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Research Article

Uncovering Biodiversity and Carbon Stock Potential in the Raghunandan Hill Reserve Forest of Bangladesh

Reham Bin Farid,[1] **Yaqub Ali**,[2] **Kazi Saifuddin Emon**,[1] **Ashraful Alam**,[1] **Iftekharul Islam Iftu**,[1] **Saddam Hossen**,[3] **and Bayezid Mahmud Khan**[1]

[1]*Institute of Forestry and Environmental Sciences, University of Chittagong, Chattogram 4331, Bangladesh*
[2]*The International Union for Conservation of Nature (IUCN), Banani, Dhaka 1213, Bangladesh*
[3]*Department of Forestry and Environmental Science, Rangamati Science and Technology University, Rangamati, Bangladesh*

Correspondence should be addressed to Yaqub Ali; yaqub.ifescu@gmail.com

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Understanding tree species composition, regeneration status, and biomass carbon storage is crucial for evaluating the sustainability of forest ecosystems under increasing anthropogenic pressure. This study assessed these parameters in Raghunandan Hill Reserve Forest (RHRF) to support evidence-based decision-making, sustainable management, and carbon budgeting. The field activity was conducted during November–December 2024 in Shahapur and Shaltila beats of RHRF using 60 randomly selected plots. Tree composition was assessed using 20 m × 20 m quadrats, and the regeneration was evaluated using 5 m × 5 m subplots. Trees with a diameter at breast height (DBH) ≥ 5 cm were recorded and analyzed for density, frequency, dominance, and Importance Value Index (IVI). Aboveground biomass (AGB) was estimated by Brown's allometric model, and carbon stock was estimated by standard conversion factors through adding 15% of belowground biomass (BGB) following MacDicken's approach. The study recorded 45 tree species under 22 families. The highest RDe (13.52%) and relative frequency (10.67%) were found for *Tectona grandis*, while *Artocarpus chama* dominated in relative dominance (25.51%) and IVI (38.63 of 300). However, the highest basal area is possessed by *Ficus benghalensis* (30 m^2/ha). Regeneration is dominated by *Shorea robusta* and *Syzygium cumini* and comprises 26 tree species (19 indigenous and 7 exotics, including 4 invasive). *Artocarpus chama* showed the highest biomass (121.07 tons/ha) and carbon stock (60.54 tons/ha). These findings underscore the ecological significance of RHRF for conserving native species, along with its potential in carbon accounting initiatives. Furthermore, the findings provide evidence for local forest management and REDD+ initiatives and contribute to international monitoring platforms such as Global Forest Watch and FAO's Forest Resource Assessment (FRA).

Keywords: aboveground biomass (AGB); biodiversity indices; carbon storage; natural regeneration; sustainable forest management; tree species composition

1. Introduction

Bangladesh is a Southeast Asian, tropical-forest country with 2.5 million hectares of forest land administered by the Bangladesh Forest Department (BFD) under the Ministry of Environment, Forest, and Climate Change [1–3]. The forests of Bangladesh have been significantly damaged over the past few decades due to disturbances by biotic and abiotic factors, impacting the regeneration and population dynamics. The primary factors contributing to forest degradation in Bangladesh include agricultural expansion, excessive extraction of wood and non-wood resources, urbanization, deforestation, and inadequate management techniques [4–7]. The deterioration of forests in Bangladesh has resulted in a serious decline in biodiversity [8]. Quantitative data regarding tree species composition and distribution are essential for comprehending the structure of a forest community and for developing conservation strategies for

that community [9]. The diversity of species as well as the regeneration status of tree species significantly reflects the characteristics of the forest, as they furnish supplies and habitat for nearly all other forest species [3, 10, 11]. The existence of species within a community is contingent upon the status of regeneration. In forest management, regeneration studies delineate the present state and probable future alterations in forest species and structural composition [12, 13].

Natural regeneration is a biotic procedure that can be aided and managed to upsurge forest coverage and attain the recovery of the inherent ecosystem or some of its functions. Ecological restoration depends on natural regeneration processes for attaining forest ecosystem regeneration [14]. The assessment of regeneration has become an effective technique for evaluating the overall condition of the forest [15–17]. The natural regeneration process has led to the development and evolution of tree-dominant plant groups, significantly influencing forest structure [15, 18]. Plants uphold and increase their populations temporally and spatially through the regeneration process. This intricate ecological process encompasses asexual and sexual reproduction, seed dispersal, and seedling establishment in response to environmental variables [19]. The population structure pattern of trees can indicate the regeneration profile, which is utilized to assess their regeneration condition [14].

Evaluating the aboveground biomass (AGB), belowground biomass (BGB), and carbon stock is vital for monitoring the improvement or stability of reestablished forest areas and helps to assess the retrieval of the ecosystem, carbon sequestration, and the inclusive role of restoration efforts in fighting climate change phenomena [20–22]. The forest ecosystems act as key carbon sinks, storing extensive amounts of carbon. The tree biomass and carbon storage can be quantified through the application of allometric models [23–25]. As a reserve forest, its floral composition and diversity need to be recognized for development planning and administrative decision-making. Some studies have been conducted to know the species distribution pattern along with environmental variables and disturbance, to develop and compare allometric models for predicting leaf area and biomass of *Artocarpus chaplasha* in Raghunandan Hill Reserve Forest (RHRF) [26, 27]. However, RHRF lacks detailed information regarding structural composition, regeneration status, and carbon stock of tree species.

Many studies in the South Asian region highlight the importance of forests like RHRF for successful biodiversity restoration and climate mitigation. For example, Batool et al. [28] emphasized the importance of community-based forest restoration for improved carbon sequestration and biodiversity conservation. However, according to Farhadinia et al. [29], most of the Asian countries fail to fulfill their biodiversity targets because of habitat fragmentation and lack of policy implementation. Moreover, Malik et al. [30] demonstrated the regional AGB carbon stock dynamics in a changing land use and cover condition and encouraged sustainable forest management. Similarly, nature-based climate adaptation strategies with afforestation and restoration in a degraded forests ecosystems in South Asia were proposed by Qadir et al. [31]. While Weiskopf et al. [32] showed that loss of biodiversity significantly reduces the terrestrial biomass carbon stock, Yadav et al. [33] prioritize the role of native tree species for preserving the diversity of nature. These studies further emphasized the importance of biodiversity and biomass carbon-related study in RHRF to support not only national but also regional carbon budgeting and biodiversity conservation.

Therefore, the study was designed to uncover the quantitative information regarding the species composition, regeneration diversity, AGB and BGB, and carbon stock of tree species in RHRF. Understanding the carbon stock potential of a forest is not only essential for local forest conservation efforts but also crucial for contributing to the global climate action under frameworks like REDD+ and the Paris Agreement. The quantitative site-level data also help to bridge the gap between field-based research and global forest monitoring platforms, such as Global Forest Watch and FAO's Forest Resource Assessment (FRA).

