International Journal of
Innovative Research

International Journal of Innovative Research, **10(2)**:52–60, 2025
ISSN 2520-5919 (online)
www.irsbd.org

RESEARCH PAPER

Shimul mul (*Bombax ceiba*) Performance and Environmental Response under Medicinal Tree-Based Agroforestry

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ARTICLE HISTORY

Received: May 18, 2025
Revised: July 29, 2025
Accepted: August 23, 2025
Published: August 31, 2025

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ABSTRACT

This study assessed the growth, yield, and environmental benefits of Shimul mul (*Bombax ceiba*) intercropped with three medicinal trees viz. Amloki, Haritoki, and Bohera under agroforestry systems in Bangladesh. Growth and yield of Shimul mul were significantly influenced by tree species and distance from tree bases. Amloki-based systems promoted the tallest plants, longest leaf rachis, robust root development, highest fresh yield and biomass, while Haritoki exerted the strongest competitive effects. Wider spacing (137–204 cm) reduced resource competition, achieving yields comparable to open-field conditions. Positive correlations between light intensity and yield (R^2 = 0.817–0.884) highlighted canopy structure as a key determinant of intercrop performance. Land Equivalent Ratio (LER) exceeded 1.0 for all combinations (1.67–1.74), indicating enhanced land-use efficiency. Agroforestry slightly improved soil fertility, particularly under Amloki, and carbon sequestration was highest in Bohera. Overall, integrating Shimul mul with medicinal trees especially Amloki enhances productivity, sustainability, and climate resilience, supporting its promotion as a viable agroforestry strategy in Bangladesh.

Keywords: Agroforestry, Carbon Sequestration, LER, Light Intensity, Medicinal Trees, Shimul mul, Soil Fertility

Introduction

Agroforestry is widely recognized as an ecologically sound and economically viable land-use strategy that integrates trees with agricultural crops to enhance resource use efficiency, ecosystem stability, and rural livelihoods. In tropical and subtropical regions, where land degradation, climatic variability, and population pressure increasingly undermine agricultural productivity, agroforestry offers a resilient and multifunctional alternative (Nair, 1993; Leakey, 2014). By improving soil fertility, regulating microclimate, enhancing biodiversity, and diversifying income sources, agroforestry systems have become indispensable for smallholder farmers striving to maintain sustainable production (Rahman *et al*., 2019). Within this broad framework, medicinal tree-based agroforestry has gained prominence for its dual benefits: it provides high-value medicinal products while simultaneously contributing to ecological restoration.

Medicinal tree species such as *Phyllanthus emblica* (Amloki), *Terminalia chebula* (Haritoki), and *Terminalia bellirica* (Bohera) hold significant value in Ayurvedic, Unani, and traditional healthcare systems due to their fruits and bark rich in antioxidants, tannins, vitamin C, and other bioactive compounds (Kala, 2005; Parrotta, 2001; Singh *et al*., 2011). Integrating a medicinal plant like Shimul mul (Bomba ceiba) with these tree species provides an effective strategy for developing productive and ecologically balanced agroforestry systems. Such integrations enhance resource-use efficiency, improve soil health, and support sustainable livelihoods through diversified medicinal plant production.

Among the potential companion species for such systems, Shimul Mul (*Bombax ceiba*) is particularly noteworthy. B. ceiba is a fast-growing deciduous species distinguished by its ecological adaptability, rapid juvenile development, and multiple uses. It grows successfully across diverse landscapes including plainlands, homesteads, floodplain edges, and char areas and tolerates both seasonal flooding and drought (Hossain and Islam, 2018). Its open canopy architecture, deep rooting pattern, and ability to contribute substantial leaf litter make it highly suitable for association with medicinal tree species that require partial sunlight during initial growth stages (Kumar *et al*., 2009; Hossain and Bari, 2017). In addition, Shimul mul is an important medicinal root crop known for its cooling, demulcent, and anti-inflammatory properties. Its roots are widely used to treat digestive and urinary disorders due to their rich starch and mucilage content. The crop also provides strong market potential, supporting income generation and diversification in agroforestry systems.

Despite these advantages, scientific understanding of Bombax ceiba performance within structured medicinal tree-based agroforestry systems remains inadequate. Previous research has largely emphasized its taxonomy, ethnomedicinal properties, or general silvicultural behavior. However, comprehensive assessments of its growth performance, biomass accumulation, carbon sequestration potential, and environmental response particularly in interaction with medicinal tree species are limited. Such knowledge is essential because species compatibility, canopy overlap, root interaction, and nutrient-sharing dynamics greatly affect the productivity and resilience of mixed agroforestry systems (Jose, 2009; Young, 1997).

