



Comparative assessment of biomass and soil characteristics of teak (*Tectona grandis* Linn. F) plantations and natural mixed forests in Bara District, Nepal

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Abstract

Rapidly expanding teak plantations are often considered ecologically inferior to natural forests because they deplete key soil nutrients, which can reduce long-term biomass production and ecosystem health. This study compares the biomass and soil characteristics of teak planted forests (TPF) and natural mixed forests (NMF) in the lowland of Nepal to fill a research gap in the region. A systematic sampling of 15 plots (20 x 20 m² each) in each forest was conducted to assess trees, saplings, seedlings, and soil properties. The study found that while ten species in the NMF had good regeneration, the high density of teak saplings in the TPF limited regeneration to only one, restricting the growth of other species. Despite these differences in species composition, both forests had a similar total biomass. Soil nutrient properties were significantly lower in the TPF than in the NMF, which received greater nutrient input from annual litterfall and understory growth. However, the lower disturbances in the TPF might have led to comparable levels of organic matter, nitrogen, soil moisture, and sand percentage to NMF. In the TPF, biomass was positively linked to soil pH and nitrogen, while in the NMF, it was related to organic matter, sand, nitrogen, potassium, and canopy cover. The CCA analysis also showed that teak thrived in sand-rich soil with high organic matter, while other species from the study area are found in nutrient-rich conditions. This could be the reason that the NMF had high tree species diversity compared to TPF. This difference may explain the higher tree species diversity observed in the NMF compared to the TPF. The study concludes that while teak monocultures are established primarily for their known economic viability, mixed-species plantations are nevertheless a preferable alternative for achieving a better balance between economic interests and essential environmental integrity.

Keywords: Canopy cover, diversity, monoculture, nutrient, regeneration

Introduction

The escalating global population has led to ever-increasing demand for energy, fiber, and wood products. Therefore, the silviculture practices play a crucial role in meeting the increasing demands for natural resources (Alan, 2020; Gardiner & Moore, 2013). However, with drastically changed land use patterns, there was a noticeable decline in soil quality and its fertility (Khaledian et al., 2017). Hence, planted forests are considered inferior to natural forests (Islam et al., 2001). A comparable trend has been observed in Nepal, where there has been a substantial increase in plantation activities for high-value timber production (Bhatta et al., 2009; Bhattarai & Conway, 2008). The expansion of plantations in Nepal can be traced back to 1960s, and this trend continues to grow (Bhattarai & Conway, 2008).

Teak (*Tectona grandis* Linn. F) belongs to the family Verbenaceae (Nordahlia et al., 2014) and is the most valuable and demanding tropical hardwood due to its strength, aesthetic qualities (Miranda et al., 2011), fine grain, and durability (Singh et al., 2010). This is native to South and Southeast Asia, mainly India, Indonesia, Lao PDR, Malaysia, Myanmar, and Thailand (Miranda et al., 2011; Pandey & Brown, 2000). It was naturalized some 400-600 years ago in Java, Indonesia (Pandey & Brown,

2000), and Indonesia is the largest producer of teak in the global market (Ombina, 2008). This is a monoecious species with rare self-pollination; however, the germination of this species is poor (Slator et al., 2013). This is a large deciduous tree species with a rounded crown, cylindrical stem, and is more than 25-30 m tall (Pandey & Brown, 2000; Zanin, 2005), and it contributes about 15% of all forest plantations globally (Singh et al., 2010). Teak is an important, fast-growing, and high-yielding tree species (Palanisamy et al., 2009). This is an emerging hardwood tree species with high-value timber, used in the afforestation of about 70 countries around the world (Sreekumar & Sanil, 2021) and also in some regions of lowland in Nepal (Koirala et al., 2021). According to Bhattarai and Conway (2008), during the transition period (1996-2003), over 4,585 hectares of mixed forests had been converted into secondary growth of teak in the Bara District of Nepal for maximum commercial value.

Growth of the tree varies with environmental gradients (Ferrero et al., 2013; Ni et al., 2022). Considerably, climatic variables and nutrients of soil are the factors that affect the biomass production (Ali et al., 2020; Luo et al., 2012). While there are no uniform, global effects of soil productivity on forest biomass (Thiffault et al., 2011), site-specific studies demonstrate that long-term

degradation can manifest as a decrease in harvestable biomass over extended periods (Matsuo et al., 2024; Zhang et al., 2022). However, there is a need for the study of forest biomass and factors like degradation of soil nutrients that cause natural variability in biomass (Laurance et al., 1999). The study of forest biomass is the key to understanding the fluxes of nutrients in an ecosystem and energy flow in the environment (Thakur et al., 2019). Singh and Singh (2002) reported that soil nutrients present in the soil of the planted area are higher compared to non-planted areas. A study by Chauhan et al. (2010) reveals that there is a significant impact of soil characteristics on trees and sapling growth in a natural forest.

There is very limited research conducted on biomass production of teak planted forest (TPF) and natural mixed forest (NMF) concerning soil nutrients in the lowland of Nepal, and the published data on different climatic zones are insufficient. Correspondingly, the linkage between biomass and the nutrients in the teak forest has yet to be established in any research on similar climatic zones. Teak is not an erosive species itself (Fernández-Moya et al., 2014) but produces allelopathic effects (Mensah et al., 2015). The aqueous leaf of teak inhibits the seeds from germinating and seedlings from growing (Biswas & Das, 2016). Teak has been planted due to its higher yield of biomass and to meet the demand for forestry products. However, the disadvantages of this plantation are the loss of soil quality and fertility (Asigbaase et al., 2024; Fernández-Moya et al., 2015). There is inadequate research on the species teak and its associated nutrients. Hence, this study compares the soil nutrients, biomass, and regeneration of NMF and TPF of the Sahajath CollabMcorative Forest of Bara District, Nepal.

Materials and methods

Study area

The study was conducted in Bara District of Nepal, where most of the forests are located in the northern part of the district (Bhattarai & Conway, 2008). The specific research sites are located within Sahajath Collaborative Forest, geographically bounded by Bakaiya River to the east and Pasaha River to the west. The forest is located between the latitudes 27° 10' 00'' and 27° 00' 30'' N and the longitudes 85° 00' 32'' and 85° 04' 09'' E with an altitude between 97-165 masl (Fig. 1).