2. Materials and Methods

2.1. Study Site. The RHRF was officially designated as a reserved forest on October 22, 1914. The Raghunandan range consists of four beats: Shahapur, Shaltila, Shahjibazar, and Jagdishpur. The two beats, Shahapur and Shaltila, were selected as representative areas of the entire RHRF, as they collectively cover a significant portion (71.23%) of the total forest area and the other beats managed under the leased territory of BFIDC (Figure 1). The average annual rainfall in the area is 4162 mm, with January being the coldest month (minimum temperature about 9.6°C) and May and October being the hottest (average maximum temperature around 34.8°C) [34]. During December, the relative humidity is around 74%, whereas it exceeds 90% in July and August. The forest area is undulating, with slopes and hillocks ranging from 10 to 50 m spread in the forest, and it is drained by a number of small, sand-bedded streams that are completely dry at the end of the rainy season [26]. The study site, Shahapur and Shaltila beat of RHRF, is located between 24°05′ and 24°10′ N and 91°25′ and 91°30′ E under Sylhet Forest Division (Figure 1). It is located about 130 km northeast of Dhaka along the Dhaka-Sylhet Highway. The combined area of the two beats spans about 2472.75 ha. It is characterized by evergreen or semievergreen mixed vegetation. The landscape includes a variety of vegetation types, such as natural forest, plantation forest, mixed forest, bamboo groves, and open grasslands [34].

2.2. Sampling Design. This study was conducted through a random quadrat survey. The quadrat survey provided data for assessing the tree species and regeneration composition, diversity, phytosociological attributes, and structural composition. The randomized quadrat samples generated using the ArcGIS Pro randomization tool were used for the inventory of the tree species. A team of five members conducted a seven-day field survey between November and

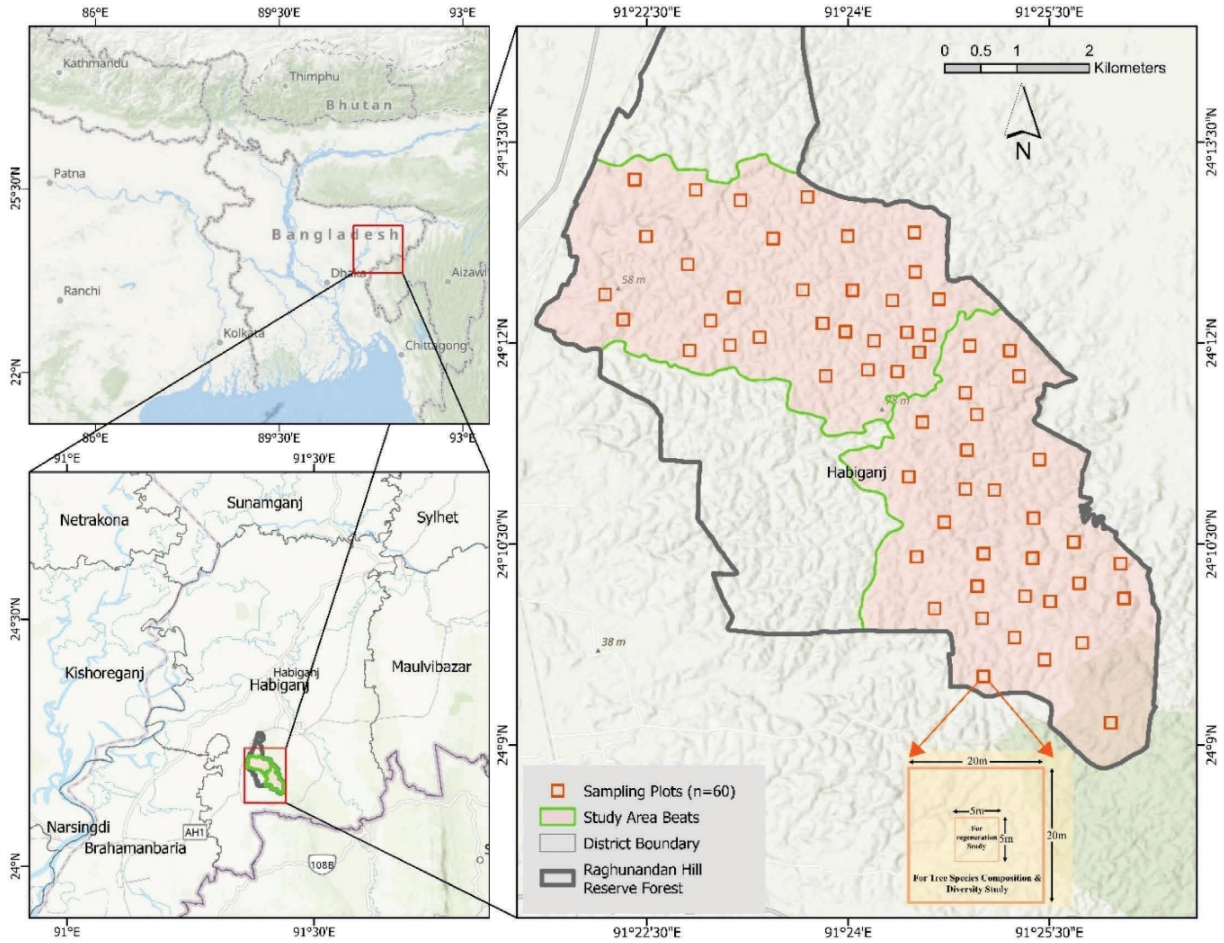

FIGURE 1: Map of the Raghunandan Hill Reserve Forest showing the location of sampling plots ($n = 60$) in the Shahapur and Shaltila forest beats.

December 2024 to comprehensively cover the whole study area. A total of 60 sample plots for tree composition and regeneration status (30 sample plots for each beat) were taken from the Shahapur and Shaltila beats of the RHRF. The sample plot size was determined considering the type and composition of the forest in the study area. For the assessment of the tree species composition, plot sizes were considered as 20 m × 20 m, and for the regeneration study, plots were occupied at the center of each plot with a size of 5 m × 5 m.

The randomly generated sample plots encompassed both natural and plantation forests with varying levels of tree canopy density. The exact location of each predetermined plot was identified using a GPS device. The area of each plot was outlined using measuring tape and rope. Plants with a diameter at breast height (DBH) ≥ 5 cm were documented as trees from the quadrats. In each of the sample plots, the tree species were counted using their scientific and local names.

2.3. Analysis of Field Data. Detected plants were organized taxonomically and categorized according to their habit form. The RDe (RDe), relative frequency (RF), relative abundance (RA), relative dominance (RDo), and Importance Value Index (IVI) were estimated following the methods of Bhadra and Pattanayak [35] and Yakob and Fekadu [36] to study vegetation composition and structure (Equations (1)–(6)):

$$\mathrm{RF} = \frac{\text{frequency of one species}}{\text{total frequency}} \times 100, \quad (1)$$

$$\mathrm{RDe} = \frac{\text{total no. of individuals of the species}}{\text{total no. of individuals of all the species}} \times 100, \quad (2)$$

$$\mathrm{RA} = \frac{\text{abundance of one species}}{\text{total abundance}} \times 100, \quad (3)$$

$$\mathrm{RDo} = \frac{\text{basal area of one species}}{\text{total basal area}} \times 100, \quad (4)$$

$$\mathrm{IVI} = \mathrm{RDe} + \mathrm{RF} + \mathrm{RDo}\ (\text{mature trees}), \quad (5)$$

$$\mathrm{IVI} = \mathrm{RDe} + \mathrm{RF} + \mathrm{RA}\ (\text{regenerating seedlings}). \quad (6)$$

2.4. Diversity Indices Calculation. Four diversity indices, that is, Margalef's species richness index (R) (7) Shannon–Wiener's diversity index (H) (8) Simpson's diversity index

(D) (9), and Species evenness index (E) (10), were evaluated following Margalef [37], Shannon and Wiener [38], Simpson [39], and Pielou [40], respectively, to understand the tree species diversity:

$$\text{Margalef's species richness index, } \mathrm{R} = \frac{(\mathrm{S}-1)}{\mathrm{Ln}\,(\mathrm{N})}, \tag{7}$$

$$\text{Shannon–Wiener's diversity index, } \mathrm{H} = -\sum_{\mathrm{i}=1}^{\mathrm{n}} (P_i)\ln(P_i), \tag{8}$$

$$\text{Simpson's diversity index, } \mathrm{D} = \Sigma P_i^2, \tag{9}$$

$$\text{Pielou's species evenness index, } \mathrm{E} = \frac{\mathrm{H}}{\mathrm{Ln}\,(\mathrm{S})}. \tag{10}$$

Here, H = Shannon–Wiener's diversity index, N = total number of trees in all studied species, P_i = number of tree individuals of ith species/total number of individuals, and S = total number of species.

