Sustainable Forests & Livelihoods (SUFAL) Project
Forest Department
Ministry of Environment, Forest and Climate Change

Compendium of Forestry Research under the SUFAL Innovation Grant

Volume 2

SUFAL

THE WORLD BANK
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This publication is an output from the Sustainable Forests & Livelihoods (SUFAL) Project implemented by Bangladesh Forest Department (BFD) under the Ministry of Environment, Forest and Climate Change.

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Dr. Farhina Ahmed
Secretary
Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh

Message

I am pleased to share this volume of research outputs generated under the SUFAL Innovation Grant (SIG) Program, an integral component of the Sustainable Forests and Livelihoods (SUFAL) Project of the Bangladesh Forest Department under Ministry of Environment, Forest and Climate Change. This compilation reflects a significant step forward in our collective efforts to ground forest management and wildlife conservation in robust scientific evidence.

Bangladesh is endowed with a remarkable diversity of flora and fauna, yet this heritage is under mounting pressure from rapid land-use change, habitat fragmentation, climate-induced stresses, and the growing interface between people and wildlife. These complex challenges cannot be addressed through traditional management practices alone. They require interdisciplinary inquiry, empirical data, and context-specific solutions that link ecological integrity with human wellbeing.

The SIG program was conceived precisely with this vision in mind. By offering competitive grants to researchers, universities, and specialized institutions, the program has created space for innovative ideas, rigorous fieldwork, and analytical research on Forestry, wildlife and biodiversity issues.

The findings presented here do not remain confined to academic discussion; they generate clear, actionable recommendations for managers, planners, and policymakers. They provide insights that can inform zoning and management plans, improve conflict mitigation measures, strengthen community participation, and enhance the resilience of forest, wildlife and ecosystems to climate and other anthropogenic pressures.

I wish to acknowledge the dedication of the researchers and their teams, the guidance provided by the various review committees, and the support of partner organizations and development partners who have contributed to the success of the SIG program. Their combined efforts have ensured that the studies uphold scientific rigor while remaining closely aligned with national conservation priorities and international commitments.

It is my expectation that this publication will be used widely by conservation practitioners, government agencies, academia, development partners, and civil society to inform decision-making and to inspire further research and innovation. As we strive to conserve Bangladesh’s forest, wildlife, biodiversity and ecosystems for present and future generations, evidence-based knowledge such as that contained in this volume will remain one of our most valuable assets.

Dr. Farhina Ahmed

Md. Amir Hosain Chowdhury
Chief Conservator of Forests
Bangladesh Forest Department

Message

Forests and wildlife in Bangladesh play a vital role in maintaining ecological balance, supporting livelihoods, and contributing to national development. To manage these resources wisely, we need a clear understanding of forest dynamics, species ecology, ecosystem services, and the social context of resource use.

This publication represents significant research on both forestry and wildlife supported by the SUFAL Innovation Grant (SIG) Program of the Sustainable Forests and Livelihoods (SUFAL) Project. The studies compiled here reflect a strong commitment to grounding conservation and forest management in scientific evidence, practical field experience, and the realities faced by forest-dependent communities in Bangladesh.

The research presented in this volume responds to that need. It includes work on forest restoration and productivity, co-management and collaborative forest management, biodiversity assessment, species conservation, human–wildlife interaction, and climate-resilient management practices. Together, these studies demonstrate how well-designed research can guide more sustainable and inclusive management of forests and wildlife.

The importance of this publication lies in its ability to translate research findings into practical guidance. The results offer concrete suggestions for improving forest management plans, enhancing protection and restoration measures, designing and managing Reserved Forests and Protected Areas, and supporting communities that depend on forests and wildlife for their livelihoods. As such, this volume is intended to serve not only researchers and academics but also policymakers, forest managers, conservation practitioners, and development partners.

I hope that the insights and recommendations contained here will be widely used to strengthen evidence-based decision making in the forestry and biodiversity sectors of Bangladesh. This publication will help to formulate our future policies, improve field practices, and inspire further research and innovation. It will make a long lasting contribution to the conservation of our forests, biodiversity and wildlife for present and future generations.