The total forest area of Sahajath Collaborative Forest currently spans approximately 2,000 hectares. The teak planted forest (TPF) area comprises 57.3 hectares, a comparatively small portion of the total (MFSC/GoN, 2017). This area is projected to decrease further due to the proposed development of the Nijadh International Airport (Geschewski et al, 2022; Pant et al., 2021). The forest is primarily composed of valuable *Shorea robusta* alongside a diverse mix of tropical and sub-tropical species. The region exhibits a tropical to sub-tropical climate characterized by a pronounced dry season during the winter months and a humid summer season.

The region experiences mean summer temperatures of 34°C, while yearly maximum summer temperatures exceed 42°C. The area receives annual rainfall ranging between 1200 to 1500 mm (JSSMC, 2020).

Sampling methods

A systematic sampling approach was employed at a sampling intensity of 1% (DoF/GoN 2012), resulting in the establishment of 15 sampling plots at 200 m intervals within each of the two distinct forest types, viz., teak-planted forest (TPF) and natural mixed forest (NMF) of Sahajath Collaborative Forest. A total of 30 plots (20 x 20 m) were established for tree data collection. Within each plot, a 5 x 5 m subplot was designated for sapling assessment, and a 1 x 1 m subplot was further established within the sapling subplot for seedlings (DoF/GoN, 2012). Sampling in TPF was quite uneven, this is because the patches were covered with grassland and barren lands in the straight line sampling. Therefore, such grasslands and barren lands have been discarded.

DBH class distribution was used to predict the overall regeneration status of tree species. Individuals with DBH ≥ 10 cm were classified as trees. Further, individuals with DBH < 10 cm and a height >137 cm were classified as saplings, while individuals < 137 cm were classified as seedlings. The density of trees, saplings, and seedlings was calculated following Kent and Coker (1992). The regeneration status of individual species was determined by using the criteria given by Shankar (2001). The canopy cover was measured through direct observation. With the help of a canopy cover, the forest was divided into different categories (Gurung & Kokh, 2011).

The aboveground tree biomass (AGTB) was calculated by measuring diameter at breast height (137 cm) and tree height by using allometric equations developed by Chave et al. (2014) for tropical wet forests. The wood density for each tree species was obtained from Zanne et al. (2009). The belowground tree biomass (BGTB) was estimated by following MacDicken (1997). The total biomass of tree species was estimated by summing up aboveground and belowground tree biomass. Trees with DBH > 10 cm were only considered for tree biomass estimation.

Soil sample collection and analysis

Soil samples were collected from the four corners of each plot and then combined to create a composite sample. A representative 200 g of soil sample from each plot was collected for laboratory analysis. The physicochemical parameters, viz., pH, electrical conductivity (EC), moisture content, bulk density, nitrogen, phosphorus, and potassium of the soil of forests were analyzed. The pH and EC were determined in the field by using a multiprobe (Hanna Combo HI 98129, Romania). The soil moisture and texture were measured by gravimetric method and hydrometer method (Rajbhandari, 2005). The bulk density of soil was measured using core method, following the procedure outlined by Blake and Hartge (1986). Further, the

nitrogen, available phosphorus, and potassium were determined by Kjeldahl digestion method, spectrophotometric method, and flame photometer

method, respectively (Trivedy & Goel, 1984) in the laboratory of Central Department of Environmental Science, Tribhuvan University, Kirtipur, Nepal.

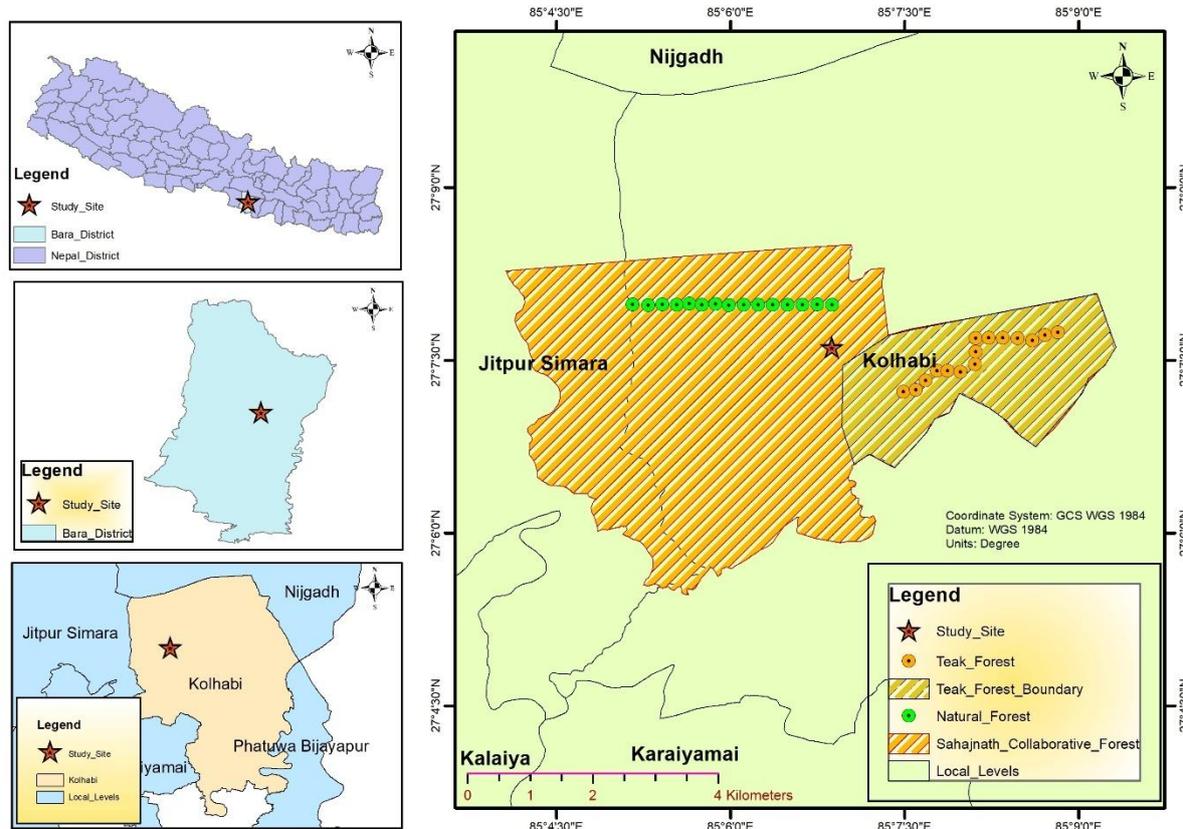


Figure 1. Location of the study area (a) map of Nepal showing Bara District (b) location of Sahajmath Collaborative Forest in Bara District, (c) study area and its nearby location, and (d) sampling point at NMF (green circle) and TPF (orange circle).