2.5. Tree Carbon Measurement. Trees absorb CO_2 from the atmosphere, and stored organic carbon biomass includes both aboveground and belowground. The AGB for individual trees was estimated using (11) [41]. The BGB was determined considering 15% of the AGB [42]. A default value of 0.49 was used to convert the biomass value into carbon content [43, 44]:

$$\mathrm{Y} = \mathrm{Exp.}\left\{-2.4090 + 0.9522\ln\left(\mathrm{D}^2 \times \mathrm{H} \times \mathrm{S}\right)\right\}, \tag{11}$$

where Y = aboveground biomass (kg), H = height of tree in meters, D = DBH, and S = species-specific wood density (g/cm^3) of tree species.

So far, literature has shown that Brown's model is one of the most suitable methods for estimating biomass carbon stocks in tropical forests [41, 42]. Many recent studies also used this model and suggested where the site-specific allometric equations were not available, like RHRF [45, 46].

3. Results

3.1. Tree Species Diversity. Forests harbor an incredible diversity of tree species, each playing a unique role in maintaining ecological balance, supporting livelihoods, and enriching biodiversity. A total of 45 tree species under 22 families were found in RHRF, where Fabaceae includes the maximum number (6) of the species, followed by Combretaceae (4), Meliaceae (3), Dipterocarpaceae (3), Mimosaceae (3), Moraceae (3), Myrtaceae (3), Dilleniaceae (2), Rubiaceae (2), and Verbenaceae (2) (Figure 2(a)). High-value timber species such as *Tectona grandis* (Teak), *Swietenia mahagoni* (Mahogany), and *Shorea robusta* (Sal) have been found in the highest percentage among the 45 species (Figure 2(b)). Several species contribute to medicinal applications, such as *Terminalia arjuna* (heart health), *Syzygium cumini* (diabetes treatment), and *Terminalia chebula* (dying and medicine). Some trees, like *Ficus benghalensis* and *Samanea saman,* provide shade, soil stabilization, and ecological benefits (Table 1).

3.2. Conservation Status of the Tree Species. The documented species were classified into five conservation categories (Supporting Table 1), namely, endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), and not evaluated (NE), according to the latest plant red list of Bangladesh [47, 48]. A total of 82% of the species were classified as LC, which constitutes the largest proportion of tree species across all categories. In contrast, 2% of the tree species were categorized as EN, 7% as VU, 2% as NT, and 7% as NE (Figure 3).

3.3. Structural Composition of the Tree Species. The structural composition of the tree species was calculated under 9 diameter classes based on DBH distribution and six height classes based on their height distribution. The diameter ranges were 1–20, 21–40, 41–60, 61–80, 81–100, 101–120, 121–140, 141–160, and 161–180 cm, respectively. The diameter range of 21–40 cm was represented by a maximum of 58.21% (1298 individuals) of the trees. Individuals of nearly every recorded tree species were observed in this diameter class. On the other hand, 121–140 and 161–180 cm include the lowest percentage (0.04%) of individuals, with one individual each (Figure 2(e)).

The height (m) ranges were 0–5, 6–10, 11–15, 16–20, 21–25, and 26–30 m, respectively. The height range of 16–20 m was represented by a maximum of 54.08% of trees belonging to 1206 individuals of 22 species. The trees of nearly every species were observed in this diameter class. On the other hand, 26–30 m includes the lowest percentage (0.36%) of individuals, with eight individuals of two species (Figure 2(f)).

On the other hand, the highest basal area (m^2/ha) belongs to *Ficus benghalensis* (30), followed by *Artocarpus chama* (13.96), *Chickrassia tabularis* (7.45), *Lagerstroemia speciosa* (6.97), *Syzygium cumini* (6.38), *Xylia xylocarpa* (6.76), *Swietenia mahagoni* (6.64), *Shorea robusta* (6.11), *Tectona grandis* (5.61), and *Dalbergia sissoo* (7.98) for sample plots in RHRF (Figure 2(d)).

3.4. Phytosociological Attributes of the Tree Species. The IVI of the tree species revealed the overall dominance of different species in the RHRF. The *Artocarpus chama* was represented by maximum (25.51%) RDo, followed by *Swietenia mahagoni* (9.39%), *Tectona grandis* (7.86%), *Shorea robusta* (6.79%), and *Chickrassia tabularis* (5.90%). On the other hand, *Swintonia floribunda* (0.003%), *Mesua ferrea* (0.02%), *Adina cordifolia* (0.04%), and *Terminalia chebula* (0.12%) were represented by the lowest RDo (Table 2). *Tectona grandis* possesses both the highest RF (10.67%) and the highest RDe (13.57%), whereas *Dalbergia sissoo* represents the highest RA (0.135%) (Table 2).