Environmental responses of tree species including morphological adjustments, physiological performance, and biomass allocation are influenced by soil fertility, moisture availability, microclimatic conditions, and competitive interactions within agroforestry environments. The presence of trees modifies environmental parameters by altering light distribution, reducing temperature fluctuations, increasing soil moisture retention, and enhancing organic matter inputs. These changes may either support or challenge the growth of associated medicinal species, depending on system design, spacing, canopy management, and resource competition (Pandey, 2007). Understanding these microenvironmental dynamics is essential for selecting compatible species combinations and optimizing system productivity.

Carbon sequestration is another critical ecosystem service provided by tree-based systems. Through the capture and long-term storage of atmospheric CO_2 in biomass and soil, agroforestry contributes significantly to climate change mitigation (IPCC, 2006; Garrity, 2004). Medicinal tree-based agroforestry, in particular, tends to accumulate substantial carbon due to high tree density and rapid biomass turnover. However, the carbon dynamics of Bombax ceiba in such systems—especially in relation to above- and below-ground biomass partitioning, age-specific growth, and whole-system carbon accumulation remain insufficiently documented. Standardized allometric models (Chave *et al.*, 2014) now make it possible to accurately estimate these parameters and evaluate carbon storage potential under different system configurations.

Considering these gaps, there is a clear need for systematic investigation into the performance and environmental response of Shimul mul (*Bombax ceiba*) under medicinal tree-based agroforestry. Such research can offer insights into species compatibility, growth interactions, biomass and carbon dynamics, and microenvironmental modifications within mixed systems. This knowledge is essential for designing productive, climate-adaptive agroforestry models that can support rural livelihoods while enhancing ecological functions.

The present study addresses these knowledge gaps by evaluating the growth, biomass, carbon stock, soil properties, and microenvironmental responses of Bombax ceiba when integrated with medicinal tree species. By analyzing tree–tree interactions and environmental modifications within this agroforestry model, the study aims to generate evidence-based recommendations for developing resilient, high-value medicinal tree-based systems. Ultimately, this research contributes to the broader recognition of agroforestry as a multifunctional land-use strategy that enhances ecosystem health, increases carbon sequestration, improves farm productivity, and supports sustainable development. By documenting the ecological behavior and environmental response of Shimul mul within medicinal tree-based agroforestry, the study provides a foundation for designing more productive, resilient, and environmentally beneficial land-use systems in regions where sustainable resource management is increasingly essential.

Materials and Method

This experiment was carried out at Agroforestry Field Laboratory, Bangladesh Agricultural University in Mymensingh district of Bangladesh (Figure 1).

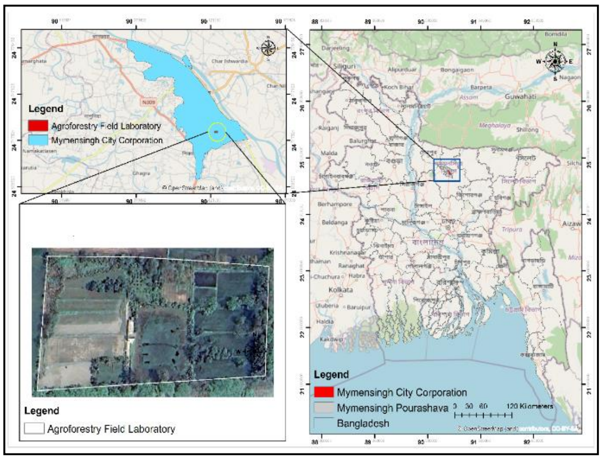

Figure 1. Location of the study area (Agroforestry Field Laboratory).

Figure 2. Medicinal tree plantation in experimental field

In this research study, Shimul mul was cultivated under three medicinal tree species viz. Amloki (*Phyllanthus emblica*), Haritoki (*Terminalia chebula*), and Bohera (*Terminalia bellirica*). These tree species were previously established in 2018 following a strip plantation system with a spacing of 4.2 m × 4.2 m (Figure 2). Shimul mul (*Bombax ceiba*) was grown around each tree species following a two-factor Randomized Complete Block Design (RCBD) with four replications. The spacing for Shimul mul plants was maintained at 20 cm × 40 cm. The experimental factors were as follows:

Factor A: Medicinal tree species – Amloki (A), Haritoki (H), and Bohera (B)

Factor B: Distance from tree base – T_1 = 0–68 cm, T_2 = 68–136 cm, and T_3 = 136–204 cm.

A control treatment (T_0) consisted of Shimul mul cultivated without any tree association.

Regular intercultural operations viz. including gap filling, weeding, irrigation, pest and disease management, and fertilization were carried out as required to ensure uniform growth of Shimul mul. Mature plants were harvested at physiological maturity. Growth and yield parameters such as plant height (cm), leaf rachis length (cm), root length (cm), root girth (cm), and fresh weight per plant (g) were recorded. Yield was calculated in tons per hectare (t/ha), and yield reduction (%) for each medicinal tree combination was determined using a standard formula in comparison with the control (T_0). The Land Equivalent Ratio (LER) was computed following Mead and Willey (1980) based on the relative yields of Shimul mul and medicinal tree species to evaluate productivity advantages under intercropping.