Data analysis

Two statistical approaches were applied to determine the associations between soil variables and tree biomass. Firstly, Kendall's rank correlation was tested to evaluate the individual relationships between each soil variable and biomass in TPF and NMF based on non-normality distribution of data due to small sample size. The Shapiro-Wilk test was used to test the normality. Mean and standard deviation were calculated for normal data, while for those that were not normal, median and interquartile range (IQR) were calculated. Secondly, an ordination analysis was conducted to determine how variation in soil characteristics influences the tree biomass. An ordination analysis was conducted to assess how variation in soil characteristics influences tree biomass. Canonical Correspondence Analysis (CCA) was employed to identify the primary gradients in soil variables associated with variation in tree biomass. Statistical differences between TPF and NMF were evaluated using t-tests and Wilcoxon tests, accounting for data variability. Data analysis and statistical computations were performed using R version 3.5.1 and MS Excel.

Results and Discussion

Regeneration and canopy cover in TPF and NMF

Among the eight species found in the TPF of Sahajmath Collaborative Forest, teak showed good regeneration, while other species were found only occasionally. The other five species (*Aegle marmelos*, *Alangium salviifolium*, *Acacia catechu*, *Dalbergia sissoo*, and *Murraya koenigii*) had no regeneration status, which shows a failure to successfully regenerate into the next generation. This might be due to factors such as competitive exclusion by the dominant teak stand in this planted forest. However, *Cassia fistula* had a new regeneration status in the forest, while *Mallotus philippensis* showed poor regeneration (Table 1). Similarly, a total of 26 species were recorded in the NMF, showing different regeneration statuses. Among those species, 10 species had good regeneration, one species had fair regeneration, two species had poor regeneration, twelve species had no regeneration, and one species had a new regeneration status. The *Shorea robusta* had the highest regeneration status, whereas *Buchanania latifolia* appeared as the newest species in the forest (Table 2). The regeneration status showed that the density of the overall tree in NMF (433.33 stems/ha) was found to be higher than in TPF (396.66 stems/ha).

Table 1. Species regeneration status of TPF in Sahajnaath Collaborative Forest

SN	Name of Species	Tree density (stems/ha)	Sapling density (stems/ha)	Seedling density (stems/ha)	Regeneration Status
1	<i>Tectona grandis</i>	345.00	3,013.33	31,333.33	Good
2	<i>Aegle marmelos</i>	1.67	-	-	None
3	<i>Alangium salviifolium</i>	6.67	-	-	None
4	<i>Acacia catechu</i>	6.67	-	-	None
5	<i>Dalbergia sissoo</i>	8.33	-	-	None
6	<i>Murraya koenigii</i>	1.67	-	-	None
7	<i>Cassia fistula</i>	-	26.67	1,333.33	New
8	<i>Mallatus philippensis</i>	26.67	80.00	-	Poor
		396.68	3,120	32,666.66	

Table 2. Species regeneration status of NMF in Sahajnaath Collaborative Forest

SN	Name of Species	Tree density (stems/ha)	Sapling density (stems/ha)	Seedling density (stems/ha)	Regeneration Status
1	<i>Dysoxylum gobara</i>	25.00	293.33	3,333.33	Good
2	<i>Shorea robusta</i>	170.00	1,440.00	22,666.67	Good
3	<i>Mallatus philippensis</i>	53.33	453.33	3333.33	Good
4	<i>Terminalia nudiflora</i>	15.00	26.67	666.67	Good
5	<i>Grenia subinaequalis</i>	5.00	26.67	-	Poor
6	<i>Musa velutina</i>	11.67	26.67	1,333.33	Good
7	<i>Diospyros oojinense</i>	1.67	-	-	None
8	<i>Careya operculatus</i>	1.67	-	-	None
9	<i>Diospyros pentagyna</i>	20.00	160.00	1,333.33	Good
10	<i>Cassia fistula</i>	5.00	-	-	None
11	<i>Cinnamomum graveolens</i>	5.00	80.00	666.67	Good
12	<i>Syzygium cumini</i>	5.00	-	-	None
13	<i>Terminalia alata</i>	5.00	-	-	None
14	<i>Ficus racemose</i>	1.67	-	-	None
15	<i>Alstonia scholaris</i>	1.67	160.00	2,000.00	Good
16	<i>Schleichera oleosa</i>	3.33	-	-	None
17	<i>Kydia calycina</i>	15.00	26.67	2,000.00	Good
18	<i>Dalbergia latifolia</i>	3.33	-	-	None
19	<i>Cipadessa baccifera</i>	5.00	53.33	-	Poor
20	<i>Stereospermum personatum</i>	10.00	-	2,000.00	Fair
21	<i>Adina cordifolia</i>	6.67	-	-	None
22	<i>Ficus religiosa</i>	1.67	-	-	None
23	<i>Helicteres flaccidum</i>	5.00	-	-	None
24	<i>Holarrhena pubescens</i>	3.33	-	-	None
25	<i>Anogeissus latifolius</i>	33.33	133.33	666.67	Good
26	<i>Bridelia latifolia</i>	-	53.33	2,000.00	New
		413.34	2,933.33	42,000	

The regeneration status of NMF and TPF often shows distinct patterns, with NMF generally exhibiting higher overall tree density. This phenomenon is supported by several studies that compare natural and plantation forests. In a study conducted in Barnawapara Wildlife