Md. Amir Hosain Chowdhury

Gobinda Roy
Project Director
Sustainable Forests and Livelihoods (SUFAL) Project
Forest Department
Government of the People's Republic of Bangladesh

Foreword

Sustainable Forests and Livelihoods (SUFAL) Project has supported research and innovation through its Innovation Grant Program, designed to strengthen forestry and biodiversity knowledge in Bangladesh. SUFAL Innovation Grant (SIG) is one of the unique features of SUFAL Project guided by the Innovation Grant Manual. This mechanism was designed to promote scientific and applied research on forestry, wildlife, and biodiversity conservation, while also ensuring transparency, accountability, and quality in both the selection and implementation of research initiatives.

Through this competitive process, 34 research grants were awarded to researchers and institutions after rigorous evaluation. Each proposal and subsequent deliverable was carefully reviewed by the Deliverable Review and Comments Committee, the Research Proposal Evaluation Committee, and the Forestry and Wildlife Research Review Council. This multi-tiered scrutiny ensured that the work undertaken met high professional standards and directly addressed the needs and challenges in forestry and wildlife management.

SUFAL Project also organized result dissemination workshops, where researchers shared their findings with policymakers, practitioners, academics, and other stakeholders. These events served not only as a platform for knowledge exchange but also as an opportunity to foster collaboration and dialogue around future research priorities. Following this, the researchers submitted their final reports, marking the successful completion of all 34 studies under the SIG program.

To make these findings widely accessible, SUFAL is now publishing four volumes of research summaries: two focusing on forestry and two on wildlife. These volumes present the essence of the research in a concise and structured manner, allowing stakeholders, decision-makers, and development partners to draw practical lessons and insights. The outcomes documented here will help shape evidence-based policies, strengthen conservation practices, and guide further research and innovation in the forestry and biodiversity sector of Bangladesh.

I would like to extend my sincere gratitude to the dedicated researchers, the review committees, partner institutions, and the World Bank for their valuable support. Their commitment and contributions have made it possible to generate a body of knowledge that will serve the sector for years to come. This publication will not only enrich our understanding but also support Bangladesh for achieving its national priorities and international commitments related to forest, biodiversity and wildlife conservation.

Gobinda Roy

Table of Content

Research Title

Monitoring Mangrove Community Health and Structure based on Mangrove Health Index (MHI) and Remote Sensing approaches in the potential coastal mangrove sites in Bangladesh

by

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1. Introduction

Coastal mangrove forests are among the most productive and carbon rich ecosystems on the earth (Spalding et al. 2010; Donato et al., 2011). Mangroves are recognized as the most biologically important ecosystems of wetlands as they provide various goods and services to the society as well as benefits to the coastal and marine systems (Valiela et al., 2001; Giri et al., 2011; Kanniah et al., 2015; Rhyma et al., 2015).

The coastal zone of Bangladesh covers an area of 47,201 km^2 extending along the Bay of Bengal. It lies between latitude 21°-23° N and longitude 89°-93° E. The coastal zone constitutes 20% of the country's area and 28% of the population of Bangladesh (Islam, 2004). Mangroves are available in the form of natural forests (the Sundarbans) and planted forests (in Barisal, Noakhali, Chittagong and Cox's Bazaar Coastal Areas) together covering about 50% of the forest area of Bangladesh. The coastal mangrove forests constitute about 60% of the commercial productive forests including plantations, it covers 580 km^2. It extends along the coast in isolated groups with the exception of the Sundarbans, which accounts for 74% of the reserve forest of the country.

Mangroves are important to people due to the invaluable goods and services produced in an environmentally safe, economically efficient and socially acceptable manner; the mangrove products include timber and various forest items (Aschbacher et al., 1995; Putz and Chan, 1986). One of the major goals of the 2030 Agenda for Sustainable Development is to protect, restore, and conserve the biodiversity and sustainable use of natural forests. Mangroves comprise only a small percentage of the global tropical forest area, but ensure food security for millions of people, and health and protection of coastal zones (Suman, 2019). Thus, management and sustainable use of coastal mangrove is inevitable for achieving SDG 2030.