Solar radiation was measured at two-hour intervals in four orientations (north, south, east, and west) and at varying distances from tree bases using a digital lux meter (Model HI957500, Hanna Instruments). Correlation analysis between light intensity and Shimul mul yield was conducted separately for each tree species to assess shading effects.

Soil samples (0-15 cm) were collected before planting and after the experimental cycle from each treatment plot to determine changes in soil fertility. Composite samples were air-dried, ground, and sieved (2 mm) for laboratory analysis. Soil pH was measured using a glass electrode pH meter in a 1:2.5 soil-to-water solution (Jackson, 1973). Organic carbon was determined by the Walkley and Black (1934) wet oxidation method, while total nitrogen was analyzed using the Kjeldahl digestion and distillation method (Bremner and Mulvaney, 1982). Available phosphorus was determined using the Olsen method (Olsen *et al.*, 1954), available potassium through flame photometry after ammonium acetate extraction (Jackson, 1973), and available sulfur using the turbidimetric method (Chesnin and Yien, 1951).

Above-ground biomass and total carbon stock for each medicinal tree–Shimul mul combination were estimated using allometric equations from Chave *et al.* (2014). Below-ground biomass was derived using a root-to-shoot ratio of 0.26 (Mina *et al*., 2023). Total tree biomass was calculated by summing above- and below-ground components, and carbon content was estimated following IPCC (2006), assuming 50% of total biomass as carbon (TTC = TTB × 0.5).

All collected data were analyzed using Analysis of Variance (ANOVA) appropriate for RCBD, and treatment means were compared using the Least Significant Difference (LSD) test at the 5% level of significance using Statistix 10.

Results

Shimul mul is cultivated under three medicinal tree species viz. Amloki, Haritoki, and Bohera (Figure 3). Growth and yield performances Shimul mul are explained in this section separately.

Figure 3. Different research activities of Shimul mul with medicinal trees in the experimental field

Growth performances of Shimul mul under different medicinal tree species:

The growth and yield attributes of Shimul mul varied significantly ($p < 0.01$) under different medicinal tree species (Table 1).

Table 1. Effect of different medicinal tree species on growth and yield contributing parameters of Shimul mul

Tree species	Plant height (cm)	Length of leaf Rachis (cm)	Root Length (cm)	Root girth (cm)	Fresh wt. /plant (g)
Amloki (A)	54..54 a	16.42 a	13.75 a	4.78 a	61.69 a
Haritoki (H)	51.27 c	15.43 b	12.05 b	4.31 b	58.40 c
Bohera (B)	52.12 b	16.02 a	13.54 a	4.65 a	60.14 b
CV (%)	5.27	8.73	5.75	6.64	6.17
Level of Sign.	**	**	**	**	**

Means in column followed by the different letter are significantly different by LSD at P ≤ 0.05

Among the treatments, Amloki-based systems exhibited the most favorable growth performance, producing the tallest plants (54.54 cm), the longest leaf rachis (16.42 cm), and the highest root girth (4.78 cm). Amloki also generated the greatest fresh weight per plant (61.69 g), indicating superior biomass accumulation. Haritoki resulted in the lowest values for most growth parameters, including plant height (51.27 cm), leaf rachis length (15.43 cm), root length (12.05 cm), and fresh weight (58.40 g). Bohera performed moderately, producing growth and yield values that were significantly higher than Haritoki but slightly lower than Amloki for several traits. Notably, Bohera-supported plants showed root length (13.54 cm) and root girth (4.65 cm) comparable to Amloki, suggesting favorable belowground development (Table 1).

The growth and yield attributes of Shimul mul varied significantly with distance from the base of medicinal trees, as shown in Table 2. The control treatment (T_0), where plants were grown in open field conditions, consistently exhibited the highest values for plant height, leaf rachis length, root length, root girth, and fresh biomass, indicating optimal growth without competition. Among the agroforestry distances, plants grown at the farthest distance (T_3, 137–204 cm) performed markedly better than those nearer to the tree base, with values approaching those of the control. In contrast, the closest distance (T_1, 0–68 cm) recorded the lowest measurements across all parameters, suggesting that intense shading, below-ground competition, and possible allelopathic effects from the medicinal trees greatly suppressed Shimul mul growth. The intermediate distance (T_2, 69–136 cm) showed moderate performance but remained significantly lower than T_3 and T_0. Overall, the results clearly indicate that increasing distance from medicinal tree bases reduces competitive stress, allowing better growth and higher biomass accumulation, with T_3 proving to be the most favorable spacing for Shimul mul under tree-based agroforestry systems.