Sanctuary of India, natural forests exhibited a tree density of 960 stems/ha that was significantly higher than the 340 stems/ha found in the teak plantation (Lal et al., 2015). Similarly, another study in Katarniaghat Wildlife Sanctuary of India reported that tree densities

were generally higher in natural forests compared to plantations (Tripathi & Singh, 2009). However, tree density in NMF (433.33 stems/ha) is notably lower in natural forest (773.50 stems/ha) reported by Bhujyu and Yonzon (2004) from a similar geographical region of Nepal. This decline may indicate a degradation of the Sahajunath Collaborative Forest, possibly due to human disturbances such as cattle grazing and the collection of fodder and firewood. In comparison, the tree density in the TPF (396.68 stems/ha) was higher than the 37-year-old teak plantation in Northern Thailand, which had a density of 316 stems/ha. On the contrary, the saplings in TPF (3,173.33 stems/ha) compared to NMF (2,933.33 stems/ha) were found slightly higher, which is highly contributed by *Tectona grandis* in TPF, but in NMF, *Shorea robusta* had a high sapling density. The study by Alem & Woldemariam (2009) highlighted that sapling density in natural forests was higher, while in plantations it was lower, indicating a trend where natural forests support more saplings. However, in some cases, specific species like *Lagerstroemia parviflora* showed better regeneration in teak plantations, suggesting variability in sapling success depending on species and environmental conditions (Lal et al., 2015). While the findings support the superiority of natural forests in terms of tree density, the presence of certain species thriving in plantations indicates that management practices and species selection can influence regeneration outcomes in TPF. Further, the seedling density of NMF (42,00 stems/ha) is comparatively higher than that of TPF (34,666.66 stems/ha). The higher seedling density in NMF compared to TPF can be attributed to several ecological and biological factors. Natural mixed forests typically support a greater diversity of species, which enhances seedling establishment and survival rates. In contrast, teak plantations often exhibit lower soil fertility and reduced species diversity, leading to diminished seedling density (Fernández-Moya et al., 2015; Kaewkrom et al., 2005; Abdullah et al., 2018). Natural mixed forests contain a variety of species, which promotes a more robust ecosystem. This diversity allows for a greater number of niches and microhabitats, facilitating higher seedling establishment rates (Trujillo-Miranda et al., 2021). In contrast, teak plantations are often monocultures, which can limit the ecological interactions necessary for seedling growth (Pande et al., 1988). Studies indicate that teak plantations experience greater soil fertility loss over time compared to mixed forests, which can negatively impact seedling growth and survival (Prasad et al., 1985).

The average canopy cover was found to be 65 ± 15.118 and 46 ± 21.314 percent in TPF and NMF, respectively. The canopy cover in both the forests is significantly different ($p = 0.009$), and was observed to be higher in the TPF, which might be due to higher sapling density. The maximum and minimum canopy cover in TPF were found to be 90 % and 40 %, respectively. In contrast, the maximum and minimum canopy cover in NMF were found to be 80 % and 10 %, respectively. The maximum and minimum percent of canopy cover in TPF shows 'dense forest' to 'degraded forest' category, whereas in

NMF it shows 'dense forest' to 'non forest'. Teak plantations often exhibit higher and more uniform canopy cover compared to naturally managed forests. This is attributed to the regular spacing, even-aged structure, and management practices typical of planted forests, while NMFs are subject to natural disturbances and variable regeneration, resulting in more heterogeneous and often lower canopy cover, which promotes rapid canopy closure and reduces gaps (Behera et al., 2017; Vongkhamho et al., 2022; Widiyatno et al., 2023). The 'dense forest' (71-100 %) indicates robust forest health, crucial for biodiversity and carbon sequestration, the 'degraded forest' (11-40 %) is characterized by sparse tree cover, indicating ecological stress or human impact and the 'non forest' (0-10 %) are the forest with areas with minimal or no tree cover (Gurung & Kokh, 2011). The canopy cover is an important parameter for the bulk density (Boley et al., 2009). It was believed that low canopy cover can penetrate the soil much faster by rainwater (Fengchi et al., 2022; Tao et al., 2020). This reduces the microbial activities of the soil due to soil compaction and reduces moisture-retention capacity as well (Bargali et al., 1993). It may also reduce the stomatal conductance due to the hydraulic constraints (Gower et al., 1996). Less disturbance, no vegetation on the forest floor, and less trampling effect with the mature trees might have supported high canopy cover in TPF. Whereas, the less canopy cover in NMF might be due to natural and anthropogenic disturbance that plays a significant role in reducing canopy cover (Krüger et al., 2025; Kramer et al., 2020).

Biomass of TPF and NMF

The median total biomass was 363.21 t/ha (IQR = 206.67 t/ha) in NMF, and that of TPF was 308.15 t/ha (IQR = 178.38 t/ha). The total biomass between NMF and TPF was not significantly different from each other ($W = 137$, $p = 0.325$). The average total biomass was found to be 331.398 ± 128.422 t/ha in TPF and that of 424.504 ± 251.128 t/ha in NMF, which is not significantly different from each other ($p = 0.325$) (Fig. 2). While there was no overall difference in biomass between the two forests, biomass variation was observed at the plot level. The highest biomass (1,157.37 t/ha) was found in the *Shorea robusta*-dominated plot, while the lowest (115.22 t/ha) was recorded in the mixed species composition with *Dysoxylum gobarua*-dominated plot of the NMF. This aligns with findings in other research on Nepalese forests, highlighting that *Shorea robusta*, as the dominant species in the forest, contributes higher biomass compared to the forest with other tree species (Ayer et al., 2024; Gautam et al., 2023; Giri et al., 1999; Paneru and Chalise, 2022; Ulvdal, 2016). On the other hand, in the TPF, biomass ranged from a minimum of 131.08 t/ha to a maximum of 577.08 t/ha, with the highest values found in plots containing a greater number of mature trees. The variation in biomass was higher in the NMF due to its higher species diversity, while it was lower in the TPF. The average AGTB and BGTB in the TPF were 288.172 ± 111.672 t/ha and 43.226 ± 16.751 t/ha, respectively. Similarly,

the average AGTB and BGTB in the NMF were 369.134 ± 218.372 t/ha and 55.37 ± 32.756 t/ha, respectively. There was no difference in average AGTB and BGTB ($p = 0.325$) found between these two forests (Fig. 3). This suggests that teak plantations can accumulate

biomass at rates similar to natural forests under similar functional traits and ecological conditions (Ghimire et al. 2024; Gong et al. 2023; Kenzo et al. 2020; Thakur et al. 2021).