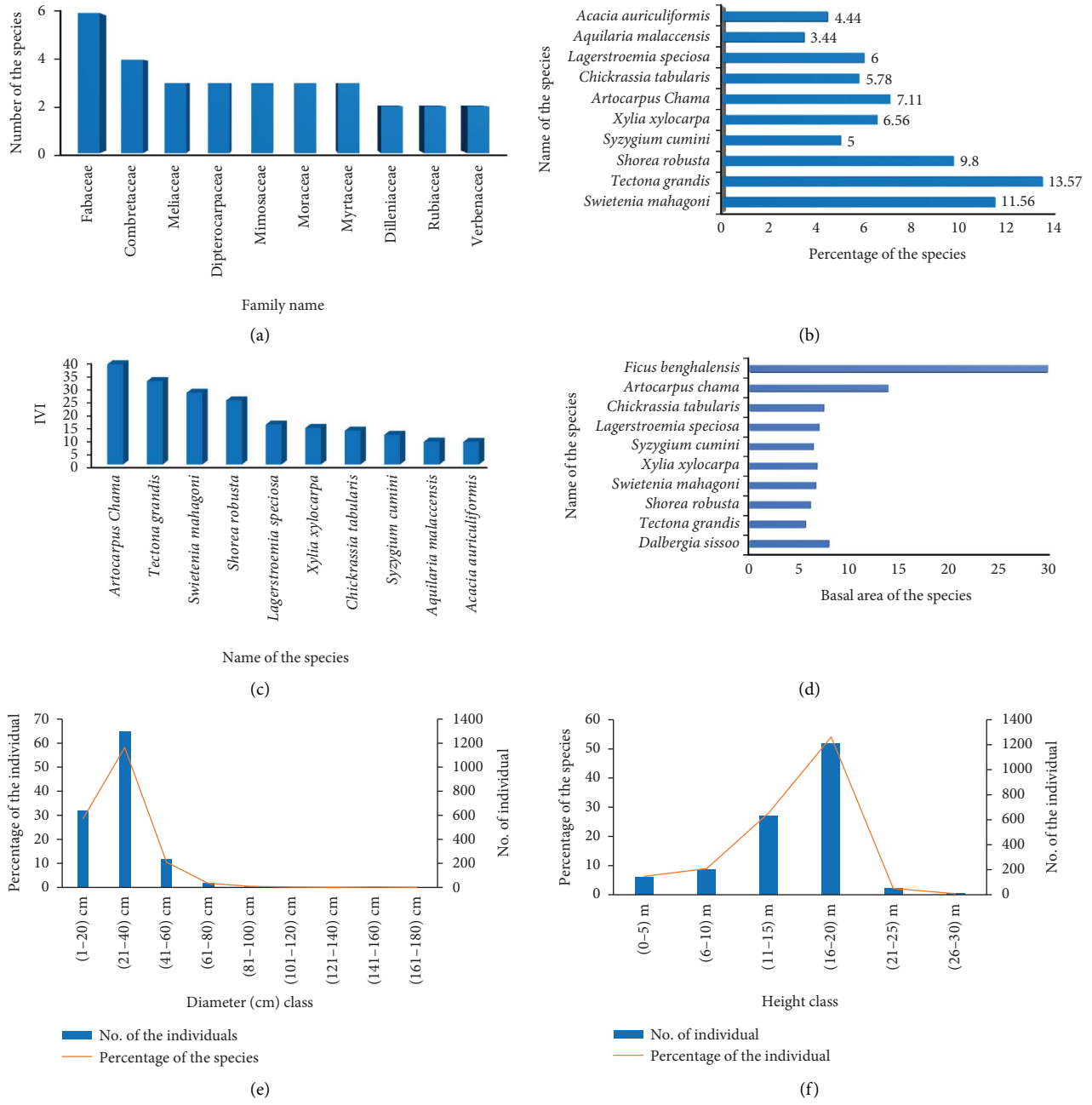

Figure 2: Tree species distribution and composition at Raghunandan Hill Reserve Forest of Bangladesh: (a) 10 families having maximum tree species, (b) 10 species having maximum percentage of tree individuals, (c) tree species having maximum IVI, (d) tree species having maximum basal area coverage, (e) tree species having highest diameter classes, and (f) tree species having maximum height distribution.

However, the IVI of the species revealed that *Artocarpus chama* represents the highest IVI (38.63 out of 300), followed by *Tectona grandis* (32.10), *Swietenia mahagoni* (27.62), *Shorea robusta* (24.69), and *Syzygium cumini* (15.38) (Figure 2(c)). On the other hand, *Adina cordifolia* (0.81), *Caesalpinia pulcherrima* (0.94), *Terminalia chebula* (1.01), and *Garcinia cowa* (1.06) appeared as the least dominant tree species, as they have the minimum IVI (Table 2).

3.5. Natural Regeneration Status. Based on quadrat survey methods, the study revealed that 26 tree species were regenerating naturally in RHRF through both seed germination and coppicing. Among the regenerating seedlings, 19 were indigenous tree species, 7 were exotic species, and within the exotic species, 4 were invasive alien species (Figure 4(d), Table 3). Among the regenerating plant species, that is, *Shorea robusta* (234 seedlings),

Table 1: Summary of dominant tree species groups recorded in the Raghunandan Hill Reserve Forest.

Group	Representative species	Ecological/economic significance
Timber species	*Tectona grandis, Swietenia mahagoni, Shorea robusta, Chickrassia tabularis, Xylia xylocarpa*	Structurally dominant, commercially valuable, key contributors to basal area and IVI.
Medicinal and multipurpose species	*Artocarpus chama, Dillenia indica, Mesua ferrea, Terminalia chebula, Syzygium cumini*	Enhance species diversity, used in traditional medicine, fruit-bearing.
Invasive/exotic species	*Acacia auriculiformis, Eucalyptus camaldulensis, Dalbergia sissoo*	Rapid-growing species that may suppress native regeneration.
Less dominant native species	*Adina cordifolia*, *Caesalpinia pulcherrima*, *Garcinia cowa*, *Terminalia catappa*	Represent low IVI values, limited ecological influence.

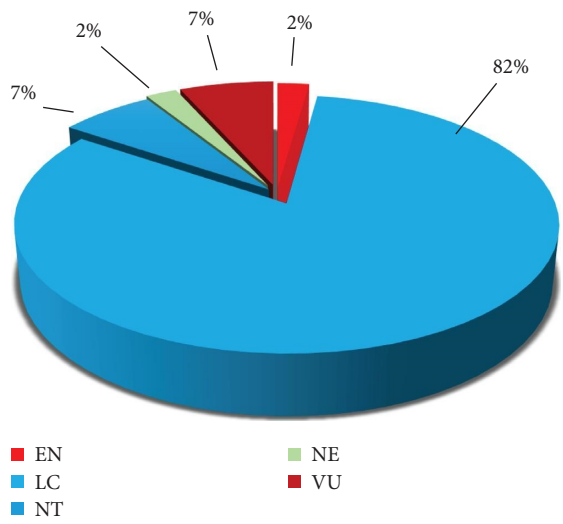

Figure 3: Percentage distribution of the documented tree species under different conservation categories of the IUCN plant red list of Bangladesh.

Syzygium cumini (198 seedlings), *Syzygium firmum* (56 seedlings), and *Terminalia bellirica* (56), were found dominant in the sampled area. A total of 720 individual seedlings were found in RHRF, where the family Myrtaceae possesses the highest number of individuals (254) (Figure 4(a)).

It was found that a maximum of 49% of seedlings belong to the 41–60 cm height class, indicating the successful establishment of recent regenerating seedlings. The notable presence of 31% seedlings in the class (21–40 cm) indicates the presence of a further ongoing regeneration process. However, only 10% are in the smallest height class (1–20 cm), indicating early-stage seedling mortality or a recent reduction in regeneration or seed germination due to competition and environmental constraints. Both the height classes (61–80 cm) and (81–100 cm) have 5% seedlings, indicating the overall success of natural regeneration in the RHRF (Figure 4(b)).

The study reveals that *Shorea robusta* has the highest RDe (32.5%), highest RA (13.59%), and maximum IVI (60.52) (Figure 4(c), Table 3). However, *Syzygium cumini* (20.62%) has the highest RF, followed by *Shorea robusta* (14.43%), *Syzygium firmum* (8.25%), and *Gmelina arborea* (7.22%) (Table 3).

3.6. Biological Diversity of Tree Species and Regeneration. Various ecological diversity indices like the Shannon–Wiener index, Simpson's index, Margalef's index, and the species evenness index were explored to depict species composition of recorded tree species. The mature tree species in RHRF exhibits a higher Shannon–Wiener diversity (3.04) and Margalef's richness index (6.47) compared with the regenerating seedling species. This indicates that the mature trees possessed higher diversity and richness compared to the regenerating seedlings. Similarly, Simpson's species dominance index showed that tree species have less dominance (0.07) than the regenerating seedlings (0.20), indicating the lower diversity of regenerating species. The species evenness index is also higher (0.98) in tree species than in regenerating species (0.67), further indicating the lesser distribution of the regenerating species than the established mature tree species (Table 4). This suggests that although natural regeneration is happening in RHRF, it is currently limited in terms of species composition and dominated by a few species such as *Shorea robusta* and *Syzygium cumini*. Effective management or enrichment planting is necessary to support the enlistment of underrepresented species to ensure the long-term forest species composition, sustainability, and resilience.