Globally, mangrove forests are found in 124 countries and territories, either as a relatively narrow fringe or as a large chunk of forest (FAO 2007). The mangrove biome, spanning over 137,760 km^2 of coastal areas in 118 countries is under severe threat. Nearly 50% of the biome has been lost since the 1950s because of inadequate habitat protection, and large-scale habitat alteration (Feller et al, 2010). The Old World or the Indo-West Pacific mangrove is the most diverse biogeographical regions with the highest number of species found in Asia (FAO 2007). The global pattern of biodiversity in mangroves showed that, over 41% of the world's mangroves exist in South and Southeast Asia (Malik et al., 2017). Already 16% of mangrove species are critically endangered, endangered or vulnerable and 10% are near-threatened (Polidoro et al., 2010). The conservation of mangrove is becoming a prime concern now a days.

Forest community structure mainly attributed to forest species composition and diversity (Feroz et al. 2013). A good health of forest indicates its sound species composition and rich biodiversity and good site quality as well. Biodiversity is certainly an important element in understanding the structure and function of forest ecosystems. It is a key issue in nature conservation (Wilson 1988) and species diversity is an important component of biodiversity (Ito, 1997). It is fundamental to total forest biodiversity, because tree species provide resources and habitats for almost all other forest species (Huston 1994; Whitmore 1998; Huang et al. 2003). Monitoring mangrove health by the application of Remote Sensing (RS) technology improves biodiversity and structure of mangrove ecosystem which are the key components of Mangrove Health Index (MHI) (Johan et al. 2017).

Mangrove Health Index (MHI) is a single metric measure or parameter that can represent, reflect, and show the quality of mangrove ecosystem (e.g. ecosystem function, ecosystem services, biodiversity, etc.) and it can be compared among sites or times. It is very simple, practical, and reliable and can be integrated with spatial data. MHI is a new approach to collect, analyze and evaluate the data of mangrove ecosystem health for long-term monitoring of an ecosystem. The Research Centre for Oceanography, Indonesian Institute of Sciences (LIPI) has developed a mangrove monitoring system with an efficient methodology and android based applications named MonMang with a spreadsheet template since 2014. During 2019, a formula of the index has been approved and validated by the expert through a national scientific conference. This new approach has not been applied in any monitoring of forest health in Bangladesh. It is expected that this would be useful tool for the planner and forest managers for the development and management of costal mangrove ecosystem scientifically.

Monitoring biodiversity is the first step in systematic conservation planning and management. As well as monitoring the health of marine ecosystems is an integral part of sustainable management of the ecosystems including mangrove. Distribution and diversity of mangrove ecosystems are two important parameters in Mangrove Health Index (MHI). The index analyses value of mangrove density, diversity, index of similarity and the number of mangrove species. (Johan et al. 2017).

2. Objectives

- To quantify mangrove vegetation structure and composition with the application of biodiversity indices and
- To measure mangrove community health in coastal mangrove areas of Bangladesh by the development of Mangrove Health Index (MHI) map using remote sensing approach.

3. Research methods

3.1 Description of the study areas

To cover the whole coastal zone of Bangladesh, the research is conducted in six coastal mangrove sites namely i) Haringhata Eco Park (HEP), Barguna, ii) Tengragiri Wildlife Sanctuary (TWS), Barguna, iii) Bara Baisdia Coastal Plantation (BBCP), Patuakhali, iv) Char Kukrimukri Wildlife Sanctuary (CKWS), Bhola, v) Nijhum Dwip National Park (NINP), Noakhali and vi) Guliakhali Coastal Plantation at Sitakundu (GCP), Sitakundu (Figure 1) which lie sharply on the costal belt starting from South-West (Patharghata, Barguna) to South-East (Sitakundu, Chottogram) part of Bangladesh.