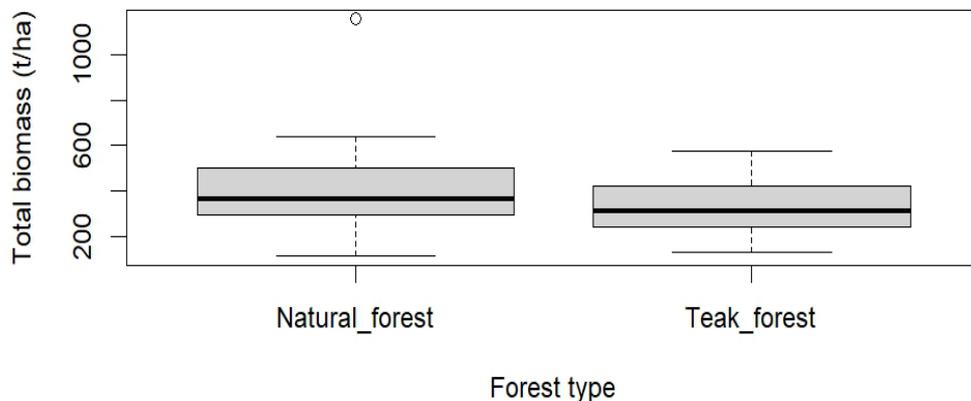


Figure 2. Total biomass in the NMF and the TPF

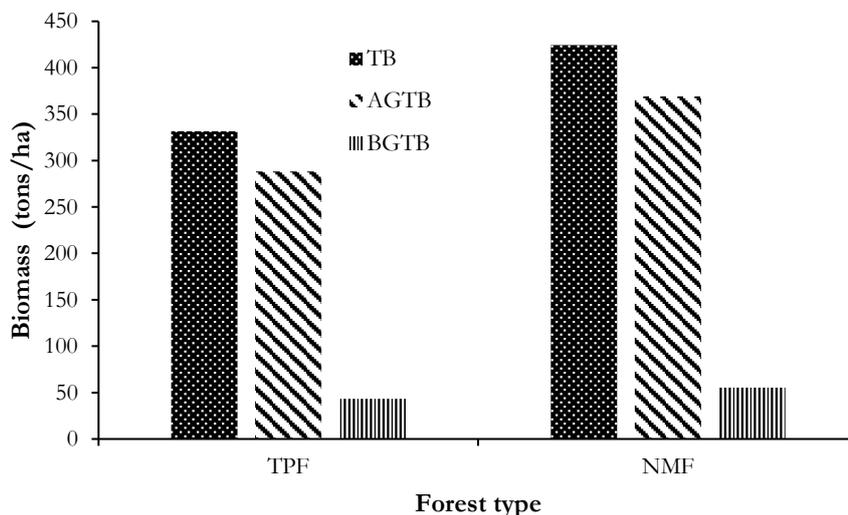


Figure 3. The total biomass (TB), aboveground tree biomass (AGTB) and belowground tree biomass (BGTB) of TPF and NMF

Physico-chemical properties of soil

The TPF and NMF showed two major categories for soil texture, which contained sandy loam to sandy clay loam forms consisting of clay, silt, and sand, with no difference in the type of soil between the two forests (Fig. 4). However, it was found that the proportion of clay, sand, and silt in the soil was significantly different. The result showed that the clay content in the NMF is higher than in the TPF. While the statistical proportion of clay was similar in both forests ($p = 0.806$). The t-test illustrates that the TPF was significantly less silty than that of the NMF ($p = 0.014$). The t-test also shows that the TPF has a higher proportion of sand content compared to the NMF ($p = 0.018$). Generally, sand content declines with soil depth, while silt and clay percentages increase. In most cases, topsoil often contains a higher sand percentage. Studies show that as

teak plantations mature, the soil texture shifts, with increased silt and clay content noted in older rotations (Alexzander et al. 1980; Jose & Koshy, 1968). This change is likely due to the accumulation of organic matter and alterations in soil structure over time. However, the study in Ghana found the opposite trend, attributed to less canopy cover, compaction, and soil weathering during the establishment of the teak plantation (Amponsah & Meyer, 2000). In the teak forest, the clay-deficient surface layer is attributed to the downward infiltration of clay particles. The lower silt and clay percentage in the surface of TPF could be a consequence of enhanced infiltration and percolation during the plantation time, which drove down the smaller particles from the surface. Furthermore, the study in Ghana revealed that the teak forest experienced less disturbance, greater canopy cover, and lower bulk

density compared to natural forests. These results are in agreement with a time series analysis of texture by Ombina (2008). In contrast, higher clay accumulation in the teak forest appears to be a temporary phenomenon, primarily occurring within the first year of plantation establishment. The combination of sedimentary loam

with high clay content in moist places adversely impacts teak growth (Kaosa-ard, 1981). Thus, site selection proves essential for establishing successful teak plantations despite the fact that teak plantations reduce soil erosion better than pasture land (Boley et al., 2009).

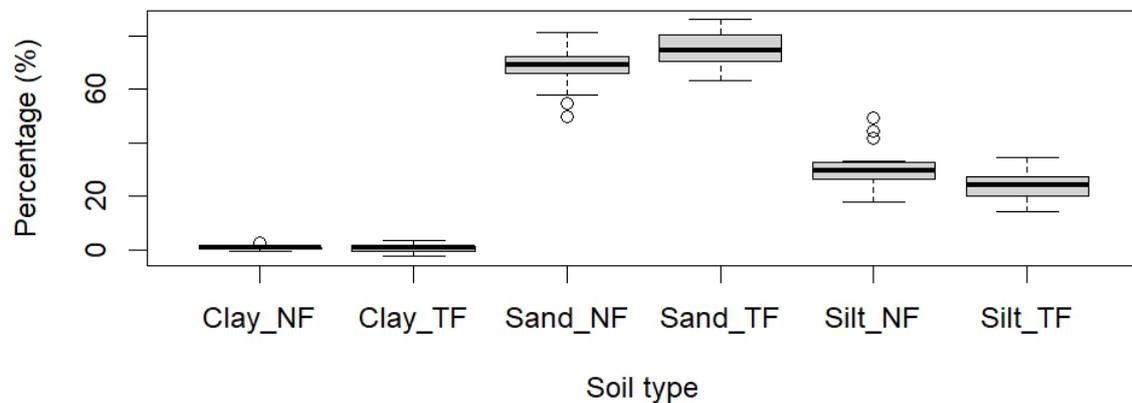


Figure 4. Box-plot of soil texture (sand, silt, and clay) in NMF and TPF with the upper and lower quartiles (box), and outliers (circles) of the data

Similarly, the average bulk density of the soil particles was found to be $1.382 \pm 0.097 \text{ g/cm}^3$ and $1.473 \pm 0.081 \text{ g/cm}^3$ in TPF and NMF, respectively. The t-statistic illustrates that TPF had significantly less bulk density compared to NMF ($p = 0.009$). Trampling by the cattle (Krishnaswamy & Richter, 2002), grazing by cattle, and less canopy cover are the major factors that increase the bulk density of the forest (Boley et al., 2009). Due to the presence of high grass and tree species diversity in NMF, the cattle grazing is high, which might have caused the trampling effect. On the other hand, less species diversity and less grass available in TPF might have decreased such activities, reducing its bulk density. The decrease in bulk density is important for plant growth because it supports infiltration, percolation, and aeration of the soil. It also supports the survival of seedlings and saplings of the trees (Pedraza & Williams-Linera, 2003). Therefore, teak plantations in TPF could be a factor contributing to the loose soil structure.