3.7. Biomass and Carbon Stock of Trees Species. In the RHRF, a noticeable difference in the total biomass and organic carbon content among the species was observed. A few dominant species exhibit exceptionally high biomass and carbon stock, highlighting their critical role in the forest carbon sink. Among all the species, *Artocarpus chama* (Chapalish) has the highest total biomass, estimated at 121.07 tons/ha, which corresponds to 60.54 tons/ha of carbon. This high-biomass accumulation is mainly due to its larger average DBH and height, which greatly affects AGB. Similarly, the *Shorea robusta* (Sal), *Xylia xylocarpa* (Lohakhat), *Swietenia mahagoni* (Mahogany), and *Tectona grandis* (Segun) also substantially contribute to the biomass stock of RHRF, with biomass values ranging from 33.55 to 53.40 tons/ha (Table 5).

In contrast, many species showed very low levels of biomass and carbon stock, likely due to their limited height and DBH distribution, smaller growth forms, or younger age classes compared to others. For example, the *Swintonia floribunda* (Civit), *Mesua ferrea* (Nageshwar), *Alstonia scholaris* (Chatian), and *Adina cordifolia* (Haldu) exhibited total biomass values less than 1 ton/ha, with corresponding organic carbon stock below 0.5 tons/ha (Table 5). However, the dominating species substantially contributed to the biomass and carbon stock and played a crucial role in long-term carbon sequestration and ecosystem stability. The lower dominance species is also essential for biodiversity conservation and ecosystem functioning. The variability among the species in biomass and carbon stocking in RHRF underscores the need for sustainable forest management with biodiversity conservation. The high-biomass species should be prioritized in carbon budgeting frameworks, focusing on the afforestation and reforestation programs aiming to maximize the carbon sequestration. At the same time, the lower biomass species should be considered for species-specific conservation strategies to preserve biodiversity and ecosystem resilience of natural forests.

4. Discussion

4.1. Species Composition. The tree species composition of RHRF demonstrates a rich biodiversity with 45 tree species belonging to 22 botanical families. The Fabaceae

Table 2: Basal area (BA), relative abundance (RA), relative density (RDe), relative frequency (RF), relative dominance (RDo), and Important Value Index (IVI) of the tree species recorded from the tree species of Raghunandan Hill Reserve Forest.

Scientific name	BA (m^2/ha)	RA (%)	RDe (%)	RF (%)	RDo (%)	IVI
Aquilaria malaccensis	6.48	3.4	3.45	2.67	2.67	8.78
Acacia auriculiformis	5.24	5.8	4.45	2.00	2.25	8.70
Terminalia arjuna	5.44	1.5	1.11	2.00	0.60	3.72
Lithocarpus elegans	5.80	1.1	0.56	1.33	0.34	2.23
Terminalia bellirica	4.66	1.5	1.56	2.67	0.62	4.85
Spondias pinnata	7.13	0.4	0.22	1.33	0.21	1.76
Ficus benghalensis	30	0.9	0.22	0.67	3.68	4.57
Dillenia indica	5.72	1.3	1.33	2.67	0.80	4.81
Michelia champaca	8.33	0.7	0.33	1.33	0.43	2.09
Artocarpus Chama	13.96	3.1	7.12	6.00	25.51	38.63
Alstonia scholaris	5.31	0.9	0.44	1.33	0.23	2.01
Chickrassia tabularis	7.45	11.3	5.78	1.33	5.90	13.02
Swintonia floribunda	1.25	0.4	0.11	0.67	0.00	0.78
Syzygium firmum	6.67	4.1	2.11	1.33	1.73	5.17
Stereospermum tetragonum	6.25	0.4	0.22	1.33	0.16	1.72
Ficus hispida	7.81	1	1.00	2.67	1.12	4.79
Eucalyptus camaldulensis	5.67	1.3	0.33	0.67	0.20	1.20
Gmelina arborea	4.96	1.5	1.56	2.67	0.71	4.93
Dipterocarpus turbinatus	6.75	2.3	1.78	2.00	1.49	5.27
Castanopsis indica	5.55	1.1	1.22	2.67	0.69	4.58
Adina cordifolia	4.25	0.4	0.11	0.67	0.04	0.81
Dillenia scabrella	6.25	0.9	0.44	1.33	0.32	2.10
Terminalia chebula	5.50	0.9	0.22	0.67	0.12	1.01
Lagerstroemia speciosa	6.97	3.9	6.01	4.00	5.37	15.38
Neolamarckia cadamba	9.06	0.9	0.44	1.33	0.67	2.45
Syzygium cumini	6.38	4.9	5.01	2.67	3.74	11.41
Bischofia javanica	6.88	1.9	1.45	2.00	1.26	4.70
Garcinia cowa	11.75	0.4	0.11	0.67	0.28	1.06
Terminalia catappa	7.50	0.7	0.33	1.33	0.35	2.01
Xylia xylocarpa	6.76	8.6	6.56	2.00	5.51	14.07
Swietenia mahagoni	6.64	4.5	11.57	6.67	9.39	27.62
Mesua ferrea	2.38	0.4	0.22	1.33	0.02	1.58
Aphanamixis polystachya	9.13	0.4	0.22	1.33	0.34	1.90
Caesalpinia pulcherrima	8.85	0.4	0.11	0.67	0.16	0.94
Samanea saman	6.14	0.9	0.67	2.00	0.46	3.13
Pterocarpus santalinus	5.83	0.7	0.33	1.33	0.21	1.88
Bauhinia variegata	4.67	1.6	2.45	4.00	0.98	7.43
Albizia procera	6.50	0.7	0.56	2.00	0.43	2.99
Shorea robusta	6.11	3.2	9.90	8.00	6.79	24.69
Tectona grandis	5.61	3.3	13.57	10.67	7.86	32.10
Bombax ceiba	15.42	0.7	0.33	1.33	1.46	3.13
Dalbergia sissoo	7.98	13.5	3.45	0.67	4.04	8.16
Cassia fistula	5.72	0.6	0.44	2.00	0.27	2.71
Hopea odorata	6.92	0.7	0.33	1.33	0.29	1.96
Firmiana colorata	8.38	0.9	0.22	0.67	0.29	1.18
Total		100	100	100	100	300

was the most dominant one, followed by the Combretaceae and others. The *Tectona grandis* (teak), *Swietenia mahagoni* (mahogany), and *Shorea robusta* (Sal) were found in the highest percentage, covering almost 35% of the areas. The results may be influenced by sampling techniques, geographical setting, and the soil and climate characteristics of the study area when compared to other tropical forests. The number of species found by the study is quite lower in comparison with a study in Moulvibazar Natural Forests of Sylhet Forest Division, where 81 native tree species under 59 genera and 33 families were reported [49]. In Rampahar Reserve Forest, a total of 50 tree species from 28 families, which closely resembles the number of tree species in RHRF [50]. In Hazarikhil Wildlife Sanctuary (HWS), a total of 162 tree species under 50 families were recorded [51]. A study in Himchari National Park (HNP) revealed 88 tree species belonging to 37 families [52] comparatively higher than the RHRF. On the other hand, in Medha Kachhapia National Park (MKNP), only 10 tree species under six families in southeastern Bangladesh 17 species belonging to 10 families were reported by Uddin et al. [53] and Dey & Akther [54], respectively, which is quite lower than RHRF.