Table 2. Effect of different distancess from medicinal base on growth and yield contributing parameters of Shimul mul

Tree species	Plant height (cm)	Length of leaf Rachis (cm)	Root Length (cm)	Root girth (cm)	Fresh wt. /plant (g)
T0	64.25 a	18.41 a	15.65 a	5.18 a	81.75 a
T1	43.32 d	13.76 d	11.37 d	3.75 c	46,66 d
T2	51.25 c	15,65 c	12.84 c	4.56 bc	61.80 c
T3	62.12 b	17.32 b	15.11 b	5.02 a	73.44 b
CV (%)	5.27	8.73	5.75	6.64	6.17
Level of Sign.	**	**	**	**	**

Means in column followed by the different letter are significantly different by LSD at P ≤ 0.05;T0=Control, T1 = 0 - 68 cm, T2 = 69 - 136 cm, T3 = 137-204 cm distance from medicinal tree

Table 3. Interaction effect (medicnal tree × distances) on growth and yield contributing parameters of Shimul mul

Tree species	Plant height (cm)	Length of leaf Rachis (cm)	Root Length (cm)	Root girth (cm)	Fresh wt. /plant (g)
T0	64.25 a	18.41 a	15.65 a	5.18 a	81.75 a
A × T1	46.61 d	14.54 d	12.22 bc	4.02 bc	49.40 f
A × T2	53.18 c	16.44 c	13.35 ab	4.83 b	66.42 d
A × T3	63.54 a	17.65 ab	14.77 a	5.33 a	75.25 b
H × T1	42.61 e	13.65 e	10.70 c	3.69 d	43.33 g
H × T2	50.18 cd	15.73 cd	12.21 bc	4.51 bc	60.55 e
H × T3	61.05 b	16.83 b	13.14 ab	4.88 b	71.33 c
B × T1	42.85 e	14.03 de	11.87 bc	3.75 c	47.25 f
B × T2	51.25 c	16.21 c	12.89 b	4.82 b	62.42 de
B × T3	62.57 ab	17.38 ab	14.46 a	5.21 a	73.75 bc
CV (%)	5.27	8.73	5.75	6.64	6.17
Level of Sign.	**	**	**	**	**

Means in column followed by the different letter are significantly different by LSD at P ≤ 0.05; A = Amloki, H= Haritoki, B = Bohera; T0=Control, T1 = 0 - 68 cm, T2 = 69 - 136 cm, T3 = 137-204 cm distance from medicinal tree

The interaction between medicinal tree species and distance from the tree base exerted a highly significant influence on the growth and yield attributes of Shimul mul (Table 3). Across all parameters, the control treatment (T_0) maintained the highest overall performance due to the absence of competition. Among the combined treatments, Amloki at the farthest distance ($A \times T_3$) produced the most vigorous growth, with values for plant height (63.54 cm), leaf rachis length (17.65 cm), root length (14.77 cm), root girth (5.33 cm), and fresh biomass (75.25 g) statistically comparable to the control, indicating that Amloki exerts the least suppressive effect when plants are grown beyond 137 cm from the tree base. Bohera at T_3 ($B \times T_3$) also performed strongly, particularly in plant height (62.57 cm), root girth (5.21 cm), and fresh weight (73.75 g), showing its compatibility with Shimul mul at wider spacing. In contrast, the poorest growth was consistently recorded at the closest distance (T_1), especially under Haritoki ($H \times T_1$) and Bohera ($B \times T_1$), where parameters such as plant height and biomass were drastically reduced, reflecting intense competition for light, nutrients, and soil moisture. Intermediate distances (T_2) under all tree species showed moderate growth but remained significantly lower than T_3 and the control. Overall, the interaction results demonstrate that both tree species identity and distance jointly determine the performance of Shimul mul, with wider spacing particularly 137–204 cm under Amloki and Bohera creating the most favorable microenvironment for optimal growth and yield.

Yield performances of Shimul mul under different medicinal tree species:

Figure 4 presents the total yield per hectare (t/ha) of Shimul mul grown under the same tree species and distance categories. The pattern of yield variation closely followed the trend observed in individual plant yield. The highest yield per hectare was obtained in open-field conditions (T_0), while yields under agroforestry treatments were comparatively lower, depending on both the distance from tree base and tree species. As distance from the tree base increased, Shimul mul yield improved, reflecting a gradual reduction in tree–crop competition. Among the tree species, Amloki-based plots again exhibited higher yield potential, followed by Bohera and Haritoki. This consistency across both figures confirms that the growth environment created by Amloki trees was more favorable for Shimul mul cultivation compared to the other medicinal species. Overall, Figure 4 demonstrates that tree species and spatial arrangement significantly influence the productivity of Shimul mul in agroforestry systems. Optimal spacing and compatible tree–crop combinations particularly Shimul mul with Amloki can help achieve better yield performance and promote sustainable land-use efficiency.