In addition, the mean soil moisture content was statistically similar between TPF ($10.991 \pm 4.806\%$) and NMF ($10.387 \pm 4.132\%$), indicating that the soil moisture of these two forests is similar. This is supported by both the homogeneity of variance ($p = 0.579$) and the non-significant difference in means (t-test, $p = 0.715$). Teaks naturally occur from very dry places to very moist places around the world (Ansari et al., 2012; Kaosa-ard, 1981; Palanisamy et al., 2009). Conversely, the tree size is very large, fluted, and replaced by the evergreen species in very moist places (Kaosa-ard, 1979). On the other hand, conversion of NMF to other land use types will massively change its soil hydraulic properties and water retention characteristics (Owuor et al., 2018; Zimmermann et al., 2006). Soil moisture is associated with changes in soil

organic carbon stock, and it quickly responds to natural disturbances and soil erosion (Lal, 2005). Soil moisture can also affect EC, but this variation is not apparent in the surface soil moisture (Bréchet et al., 2012). The moisture content of the soil is affected by different factors (Gómez-Plaza et al., 2001), among which soil properties, vegetation, and meteorological conditions are the most influential parameters (Bréchet et al., 2012).

The soil pH value of TPF (6.634 ± 0.034) is significantly lower than that of NMF (7.137 ± 0.449), indicating a more acidic soil environment in TPF compared to NMF soil, which tends to increase alkalinity (t-statistics, $p = 0.003$). This indicates that the soil of TPF is more acidic, and the soil of NMF is inclined towards alkalinity. This contrasts with the findings of Shukla et al. (2017) and Aborisade and Aweto (1990). However, Ombina (2008) found a contradictory result that shows no difference in pH between these forests, which is ultimately due to the presence of aluminium in the soil. In the case of alkaline soil in the teak plantation area, it reduces the quality of soil, and further, alkaline soil is toxic to the teak plant (Kaosa-ard, 1981). The pH value up to 8.0 in the hot and dry season was noted, but this species showed poor growth in acidic soils (Palanisamy et al., 2009). The results of laboratory tests from the various studies also reported that the teak plant has an allelopathic effect because it has a higher concentration of phenolic acid present in its foliage (Biswas & Das, 2016; Fernández-Moya et al., 2014).

The electrical conductivity (EC) for TPF ($45.133 \pm 12.867 \text{ } \mu\text{S/cm}$) compared to NMF ($278.33 \pm 61.049 \text{ } \mu\text{S/cm}$) was significantly low (Wilcoxon test, $p=3.358e^{-06}$). The lowest EC was also observed in teak planted forest in comparison to dry miscellaneous and mixed sal

forest by Shukla et al. (2017). The significantly lower EC observed in teak planted forests compared to natural mixed forests can be attributed to several interrelated factors, primarily involving soil composition and nutrient availability. Further, changes in environmental factors influence the EC of the soil. The salinity, water condition (Bennett & George, 1995), and clay mineral contents (Triantafyllis & Lesch, 2005) are the most influential parameters for the EC. The soil moisture and bedrock type are the driving forces to control EC in the teak forest by determining the mineral composition, weathering processes, and nutrient availability in soils (Bréchet et al., 2012; Moore et al., 2022).

Soil nutrient properties

The forests of TPF ($7.245 \pm 0.91\%$) and NMF ($6.682 \pm 0.793\%$) have preserved a similar proportion of organic matter, which is not statistically significant (t-test, $p = 0.083$). Likewise, the Wilcoxon test showed that there is no significant difference ($p = 0.328$) in the total nitrogen content in TPF ($0.0658 \pm 0.0319\%$) and in NMF ($0.103 \pm 0.075\%$). Whereas, phosphorus in TPF (0.967 ± 0.702 t/ha) and in NMF (4.732 ± 4.301 t/ha) ($p = 0.024$) and potassium in TPF (7.223 ± 8.984 kg/ha) and in NMF (28.878 ± 12.868 kg/ha) ($p = 1.529 \times 10^{-5}$) showed a significant difference in both forests (Table 2).

The nutrients are massively reduced in the TPF in comparison with NMF (Amponsah & Meyer, 2000; Ombina, 2008; Shukla et al., 2017). This might be due to the lower annual litterfall and understory vegetation growth of TPF results in lower nutrient content in the forest. The amount of litterfall depends on the age of the tree and the present understory vegetation. The higher amount of litterfall can enhance nutrient content together with enzyme activity (Shukla et al., 2017). The concentration of total nutrients is higher with climatic systems, rainfall patterns, moisture availability, temperature, leaching, and increasing proportion of nitrogen-fixing plants and intercropped (Kumar et al., 1998). The reduction of nutrients (OM, N, P, K, Ca, and Mg) is due to leaching and soil erosion. The soil erosion is also linked with the understory vegetation cover and OM content in soil (Amponsah & Meyer, 2000; Lal, 2005; Ombina, 2008). It can also be strongly related to pH value (Ombina, 2008) and nitrogen-fixing tree species. It was found that the fast-growing tree species deplete nutrients (Ca, K, and P) faster than the slow-growing trees (Boley et al., 2009). The poor soil quality in the plantation is due to nutrient immobilization (Aborisade & Aweto, 1990), which can further inhibit sapling growth (Asigbaase et al., 2024; Jimoh and Aliyu, 2024). This could be the reason that only the sapling of the teak plant was dominant in the TPF.