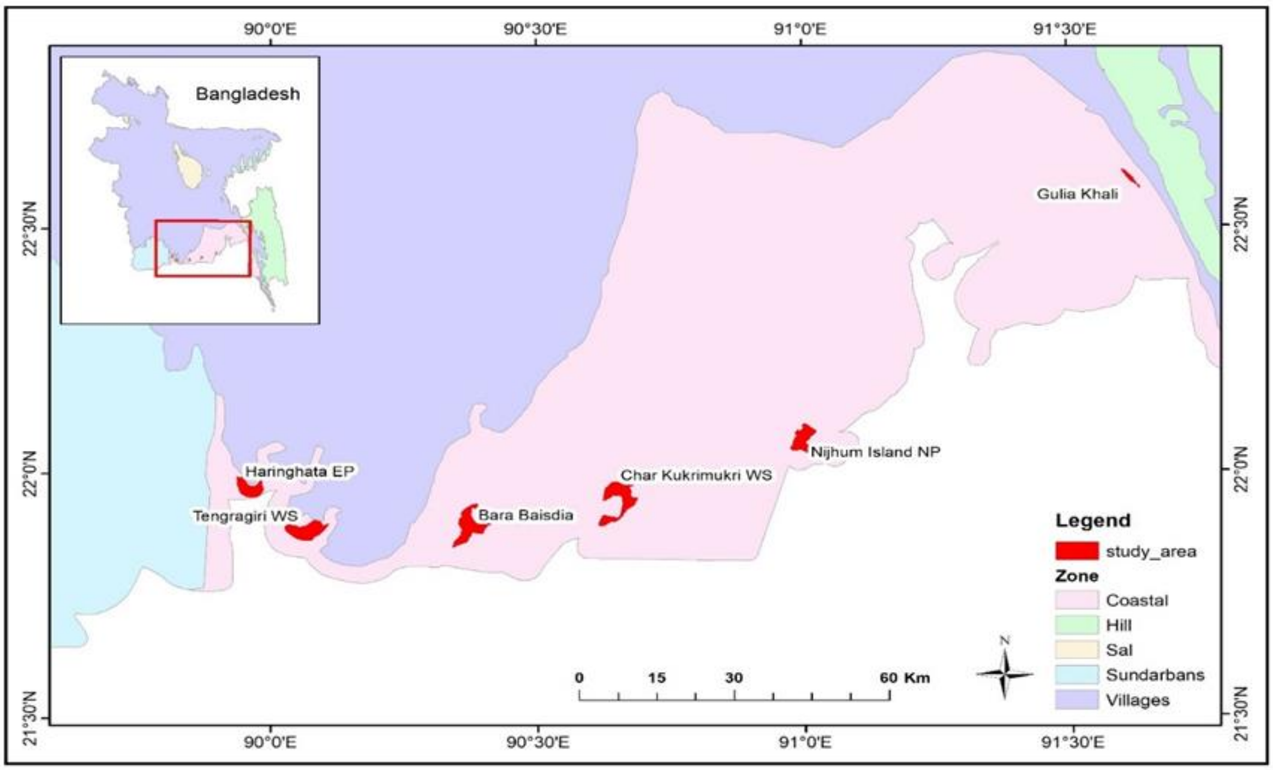

Figure 1. Study areas located in the coastal zone starting from South-West (Patharghata, Barguna) to South-East (Sitakundu, Chottogram) part of Bangladesh (Source: GoB, 2019).

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3.2 Sampling design and data collection

3.2.1 Sampling design

In order to carry out such a large-scale field survey, selection of appropriate sampling technique that captures systematically all variations in the habitat as well as maximum floral diversity is imperative.

For this proposed SIG research project, we have adopted a grid-based systematic sampling with cluster plot design. The six sampling sites are grided (each grid size: 1 km^2) on the vegetation map separately depending on the available mangrove vegetation (Figure 2). Based on the remote sensing image interpretation, available mangrove coverage is estimated in to area as 18 km^2 for HEP, 27.08 km^2 for TWS, 31.40 km^2 for BBCP, 34.48 km^2 for CKWS, 21.33 km^2 NINP and 6.91 km^2 for GCP (Table 1).