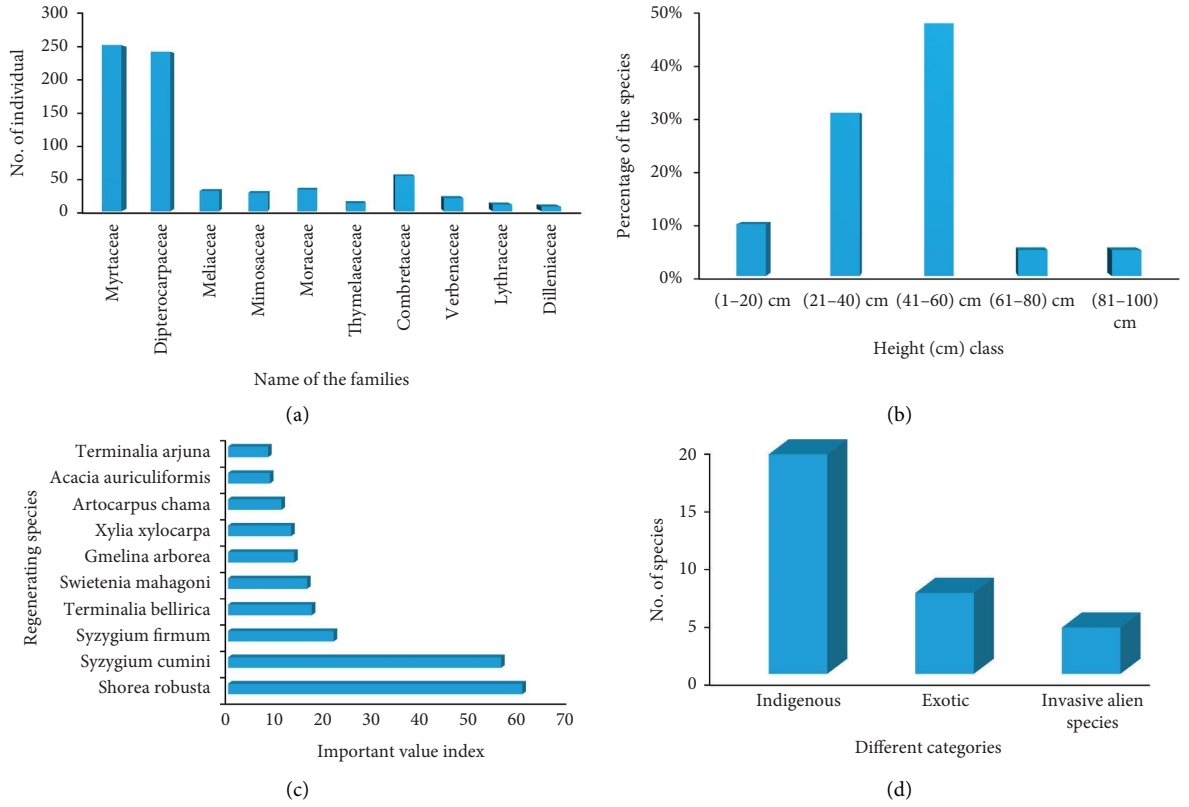

Figure 4: Natural regeneration status of tree species in Raghunandan Hill Reserve Forest of Bangladesh: (a) major regenerating species families, (b) height distribution of regenerating seedlings, (c) Important Value Index of regenerating species, and (d) categories of origin of regenerating species.

Table 3: The status, relative density (RDe), relative frequency (RF), relative abundance (RA), and Important Value Index (IVI) of the regenerated seedlings of Raghunandan Hill Reserve Forest. [Notes: I is indigenous, E is exotics, and IAS is invasive alien species].

SL no.	Local name	Scientific name	Status	RDe (%)	RF (%)	RA (%)	IVI
1	Acargula	*Grewia nervosa*	I	0.28	1.03	1.63	2.93
2	Akashmoni	*Acacia auriculiformis*	IAS	1.67	2.06	4.88	8.61
3	Arjun	*Terminalia arjuna*	I	1.67	4.12	2.44	8.23
4	Batna	*Lithocarpus polystachya*	I	0.56	2.06	1.63	4.24
5	Bohera	*Terminalia bellirica*	I	5.56	5.15	6.50	17.21
6	Chalta	*Dillenia indica*	I	0.97	3.09	1.90	5.96
7	Chapalish	*Artocarpus Chama*	I	2.78	4.12	4.06	10.97
8	Dumur	*Ficus hispida*	I	1.11	2.06	3.25	6.42
9	Bot	*Ficus* spp.	I	0.69	2.06	2.03	4.79
10	Gamar	*Gmelina arborea*	E	3.47	7.22	2.90	13.59
11	Garjan	*Dipterocarpus turbinatus*	I	1.39	3.09	2.71	7.19
12	Jarul	*Lagerstroemia speciosa*	I	1.39	2.06	4.06	7.52
13	Kadam	*Neolamarckia cadamba*	I	0.56	1.03	3.25	4.84
14	Kalo Jam	*Syzygium cumini*	I	27.5	20.62	8.05	56.17
15	K. Bhadi	*Bischofia javanica*	I	0.69	2.06	2.03	4.79
16	Kat Badam	*Terminalia catappa*	I	0.28	2.06	0.81	3.15
17	Lohakhat	*Xylia xylocarpa*	E	2.78	2.06	8.13	12.97
18	Mangium	*Acacia mangium*	IAS	0.14	1.03	0.81	1.98
19	Mahagony	*Swietenia mahagoni*	IAS	3.61	2.06	10.57	16.24
20	Pitraj	*Aphanamixis polystachya*	I	0.69	2.06	2.03	4.79
21	Sada Koroi	*Albizia procera*	E	1.11	3.09	2.17	6.37
22	Sal	*Shorea robusta*	I	32.5	14.43	13.59	60.52
23	Dhakijam	*Syzygium firmum*	I	7.78	8.25	5.69	21.72
24	Shewra	*Streblus asper*	I	0.14	1.03	0.81	1.98
25	Shimul	*Bombax ceiba*	I	0.42	1.03	2.44	3.89
26	Segun	*Tectona grandis*	IAS	0.28	1.03	1.63	2.93
	Total			100	100	100	300

Table 4: Different biological diversity indices of tree species and regeneration in Raghunandan Hill Reserve Forest.

Diversity index	Tree species	Regenerated tree species
Shannon–Wiener index	3.04	2.17
Margalef's index	6.47	3.79
Simpson's index	0.07	0.20
Species evenness index	0.98	0.67

Table 5: Total biomass and carbon stock of tree species in Raghunandan Hill Reserve Forest of Bangladesh.