Yield reduction (%) of Shimul mul with different medicinal tree species:

Figure 5 illustrates the percentage yield reduction of Shimul mul cultivated under three medicinal tree species viz. Amloki, Haritoki and Bohera at varying distances from the tree base: 0–68 cm (T_1), 69–136 cm (T_2), and 137–204 cm (T_3), in comparison with open-field control (T_0).

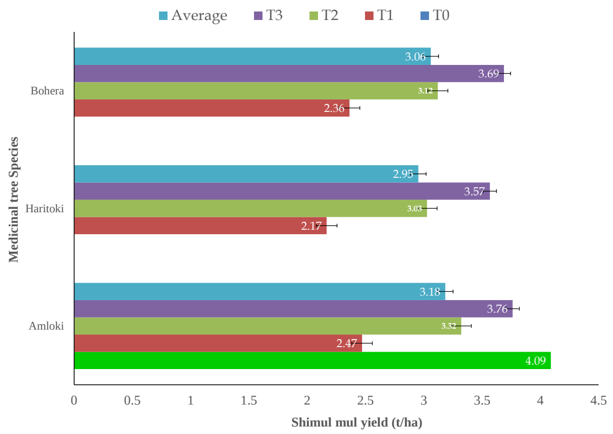

Figure 4. Yield (t/ha) of Shimul mul in association with Amloki, Haritoki and Bohera tree species (T_0 = Control, T_1 = 0 - 68 cm, T_2 = 69 - 136 cm, T_3 = 137-204 cm distance from different medicinal plants).

The yield reduction of Shimul mul varied considerably with both the associated tree species and the distance from the tree base. The recorded yield reductions were as: Amloki: 7.26% (T_1), 17.86% (T_2), and 39.65% (T_3); Haritoki: 17.86% (T_1), 35.82% (T_2), and 44.75% (T_3) and Bohera: 9.99% (T_1), 30.25% (T_2), and 41.76% (T_3). The mean yield reductions across all distances were 21.59% for Amloki, 32.81% for Haritoki, and 27.33% for Bohera. These results indicate a clear declining trend in yield as the crop was positioned closer to the tree base, where competition for vital resources such as sunlight, moisture, and nutrients was more pronounced. Among the three tree species, Haritoki exhibited the highest average yield reduction, suggesting a stronger competitive influence likely due to its dense canopy and extensive root system, which restrict light penetration and soil nutrient availability for Shimul mul. In contrast, Amloki showed the lowest average reduction, possibly owing to its relatively open canopy structure that allows better light transmission and its less competitive root system, creating a more favorable environment for intercrop growth.

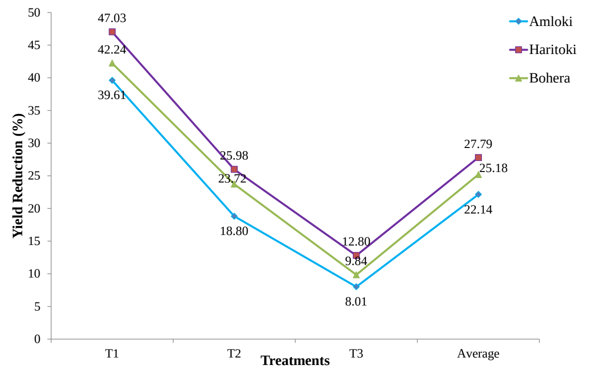

Figure 5. Yield reduction (%) of Shimul mul with Amloki, Haritoki and Bohera tree species (T_0 = Control, T_1 = 0 - 68 cm, T_2 = 69 - 136 cm, T_3 = 137-204 cm distance from different medicinal plants).

Table 4. Yield and yield attributes of medicinal tree species with or without shimul mul combination

Tree species	Parameters		With Shimul mul	Without Shimul mul
Amloki	Fruit size	Length (cm)	2.56	2.51
		Girth (cm)	3.92	3.88
	Fruit weight tree^{-1} (kg)		17.75	19.69
	Yield (t ha^{-1})		21.08	22.47
Horitoki	Fruit size	Length (cm)	3.46	3.52
		Girth (cm)	6.29	6.29
	Fruit weight tree^{-1} (kg)		46.45	51.25
	Yield (t ha^{-1})		34.42	37.25
Bohera	Fruit size	Length (cm)	4.57	5.03
		Girth (cm)	8.48	8.59
	Fruit weight tree^{-1} (g)		22.78	25.15
	Yield (t ha^{-1})		13.27	13.75

Yield of medicinal tree species:

Yield and yield attributes of Amloki, Haritoki and Bohera tree species were also observed under agroforestry and non-agroforestry system with and without Shimul mul (Table 4). During this study, no significant difference for yield and yield attributes of Amloki, Haritoki and Bohera tree species were found between agroforestry and non-agroforestry practices (Table 4).