The organic matter (OM) is influenced by soil moisture availability, temperature, soil texture, rainfall zone, and electrical conductivity (Amooh & Bonsu, 2015; Kim & Park, 2024; Li et al., 2023). Organic matter also has a proportional relationship with cation exchange capacity (CEC) and nutrient holding capacity (NHC) of soil (Peverill et al., 1999). The OM is proportionally related

to the clay content (Hase & Foelster, 1983). However, cattle grazing and the trampling effect were observed to be higher during the field assessment in the NMF. This is likely because higher species diversity and greater grass availability on the forest floor provide more attractive and abundant forage for cattle, leading to increased grazing activity and, consequently, more trampling. Hence, this effect could be the reason for similar organic matter in NMF and TPF. Organic matter is an important parameter for the distribution of the teak plant. The study in Thailand shows that the OM content was found to be higher in teak planted forest mixed with other deciduous forests than in the nearby dry *Dipterocarp* forest (Kaosa-ard, 1981). Similarly, total nitrogen forms the major mineral constituents of the leaves of the plant (Cao et al., 2007). Generally, lowland tropical forests have higher nitrogen and mass/nitrogen ratios of litterfall in comparison with the temperate forest (Vitousek, 1984). Rooting depth, precipitation, and water stresses in sandy soil play a significant role in nitrogen deficiency of soil (Drechsel & Zech, 1994).

The available phosphorus was similar in the *Gmelina arborea*, teak planted forest, and naturally managed forests in south-western Nigeria (Aborisade & Aweto, 1990). Teak plantations have a more open nutrient cycle (Aweto 2001; Yao 2021), and burning litter accelerates nutrient loss through leaching and erosion, reducing long-term soil fertility and ecosystem stability (Butler 2020; Latterini 2023). In addition, the amount of phosphorus decreased over 4-6 years of the teak plantation when other nutrients remained stable (Drechsel & Zech, 1994). Likewise, it is prone to catching fire due to the litterfall in a single dry season. Plantation forests show a severe phosphorus deficit in some areas (Vitousek, 1984).

Organic matter content was found to be higher in the teak forest. This might be due to the accumulation and decomposition of leaf litter are crucial for maintaining and enhancing OM in teak soils (Asanok et al., 2024). Organic matter content is a major source of potassium. The potassium content also depends on soil pH, as it decreases with the increasing acidity of the soil (Hossain, 2014). Mixed species plantation diminishes the nutrients at a slower rate than the replacement of nutrients. Therefore, it could be the possible reason for potassium depletion in a study area.

Canonical correspondence analysis of teak species and soil parameters

The ordination analysis, i.e., canonical correspondence analysis (CCA), shows the relationship of the species with the soil parameters. The analysis was performed to show the most significantly influenced soil parameters of the teak plant. It helped to indicate influenced species with the particular soil parameters. The ordination analysis explains the relationship of species with nutrients, such that the teak is found in sand-rich areas and higher organic matter content (Fig. 5). Species such as *Acacia catechu* and *Dalbergia sissoo* are also found in a similar environment to teak. Most of the other species

are found in nutrient-rich conditions. This could be the reason that the NMF had high tree species diversity compared to TPF. The eigen-values of CCA indicated that two components (CCA1 and CCA2) provided a good summary of the data, accounting for about 83.26 % of the total variance (Fig. 5).

The canopy cover is also found to be higher in the forest with the teak species. The canopy cover in TPF and NMF forests is also significantly different ($p=0.0093$), and it was higher in the TPF. Canopy cover was observed to be higher due to the greater number of saplings in the TPF. This phenomenon can be attributed to several factors that enhance growth and density in teak plantations. Teak plantations exhibited a higher density of saplings compared to lower figures in natural

forests (Lal et al., 2015). The presence of multiple sprouts per stump in teak management practices contributes to increased sapling numbers, enhancing overall canopy cover (Yévidé et al., 2011). Further, teak is a heliophytic species, thriving in open conditions, which allows for better light penetration and growth in plantations (Toyi et al., 2013). The structured management of teak plantations, including spacing and thinning, optimizes growth conditions, leading to a denser canopy (Toyi et al., 2013). While natural forests may have a richer species composition, they often show lower tree densities and sapling counts, resulting in less canopy cover (Lal et al., 2015; Tripathi & Singh, 2009). The basal area in natural forests does not significantly exceed that of plantations, indicating that while diversity is higher, density is lower (Tripathi & Singh, 2009).

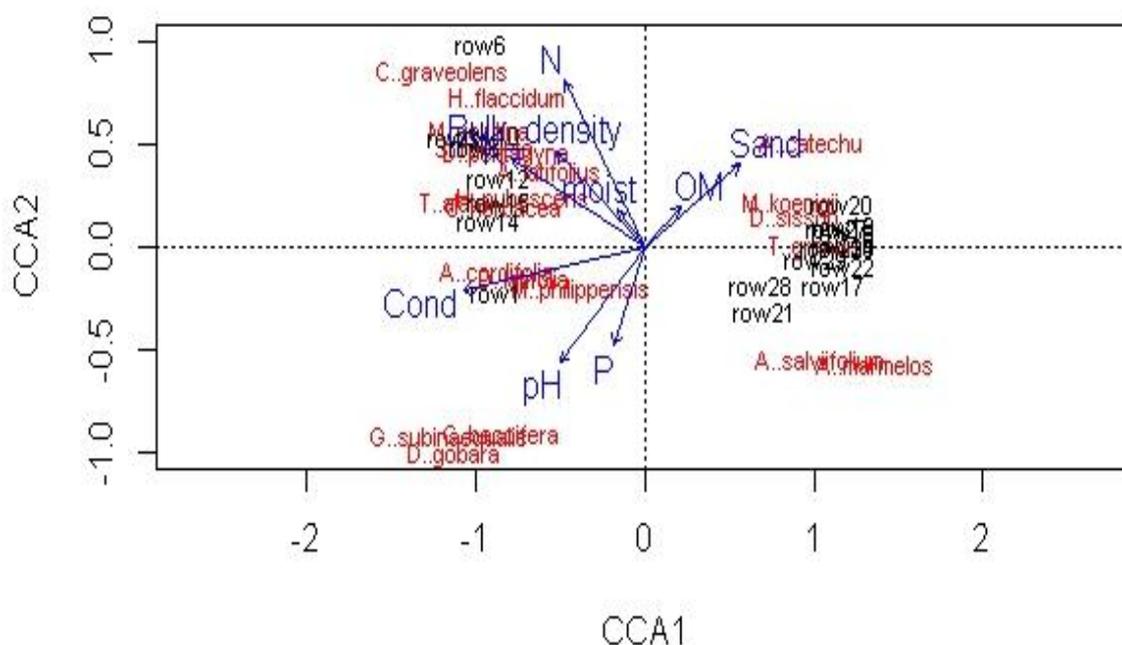


Figure 5. Canonical correspondence analysis (CCA) ordination diagram of different tree species with different edaphic factors represented by arrows in the study area. The species are abbreviated to the first letter of the genus and the full species name.