SL no.	Local name	Scientific name	Total biomass (tons/ha)	Organic carbon content (tons/ha)
1	Agar	*Aquilaria malaccensis*	13.43	6.72
2	Akashmoni	*Acacia auriculiformis*	13.33	6.67
3	Bon Amra	*Spondias pinnata*	0.68	0.34
4	Arjun	*Terminalia arjuna*	2.25	1.13
5	Kat Badam	*Terminalia catappa*	0.93	0.47
6	Batna	*Lithocarpus elegans*	1.08	0.54
7	Kanjol Bhadi	*Bischofia javanica*	7.04	3.52
8	Bohera	*Terminalia bellirica*	2.57	1.29
9	Bot	*Ficus benghalensis*	12.00	6.00
10	Chalta	*Dillenia indica*	3.20	1.60
11	Champa	*Michelia champaca*	1.73	0.865
12	Chapalish	*Artocarpus Chama*	121.07	60.54
13	Chatian	*Alstonia scholaris*	0.50	0.25
14	Chickrassi	*Chickrassia tabularis*	30.77	15.39
15	Civit	*Swintonia floribunda*	0.0031	0.0016
16	Kao	*Garcinia cowa*	1.07	0.535
17	Dhakijam	*Syzygium firmum*	9.50	4.75
18	Dharmara	*Stereospermum tetragonum*	0.55	0.275
19	Dumur	*Ficus hispida*	3.45	1.73
20	*Eucalyptus*	*Eucalyptus camaldulensis*	0.98	0.49
21	Gamar	*Gmelina arborea*	2.10	1.05
22	Garjan	*Dipterocarpus turbinatus*	7.73	3.87
23	Gutgutiya	*Castanopsis indica*	2.85	1.43
24	Haldu	*Adina cordifolia*	0.14	0.07
25	Hargeza	*Dillenia scabrella*	1.93	0.97
26	Haritaki	*Terminalia chebula*	0.67	0.34
27	Jarul	*Lagerstroemia speciosa*	19.35	9.68
28	Kadam	*Neolamarckia cadamba*	2.90	1.45
29	Rokto Kanchan	*Bauhinia variegata*	3.48	1.74
30	Lohakhat	*Xylia xylocarpa*	47.20	23.6
31	Mahagony	*Swietenia mahagoni*	39.00	19.5
32	Nageshwar	*Mesua ferrea*	0.11	0.06
33	Pitraj	*Aphanamixis polystachya*	1.27	0.64
34	Kalo Jam	*Syzygium cumini*	18.38	9.19
35	Radhachura	*Caesalpinia pulcherrima*	0.25	0.125
36	Rain tree	*Samanea saman*	2.00	1.00
37	Rokto Condon	*Pterocarpus santalinus*	0.83	0.42
38	Sada Koroi	*Albizia procera*	2.46	1.23
39	Sal	*Shorea robusta*	53.40	26.7
40	Segun	*Tectona grandis*	33.55	16.78
41	Shimul tula	*Bombax ceiba*	3.70	1.85
42	Sissoo	*Dalbergia sissoo*	20.15	10.08
43	Sonalu	*Cassia fistula*	2.63	1.32
44	Telsur	*Hopea odorata*	1.30	0.65
45	Udal	*Firmiana colorata*	0.55	0.28

Although our study found the maximum number (6) of species under Fabaceae, a previous study in Shaltila beat found the highest species number (6) belongs to the Moraceae family [26]. Again, a study in Rampahar Reserve Forest reveals Moraceae possessed the maximum number of species (six species) [50]. In HWS, the highest number of species (18) was recorded under Euphorbiaceae [51], which is comparatively higher than RHEF. The family Moraceae, with

the highest number of species (11), was also reported in the HNP of Bangladesh [52]. In comparison with other forests in Bangladesh, RHRF showed moderate species richness, which is lower than HWS and HNP but higher than MKNP and southeastern forests.

The species with the highest BA was *Ficus religiosa* (1.14 m^2/ha) in Rampahar Reserve Forest [50], while in RHRF, the highest basal area belongs to *Ficus benghalensis* (30 m^2/ha). The HNP reported the highest basal area of 10.979 m^2/ha [52] also significantly lower than the RHRF. Again, *Tectona grandis* represents maximum (13.57%) RDe, while a study in the forests of Cox's Bazar North Forest Division reflects maximum RDe and highest RF in *Dipterocarpus turbinatus* as 37.71% and 25.93%, respectively [54]. The IVI has been detected to be highest in *Dipterocarpus turbinatus* (135.82), followed by *Acacia auriculiformis* (36.89) [54] which are comparatively higher than the RHRF. On the other hand, the maximum IVI was noticed for *Acacia auriculiformis* (23.23), followed by *Tectona grandis* (13.05) by Hossen et al. [52] in HNP, which are comparatively lower than the IVI of *Artocarpus chama* (38.63), followed by Tectona grandis (32.10) in RHRF.

In RHRF, the Shannon–Wiener index is 3.04, Simpson's index is 0.068, Margalef's index is 6.47, and the species evenness index is 0.98, indicating greater diversity compared to MKNP, which exhibits a Shannon–Wiener diversity index of 1.16, Simpson's index of 0.45504, Margalef's species richness index of 1.630,003, and Pielou's species evenness measure of 0.21066 [53]. Overall, the RHRF showed a high level of structural dominance and diversity, with higher basal area, IVI, and diversity indices compared to Rampahar Reserve Forest, HNP, and MKNP, highlighting its rich composition of tree species diversity.

The structural composition of *Acacia auriculiformis* reveals its ecological dominance in RHRF. The species exhibits a basal area of 5.24 $m^2\,ha^{-1}$ and an IVI of 8.70, along with high RA (5.8%) and density (4.45%). These findings depict that the species has a fast invasion and spread potential in distributed habitats. This ascendancy is an indication of a highly adaptive invasive exotic with fast growth and high seed yield, which prevents the regrowth of native species by closing the canopy, exhibiting allelopathic effects, and absorbing excessive soil water [55–58]. The Government of Bangladesh recently (2025) restricted the plantation, harvesting, and selling of *Acacia auriculiformis* (Akashmoni) saplings in order to protect the environment, ecosystems, and biodiversity. So, the RHRF authorities should take necessary steps for the selective removal and control of natural regeneration of *Acacia auriculiformis* along with the enrichment plantation of native species.

4.2. Regeneration Status. In RHRF, the natural regeneration status indicates promising potential of natural regeneration with a total of 26 regenerating tree species, comprising 19 indigenous species and seven exotic species, including four invasive alien species. A study in the areas of northeastern Bangladesh recorded a total of 15 exotic species under nine families and 40 indigenous species under 24 families [58]. In RHRF, Myrtaceae is the dominant family, but a case study in Satchari National Park revealed a total of 31 species under 20 families, where Moraceae was the dominant family of regenerating tree species [59]. Compared with the other two studies [58, 59] in Shahapur and Shaltila, the number of regenerating species is quite lower than our findings.

In RHRF, for regenerating species, *Shorea robusta* has the highest RDe (32.5%), *Syzygium cumini* (20.62%) has the highest RF, *Shorea robusta* has the highest RA (13.59%), and the IVI of *Shorea robusta* was maximum (60.52). A study in Khadimnagar National Park and Tilagaon Eco-Park of Northeastern Bangladesh recorded the highest RDe and RF of *Tectona grandis* (11.7%) and (10.5%), respectively. The highest RA of *Senna siamea* (7.83%) is substantially lower than our findings in RHRF. Among the native tree species, *Chickrassia tabularis* possesses the greatest RDe (4.23%) and RF (4%), while *Dipterocarpus turbinatus* recorded the highest RDo at 3.92%. The *Tectona grandis* (29.66) and *Chickrassia tabularis* (10.8) have the highest IVI for exotic and indigenous species, respectively [58].

However, most of the seedlings (49%) in RHRF fell within the 41–60 cm height class, suggesting successful establishment of ongoing regeneration, while only 10% were in the 1–20 cm class, indicating early mortality or limited germination during the study period. The high value of IVI and RDe values for key native species reflect robust natural regeneration, which is crucial for the long-term sustainability and resilience of the forest ecosystem and biodiversity.