Land Equivalent Ratio (LER) analysis:

Table 5 illustrates the Land Equivalent Ratio (LER) of different medicinal tree–Shimul mul agroforestry combinations, highlighting the land-use efficiency gained through species integration. All combinations recorded LER values well above 1.0, indicating a substantial advantage of intercropping over monocropping. The Amloki–Shimul mul system exhibited the highest LER (1.74), derived from relative yields of 0.96 for Amloki and 0.78 for Shimul mul, suggesting strong complementarity and efficient resource sharing between the species. The Bohera–Shimul mul combination also performed effectively, producing an LER of 1.72, with relative yields of 0.97 and 0.75, respectively. Haritoki–Shimul mul showed a slightly lower but still positive LER (1.67), reflecting meaningful productivity gains compared to sole cropping. Overall, the results confirm that integrating medicinal trees with Shimul mul enhances land productivity by 67–74%, demonstrating the ecological and economic viability of mixed-species agroforestry systems.

Table 5. Land Equivalent Ratio (LER) of Medicinal trees and Shimul mul based agroforestry practices

Combinations	Relative yield		LER (a + b)
	Medicinal trees (a)	Shimul mul (b)	
Amloki - Shimul mul	0.96	0.78	1.74
Haritoki - Shimul mul	0.95	0.72	1.67
Bohera - Shimul mul	0.97	0.75	1.72

Relationship between light intensity and yield of Shimul mul under different medicinal trees:

The average light intensity in open field conditions was 46.39 Klux. Under Amloki, Haritoki, and Bohera trees, the average light intensities at distances of 0–68 cm, 69–136 cm, and 137–204 cm from the tree base were 29.43, 32.52, and 35.43 Klux; 18.97, 21.96, and 23.94 Klux; and 25.59, 27.36, and 33.53 Klux, respectively (Figure 6). Correlation analysis between light intensity and the yield of Shimul mul revealed R² and r values of 0.859 and 0.737, 0.817 and 0.667, and 0.884 and 0.783 under mloki, Haritoki, and Bohera trees, respectively (Figure 6). These positive correlations indicate that Shimul mul yield increases with increasing light intensity. The variation in light interception among tree species may be attributed to differences in their phyllotaxy and canopy architecture. Based on the correlation analysis, the suitability of agroforestry practices for Shimul mul cultivation can be ranked as Amloki–Shimul mul > Bohera–Shimul mul > Haritoki–Shimul mul.

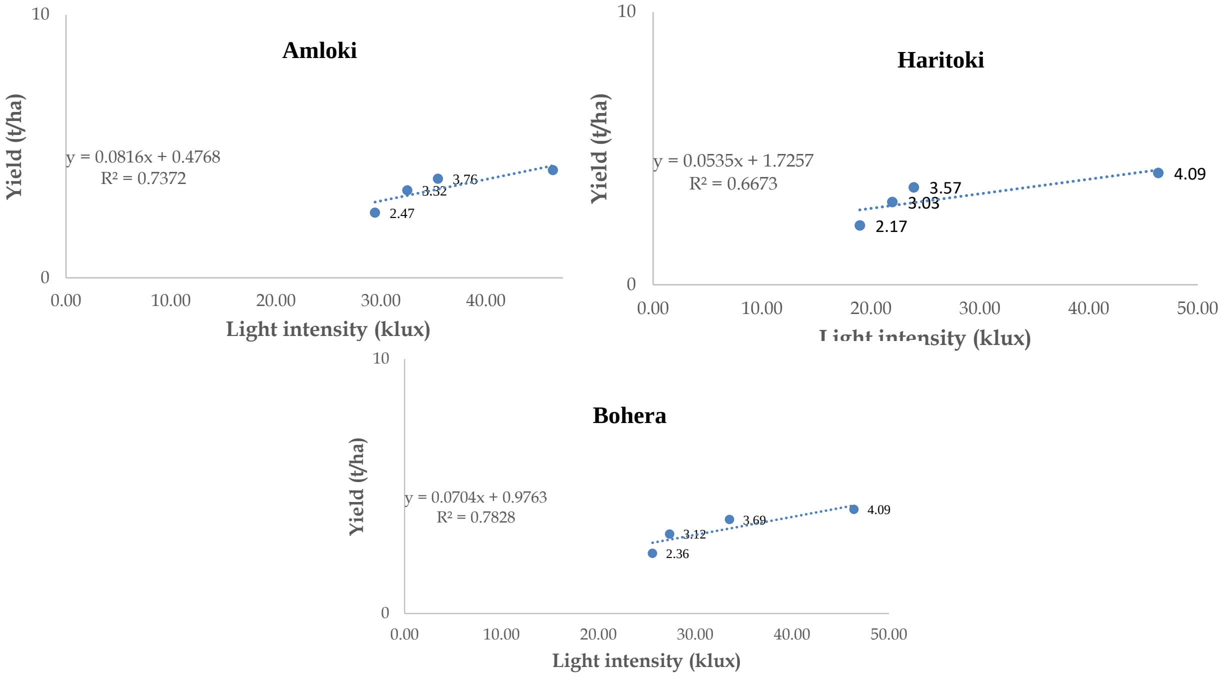

Figure 6. Relationship between light intensity and yield of Shimul mul under Amloki, Haritoki and Bohera trees in different treatments