Biomass and edaphic factors

The physical properties and nutrients of the soil were analysed with the total biomass of NMF and TPF. So, the variations in those parameters of soil were expected in TPF and NMF. In addition, the variations in biomass due to the nutrients were also expected. Soil properties have a significant role in explaining the variation in the growth of the plant biomass and its turnover rate (Cai et al., 2019).

In the TPF, the total biomass is positively and significantly correlated with pH ($\tau = 0.421, p < 0.05$) and N ($\tau = 0.414, p < 0.05$). Similarly, in NMF, the total biomass is positively and significantly correlated with organic matter ($\tau = 0.394, p < 0.05$), sand ($\tau = 0.468, p < 0.05$), N ($\tau = 0.406, p < 0.05$), canopy cover ($\tau = 0.415, p < 0.05$) and strongly positive correlation with K ($\tau = 0.546, p < 0.01$). However, strongly negative and

significantly correlated with available P ($\tau = -0.657, p < 0.01$) and silt ($\tau = -0.502, p < 0.001$). The details of the correlation study of TPF and NMF are shown in Tables 3 and 4, respectively.

The Kendall correlation analysis between the tree biomass and different soil parameters was carried out by assuming the reciprocal influence of soil properties and tree biomass. The soil parameters represent the nutrient status of the soil and the growth base of the species. The variation in those parameters affects the sustainability of the forest from a long-term perspective. It could be assumed that the reduction of nutrients in TPF is due to the plantation of teak species. From a long-term perspective, these significantly reduce the chemical properties that ultimately reduce productivity and natural biodiversity (Ombina, 2008). However, economic and political interests drove a community

towards the monoculture plantation for fast-growing trees and high-value timber, even though biodiversity

and ecological function are not matched by that of a natural forest (Scheidel & Work, 2018).

Table 3 Monitored soil parameters in TPF and NMF

Parameters	TPF	NMF	Test and significance level
pH	6.634 ± 0.378	7.137 ± 0.449	$T, p = 0.003^{**}$
Conductivity (µS/m)	45.133 ± 12.867	278.330 ± 61.049	$W, p = 3.358 \times 10^{-6}^{***}$
Bulk density (g/cm ³)	1.382 ± 0.097	1.473 ± 0.081	$T, p = 0.010^{**}$
Nitrogen (%)	0.066 ± 0.032	0.103 ± 0.075	$W, p = 0.328$
Potassium (kg/ha)	0.269 ± 0.334	1.074 ± 0.479	$T, p = 1.529 \times 10^{-5}^{***}$
Phosphorus (t/ha)	0.967 ± 0.703	4.739 ± 4.301	$W, p = 0.024^*$
Moisture (%)	10.991 ± 4.806	10.387 ± 4.132	$T, p = 0.715$
Organic Matter (%)	7.245 ± 0.914	6.682 ± 0.793	$T, p = 0.083$
Sand (%)	75.223 ± 7.164	68.646 ± 8.671	$T, p = 0.018^*$
Silt (%)	24.016 ± 6.117	31.115 ± 8.536	$T, p = 0.014^*$
Clay (%)	0.762 ± 1.520	0.869 ± 0.714	$T, p = 0.806$

*Significant value at $p < 0.05$, **significant value at $p < 0.01$, T = t-statistics, W = Wilcoxon test

Table 4 Correlation between total tree biomass and soil parameters in TPF and NMF

Parameters	Total biomass in TPF (tons/ha)	Total Biomass in NMF (tons/ha)	Test and significance level
pH	$\tau = 0.421^*$	$\tau = -0.352$	$T, p = 0.003^{**}$
Conductivity (µS/m)	$\tau = -0.029$	$\tau = -0.271$	$W, p = 3.358 \times 10^{-6}^{***}$
Bulk density (g/cm ³)	$\tau = -0.219$	$\tau = 0.295$	$T, p = 0.010^{**}$
Nitrogen (%)	$\tau = 0.414^*$	$\tau = 0.406^*$	$W, p = 0.328$
Potassium (kg/ha)	$\tau = 0.010$	$\tau = 0.546^{**}$	$T, p = 1.529 \times 10^{-5}^{***}$
Phosphorus (tons/ha)	$\tau = 0.048$	$\tau = -0.657^{**}$	$W, p = 0.024^*$
Moisture (%)	$\tau = -0.048$	$\tau = 0.219$	$T, p = 0.715$
Organic Matter (%)	$\tau = 0.279$	$\tau = 0.394^*$	$T, p = 0.083$
Sand (%)	$\tau = 0.049$	$\tau = 0.468^*$	$T, p = 0.806$
Silt (%)	$\tau = -0.039$	$\tau = -0.502^{**}$	$T, p = 0.014^*$
Clay (%)	$\tau = -0.010$	$\tau = 0.135$	$T, p = 0.018^*$
Canopy cover (%)	-	$\tau = 0.415^*$	-

*Significant value at $p < 0.05$, **significant value at $p < 0.01$, T = t-statistics, W = Wilcoxon test and τ = Kendall rank correlation coefficient

Conclusions

The study reveals the differences in regeneration, biomass, physico-chemical and nutrient properties of soil in NMF and TPF. The study exhibits good regeneration of ten tree species in NMF, as indicated by the overall density of trees, saplings, and seedlings. On the contrary, the high sapling density was observed in the TPF, dominated by the saplings of *Tectona grandis*. This suggests that the teak inhibits the growth of other sapling species, allowing it to grow abundantly despite the poor nutrient soil. Furthermore, the similar biomass content in TPF and NMF suggests that the native species in the natural forest are just as capable of growing and reaching their full size as the cultivated teak trees, given the same climate and environmental conditions. The canopy cover was observed to be higher in the TPF, which might be due to higher sapling density. The NMF shows more favourable soil nutrient content and physical properties than TPF. The lower disturbances in TPF might have resulted in relatively similar OM content, N, soil moisture, and sand percentage to NMF. The litterfall is identified as a key

contributor to higher nutrient input in many forests, and this study suggests that NMF experiences higher litterfall rates than TPF. Based on these findings, it is recommended that prioritizing mixed species plantations, including both teak and native tree species, should be preferred instead of monoculture practices to balance economic viability with environmental integrity. This option utilizes the rapid growth and high timber production of teak while delivering greater diversity and ecosystem processes, although not fully replicating a natural forest.

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