Again, regeneration status demonstrates the persistence of *Acacia auriculiformis* as an invasive alien species in the RHRF. The species has a RDe of 1.67%, an RF of 2.06%, and an RA of 4.88% for a total IVI of 8.61. These number statistics show that it continues to maintain a noticeable presence in all forest plots through self-regeneration. Moreover, *Acacia auriculiformis* is a well-known invasive species in Bangladesh, which degrade habitats and hybridize with native species, altering native genetic diversity and integrity [55, 56]. Its initial increased productivity may decrease in subsequent rotations, posing a threat to the ecosystem [60].

4.3. Biomass Carbon Potentials. The tropical forests function as a large carbon pool globally, although uncertainty remains in the measurement of their quantity. Nowadays, allometric and regression model-based biomass and carbon quantification are gaining popularity among researchers [24, 25, 61, 62]. The quantification of biomass carbon using direct remote sensing-based data is also progressing their visibility due to their easiness and cost-effectiveness [20, 22, 63–66]. However, our study used the widely used allometric model using the field data to quantify tree species-level biomass carbon potentials in RHRF.

The study revealed the significant potential of biomass carbon of RHRF, with total biomass varying widely among species. Among all the species, *Artocarpus chama* (chapalish) had the highest total biomass, estimated at 121.07 tons/ha, corresponding to 60.54 tons/ha of carbon, followed by *Shorea robusta*, *Xylia xylocarpa*, *Swietenia mahagoni*, and

Tectona grandis, each contributing 16.78–26.7 tons/ha, whereas the lowest values were found in *Swintonia floribunda* 0.0031and 0.0016 tons/ha. This variation highlights the importance of dominant species for carbon sequestration along with the low-biomass species for maintaining biodiversity and ecological balance in RHRF.

A study in Tankawati natural hill forest presented that *Dipterocarpus turbin*atus has the topmost total biomass and carbon, with 81.42 and 45.40 tons/ha, respectively, which are slightly lower than RHRF [67]. The Madhupur Sal forest in Tangail showed the total biomass of *Shorea robusta* (Sal) as 307.86 tons/ha, significantly higher than *Artocarpus chama* in the RHRF [68]. In the Sundarbans mangrove area, the carbon density mostly ranges from 100 to 250 tons/ha [20], which is also higher than the RHRF. In RHRF, the value of carbon for a single species might be close to or higher than the value of Sal and mangrove forests if considered as a stand-level assessment. The high biomass of Sal and mangrove may also be due to specific factors such as soil quality, local climate, stand age, and forest management methods that promote greater productivity [68]. Recent studies across different countries of South Asia have revealed substantial differences in forest carbon storage among dominant tree species and forest types. The RHRF represents the significant contribution of mixed tropical species such as *Shorea robusta, Artocarpus chama, Xylia xylocarpa, Swietenia mahagoni,* and *Tectona grandis* to aboveground carbon storage, ranging from 16.78 to 60.54 t C ha^{-1}. In comparison with *Pinus roxburghii* forests in *Pakistan* revealed somewhat regional variability. In Pakistan's subtropical pine forests, the mean AGB was found 79.54 t C ha^{-1} in natural stands. Coniferous species such as *P. roxburghii* generally possess dense wood and high stand uniformity, enabling greater carbon accumulation per hectare compared to the broadleaf tree species of RHRF [69].

When compared with *Shuklaphanta National Park* in Nepal, where *Shorea robusta* is the dominant species with AGB carbon store of 193.3–258.56 t C ha^{-1} [70], while in mixed middle-mountain forests around Kathmandu, AGB carbon ranges from 22.50 to 87.13 t C ha^{-1} [71]. The AGB carbon stock in RHRF appears somewhat low compared to Nepal. This variation is probably due to the maturity and density of Sal-dominated stands in Shuklaphanta, as well as better protection status, while RHRF is more fragmented and faces extraction pressure which leads to reduced biomass accumulation. This variation also might be the result of the exclusion of other important biomass carbon pools like belowground, soil, and litter carbon pools.

Similar trends were also observed in Bhutanese community forests with the dominance of oak (*Quercus*) and chestnut (*Castanopsis)* species. The biomass carbon range of 107.3–153.2 t C ha^{-1} [72] was considerably higher than RHRF values. The higher values in Bhutan community forests reflect the presence of mature temperate broadleaf forests and effective community management practices that enhance long-term carbon storage. In India's Tarai region, maximum total biomass was recorded as 145.14 t C ha^{-1} at *Melia composita* plantation and 90.43 t C ha^{-1} at *Dalbergia latifolia* plantation [73]. These values are substantially higher than the natural mixed forests of RHRF, focusing on the advantage of well-managed plantations for higher rates of carbon accumulation. However, such systems may lack biodiversity and soil stability, contrasting with the ecological resilience of mixed forests like RHRF.

In contrast to the Mediterranean downy oak ecosystem, where the carbon density ranges from 15 ± 14 tons/ha [74], the RHRF has much more carbon storage potential. The individual tree-based carbon density of RHRF is also higher than that of the forest of India, 48.5–56.3 tons/ha [22]. Overall, the forest of RHRF showed significant potential for biomass carbon storage in comparison with the national and global perspectives. Policymakers can use these findings for evidence-based decision-making for both biodiversity conservation and sustainable forest management, along with proper justification in REDD+ and global carbon budgeting.

5. Conclusion

The RHRF is an ecologically important area and a vital part of the forest ecology of Bangladesh. The present study deals with the structural composition and regeneration status of tree species and the quantification of biomass and carbon sink. The study showed that RHRF supports a moderately diverse forest ecosystem with 45 tree species belonging to 22 families, dominated by *Artocarpus chama*, *Tectona grandis*, and *Ficus benghalensis*. The estimated high value of biomass and carbon stocks in *A. chama* underscores the potential of this species in carbon storage and its function in climate change mitigation and carbon trading. Among the 26 regenerating seedling species recorded, 19 were indigenous tree species, suggesting a valuable regeneration potential of native species at the RHRF. However, natural regeneration is vulnerable due to limited diversity among the regenerating seedlings and the emergence of four invasive alien species. The structural composition of *Acacia auriculiformis* demonstrates its ecological dominance in RHRF. This ascendancy indicates a highly adapted invasive exotic with rapid growth and great seed yield that prevents native species regeneration by sealing the canopy, demonstrating allelopathic effects, and absorbing too much soil water.

The findings of the study might be useful for implementing silvicultural methods in RHRF and other areas having similar biophysical composition. To ensure sustainable management of RHRF, the study recommends strengthening monitoring of assisted natural regeneration (ANR), conserving native, EN (7%), and VU (2%) tree species by protecting regenerating seedlings from disturbances, controlling invasive species, selective removal of *Acacia auriculiformis* coupled with enrichment plantation using native tree species, control of excessive cattle grazing to safeguard the young plants, and regularly assessing regenerating sites. The study also emphasizes buffer zone establishment around RHRF to reduce human–wildlife conflict and safeguard the sensitive ecological areas. Integrating scientific research into long-term conservation strategies is also advised to improve

forest resilience and conservation outcomes. This research emphasizes more critical studies on the capacity of native species for regeneration to preserve and improve forests in the future.

Data Availability Statement

Relevant data will be made available upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

Supporting Table 1. Phytosociological parameters (BA, RA, RDe, RF, RDo, and IVI) of tree species recorded in the Raghunandan Hill Reserve Forest.

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