Soil fertility tatus of different medicinal tree-based agroforestry systems:

Table 6 shows the soil fertility status under Amloki-, Haritoki-, and Bohera-based agroforestry systems before and after the experimental study. The measured soil parameters were pH, organic carbon (Org. C), total nitrogen (N), phosphorus (P), potassium (K), and sulphur (S). In general, the results indicate a slight improvement in soil properties after the experiment in all agroforestry systems. The soil pH increased slightly, showing a minor reduction in acidity, which may have occurred due to organic matter decomposition and base cation addition from tree litter. Organic carbon and total nitrogen contents also showed small increases, suggesting enrichment of soil organic matter and improved nutrient cycling. Available phosphorus and potassium contents changed only slightly, indicating stable nutrient conditions, while sulphur content showed a minor increase under Amloki and Haritoki systems but a slight decrease under Bohera. Overall, the findings suggest that the agroforestry practices helped to maintain or slightly enhance soil fertility. Among the tree species, Amloki-based agroforestry showed the most consistent improvement in soil quality parameters.

Table 6. Soil fertility status of different Agriforestry practices before and after experimental study

Soil parameters	Time	Agroforestry Practices		
		Amloki tree - based	Haritoki tree - based	Bohera tree - based
pH	Before	5.95	5.97	6.00
	After	6.05	5.95	6.05
Org. C (%)	Before	1.20	1.12	1.17
	After	1.25	1.10	1.15
Total-N (%)	Before	0.12	0.12	0.12
	After	0.13	0.12	0.12
P (ppm)	Before	7.59	7.43	7.72
	After	7.63	7.46	7.68
K (mg/100g)	Before	0.15	0.15	0.15
	After	0.16	0.14	0.15
S (ppm)	Before	8.72	8.45	8.30
	After	8.75	8.48	8.28

Carbon Sequestration by the medicinal tree-based agroforestry system:

Table 7 illustrates the estimated above-ground biomass (AGB), below-ground biomass (BGB), total tree biomass (TTB), and total tree carbon (TTC) for three medicinal tree species, Amloki, Haritoki and Bohera, evaluated before and after each growing year over a three-year period. The results reveal a consistent and progressive increase in biomass and carbon stock across all species, indicating vigorous growth performance and a substantial capacity for carbon sequestration under the prevailing environmental conditions. For *Amloki*, AGB increased from 20.37 to 42.35 kg/tree, while BGB increased from 5.50 to 11.43 kg/tree, resulting in an increase in TTB from 25.87 to 53.78 kg/tree and TTC

Table 7. Estimated biomass and carbon stock of the medicinal tree species in the project area

Tree species	Time	AGB (kg/tree)	BGB (kg/tree)	TTB (kg/tree)	TTC (kg/tree)
Amloki	Before	20.37	5.50	25.87	12.94
	After 1st year	24.44	6.60	31.04	15.53
	After 2nd year	29.54	7.98	37.51	18.76
	After 3rd year	42.35	11.43	53.78	26.89
Haritoki	Before	24.27	6.31	30.58	15.29
	After 1st year	29.61	7.70	37.31	18.65
	After 2nd year	35.83	9.31	45.14	22.57
	After 3rd year	44.35	11.97	56.32	28.16
Bohera	Before	33.58	8.73	42.32	21.16
	After 1st year	39.96	10.39	50.36	25.18
	After 2nd year	47.15	12.26	59.43	29.71
	After 3rd year	57.55	15.54	73.09	36.55

AGB= Above-ground biomass, BGB= Below-ground biomass, TTB= Total tree biomass, TTC= Total tree carbon from 12.94 to 26.89 kg/tree. Similarly, *Haritoki* exhibited stable growth, with AGB increasing from 24.27 to 44.35 kg/tree and BGB from 6.31 to 11.97 kg/tree, leading to a TTB of 56.32 kg/tree and TTC of 28.16 kg/tree after three years. *Bohera* demonstrated the highest overall biomass and carbon accumulation, with AGB increasing from 33.58 to 57.55 kg/tree and BGB from 8.73 to 15.54 kg/tree, resulting in a maximum TTB of 73.09 kg/tree and TTC of 36.55 kg/tree. Overall, *Bohera* recorded the greatest carbon sequestration potential, followed by Haritoki and Amloki. The steady increase in biomass and carbon stock emphasizes the suitability of these medicinal tree species for agroforestry systems aimed at enhancing carbon storage and contributing to climate change mitigation.

