium racemosum*	Myrtaceae	Essential oil[10]		√
47	*Syzygium variifolium*	Myrtaceae	Essential oil[10]	√	√
48	*Tetractomia tetrandra*	Rutaceae	Psychoactive[38]		√
49	*Triomma malaccensis*	Burseraceae	Antimicrobial[3]		√
50	*Tristaniopsis merguensis*	Myrtaceae	Antioxidant[27]	√	
51	*Xylopia fusca*	Annonaceae	Antimicrobial[11] [15] [38]	√	
52	*Xylopia malayana*	Annonaceae	Anti-inflammatory[11] [15]		√

Sources:
[1](Aminudin et al., 2016); [2](Arifin et al., 2015); [3](Atmoko & Ma'ruf, 2009); [4](Bang et al., 2024); [5](Barbosa et al., 2011); [6](Batubara et al., 2010); [7](Bin Ismail et al., 2015); [8](Badan Pengawas Obat dan Makanan, 2013); [9](Brahma et al., 2022); [10](da Costa et al., 2020); [11](Denny & Kalima, 2016); [12](Feng et al., 2016); [13](Oktavianawati et al., 2023); [14](Fitmawati et al., 2020); [15](Humeirah et al., 2016); [16](Harahap et al., 2022); [17](Harneti & Supratman, 2021); [18](Haruna et al., 2017); [19](Hasan, 2011); [20](Jacinto et al., 2011); [21](Jain et al., 2014); [22](Junejo et al., 2020) ; [23](Kwapong et al., 2020); [24](Paul et al., 2019); [25](Lubis et al., 2021); [26](Mah et al., 2015); [27](Mahardika et al., 2023); [28](Mohamad et al., 2013); [29](Murdifin et al., 2017); [30](Navia et al., 2022); [31](Ong et al., 2009); [32](Salleh et al., 2022); [33](Setiawan, 2020); [34](Sudha et al., 2021); [35](Sudradjat & Timotius, 2022); [36](Syarpin & Nugroho, 2020); [37](Wibisono et al., 2020); [38](Yusro et al., 2020)

richness, obscure the presence of rare or threatened taxa, and compromise ecological interpretation (Gaston & O'Neill, 2004). For example, species within the genus Syzygium may differ significantly in ecological roles or conservation status yet are often indistinguishable without detailed morphological or molecular data.

This limitation has tangible implications for conservation stakeholders. Inaccurate identification may hinder sustainable harvesting practices (Endress et al., 2006), misinform policy decisions, and disrupt traditional medicinal knowledge systems relied upon by local communities. Genera such as Palaquium, Litsea, and Syzygium are especially problematic due to their high taxonomic complexity and overlapping vegetative characteristics. These challenges highlight the need for improved identification strategies beyond field-based morphological keys. Recent advances offer promising solutions. DNA barcoding has demonstrated effectiveness in resolving cryptic species and enhancing taxonomic resolution in tropical forests (Hebert et al., 2003). Likewise, deep learning-based image classification models have shown high accuracy in plant identification tasks, including real-time applications in natural settings (Malik et al., 2022). For instance, convolutional neural networks (CNNs) have achieved over 90% accuracy in species identification using bark texture features such as blisters and fissures (Kim et al., 2022), while support vector machines (SVMs) analyzing leaf venation patterns have reached accuracies above 80% (Ambarwari et al., 2020). Geometric morphometric approaches, particularly using secondary nerve architecture, have also proven effective in differentiating closely related species, including Shorea spp. (Ariawan et al., 2020). To address these limitations, we advocate for a multi-tiered taxonomic framework combining (1) expert system outputs, (2) herbarium-based validation, (3) ecological metadata (e.g., soil type, habitat), and (4) molecular or AI-based techniques. Such integrative taxonomy approaches can significantly improve the accuracy and reliability of biodiversity surveys, particularly in complex tropical systems.

Following initial identification, all samples were verified against voucher specimens deposited in established herbarium collections. These serve as authoritative taxonomic references and support long-term comparative analysis (Souza & Hawkins, 2017). Herbarium records are vital for tracking morphological variation, phenological shifts, and species distribution in response to climate change and anthropogenic disturbance (Veenstra, 2012; Rinawati et al., 2013; Hanski, 2015). As repositories of historical and ecological data, they continue to play a central role in guiding conservation strategies and ecosystem management (Henderson et al., 2007).

Comparative analysis of core and buffer zones The lack of significant differences in the Shannon-Wiener diversity index and *t*-tests indicates that the ecological dynamics in these zones are more complex than initially anticipated. The core zone's stability might not provide the periodic disturbances that some species require for regeneration and growth (Laurance et al., 2002). Conversely, the buffer zone's controlled disturbances might mimic natural processes that maintain species diversity (Hobbs & Huenneke, 1992). In the core zone, ecological stability is maintained by minimal human disturbance and well-preserved habitat continuity, supporting shade-tolerant, slow-growing species. In contrast, the buffer zone experiences moderate disturbances from selective extraction, which can create gap dynamics that favor pioneer species and lead to fluctuating species compositions over time. Studies have shown that buffer zones can act as transition areas, balancing conservation with sustainable use by facilitating species dispersal and promoting biodiversity recovery after disturbances (Jia et al., 2024).

Several limitations should be acknowledged in our study. The lack of significant differences might be influenced by the sample size or the specific methods used for data collection. The study's sample size may not be sufficient to detect subtle ecological differences, as larger sample sizes are often necessary for robust statistical analyses (Kang et al., 2024). Future research should employ larger sample sizes and more robust methodologies, including long-term ecological monitoring, to better understand the dynamics between buffer and core zones (Sutherland, 2006). Incorporating remote sensing and machine learning can enhance species identification and ecological assessments (Mateos & Bhatnagar, 2024).

Further investigations should also consider other factors influencing medicinal tree diversity and density, such as soil properties, microclimatic conditions, and interactions with fauna. Studies examining the impact of various disturbance regimes in the buffer zone could provide deeper insights into the mechanisms driving the observed patterns (Hobbs & Huenneke, 1992).

Our study highlights the great potential of biosphere reserves as reservoirs of medicinal tree diversity, in line with the findings of global studies that emphasize the role of protected areas in conserving biodiversity (Cocks & Dold, 2006; Purwanto et al., 2020) The identification of 52 tree species with medicinal uses within the buffer zone and core zone underscores the important role of spatial heterogeneity in supporting biodiversity, which is crucial for ecosystem resilience and the provision of ecosystem services, including medicinal resources (Dudley & Phillips, 2006).

Conclusion

The study demonstrates that the buffer zone of the GSKBB Biosphere Reserve plays a crucial role in supporting a diverse and dense population of medicinal tree species, contrary to the initial hypothesis that the core zone would exhibit higher diversity and density. This unexpected finding suggests that controlled human activities in the buffer zone may create favorable conditions for the growth and maintenance of medicinal tree species. The higher diversity and density of medicinal trees in the buffer zone indicate its potential for sustainable resource utilization, reducing the need for local communities to access the core zone for their medicinal tree needs. However, certain closely related species remain difficult to distinguish due to overlapping morphological traits, complicating biodiversity assessments. From a conservation perspective, the higher diversity in the buffer zone highlights its role as a managed landscape that balances biodiversity conservation with sustainable resource use.

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