Discussion

This study investigated the growth performance, productivity, and environmental contributions of Shimul mul cultivated under three medicinal tree species—Amloki, Haritoki, and Bohera within an agroforestry system, demonstrating that species identity, spatial arrangement, and canopy structure significantly shape intercrop outcomes. The findings align with established agroforestry concepts emphasizing complementarity, resource sharing, and ecological intensification (Nair, 1993; Jose, 2009). Shimul mul exhibited notable differences in growth and yield across the three overstorey species, with Amloki providing the most favorable conditions due to its open canopy and reduced competitive pressure. This facilitated enhanced light transmission—one of the most critical factors influencing understory crop performance (Ong & Leakey, 1999; Shiferaw *et al.*, 2020). In contrast, Haritoki exerted strong competitive effects, likely because of its dense crown and extensive root system, resulting in substantial reductions in Shimul mul growth and biomass.

The influence of spatial positioning relative to the tree base further highlighted the importance of competition gradients. Growth and yield improved progressively with increasing distance from the tree, with the best performance at 137–204 cm, where competition for light, nutrients, and moisture was substantially lower. This pattern aligns with widely reported trends in agroforestry, where competitive intensity is highest near the tree stem and decreases outward (Cannell *et al.*, 1996; Rao *et al*., 2007). Strong positive correlations between light intensity and Shimul mul yield underscore the dominance of light as the limiting resource in these systems.

Yield reduction patterns further confirmed the competitive hierarchy, with Amloki causing the least suppression and Haritoki the most. Such species-specific variations are consistent with literature highlighting the importance of canopy architecture, leaf phenology, and root distribution in determining intercrop compatibility (Schroth & Sinclair, 2003). Importantly, the Land Equivalent Ratio (LER) values for all combinations exceeded 1.0, ranging from 1.67 to 1.74, signaling clear productivity advantages of agroforestry over monocropping. These values surpass the efficiency threshold commonly associated with successful intercropping (Kumar & Nair, 2011), indicating enhanced resource use and spatial–temporal complementarity. Furthermore, the yields of medicinal trees were not negatively affected by the presence of Shimul mul, reaffirming the compatibility of the system and supporting previous findings on understory crop integration (Miah *et al.,* 2018; Bayala *et al*., 2015).

Environmental assessments revealed additional system benefits. Soil fertility improved slightly across all medicinal tree–based systems, with increases in pH, organic carbon, and nitrogen attributed to litter decomposition, root turnover, and associated microbial activity—processes well documented as key ecological functions of agroforestry systems (Schroth & Sinclair, 2003). The carbon sequestration results provide further evidence of environmental gains, as all tree species accumulated substantial biomass and carbon stocks over the study period. Bohera showed the highest carbon storage, followed by Haritoki and Amloki, aligning with global findings that agroforestry enhances carbon sinks while maintaining productive land use (Henry *et al.*, 2009; Nair, 2012). Importantly, intercropping with Shimul mul did not diminish carbon accumulation, illustrating the compatibility of productive and ecological functions.

Collectively, these results highlight the multifaceted advantages of medicinal tree–Shimul mul agroforestry, including improved land productivity, diversified income opportunities, enhanced soil health, and increased climate resilience. Among the species tested, Amloki emerges as the most suitable overstorey companion due to its favorable canopy structure, reduced competitive interactions, positive impacts on intercrop yield, and consistent soil improvements. The study provides strong evidence supporting the promotion of Amloki-based medicinal agroforestry as a sustainable land management option in regions where medicinal and fiber crops hold economic and ecological importance.

Conclusion

The study on intercropping medicinal herbs with medicinal tree species under agroforestry systems revealed significant potential for enhancing productivity and environmental sustainability. Kalomegh and Shimul mul performed best under Amloki-based systems due to its lighter canopy and lower competition for resources. Land Equivalent Ratio (LER) values greater than 1 confirmed higher land-use efficiency in all agroforestry combinations, with Amloki–Shimul mul showing the most effective utilization. Light intensity played a vital role in determining intercrop yield, as greater light availability under Amloki canopies supported better growth and biomass accumulation. The positive correlation between light intensity and yield indicates that optimizing canopy structure is crucial for improving intercrop performance. Soil fertility parameters such as pH, organic carbon, and nitrogen slightly improved after the experiment, particularly under Amloki-based systems. Biomass and carbon stock of all studied medicinal tree species increased consistently, with Bohera showing the highest accumulation and Amloki the greatest growth rate. Overall, medicinal plant-based agroforestry offers a sustainable and productive land-use strategy for Bangladesh. Hence, promoting Amloki-based agroforestry systems with compatible medicinal herbs can play a vital role in improving rural livelihoods and mitigating environmental degradation in Bangladesh.

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