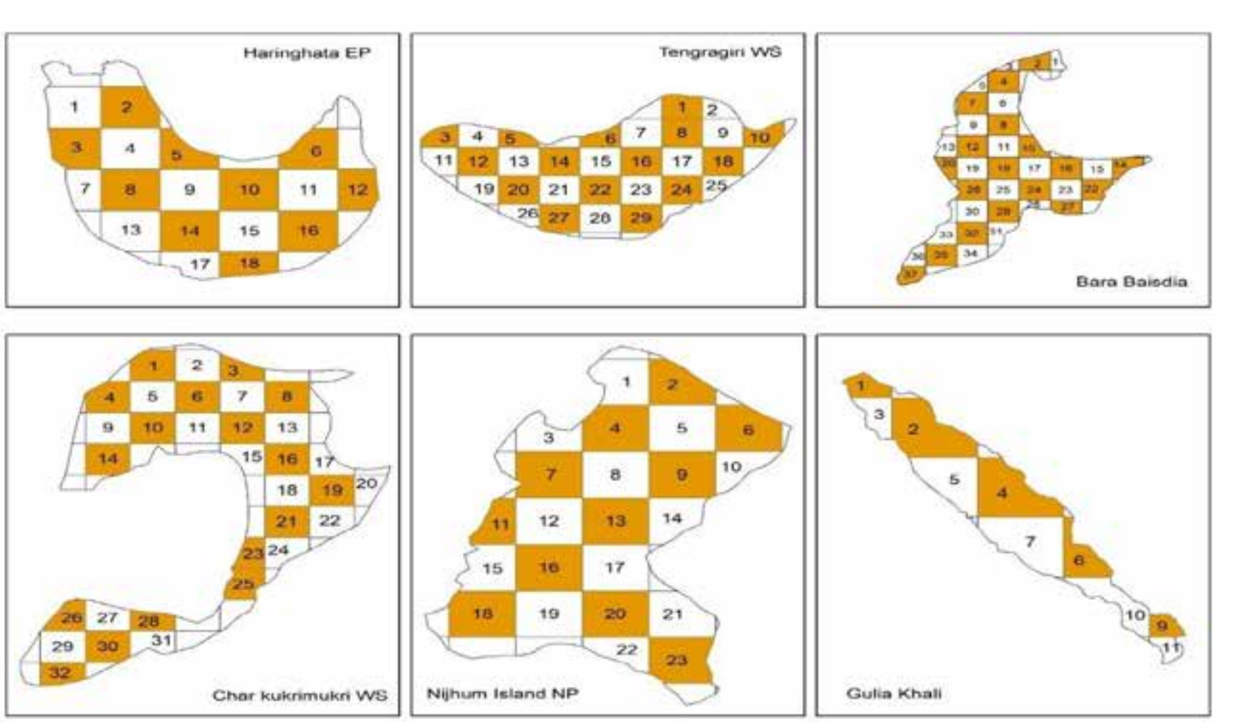


Figure 2. Grids (each grid size: 1 km^2) with orange color marking selected systematically in six sampling sites and later four sampling plots (each plot size 10 m x 10 m) established in each gird.

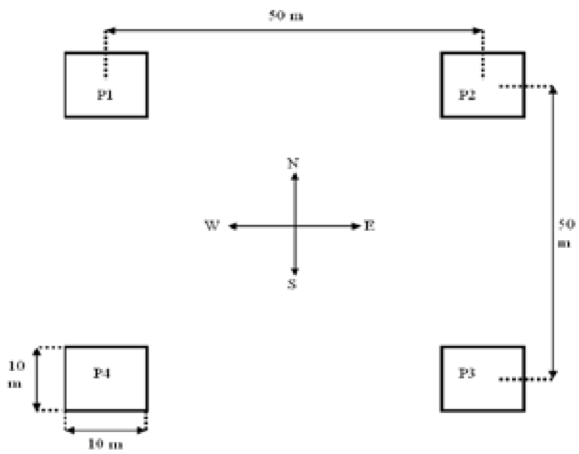


Figure 3. Schematic diagram showing cluster sample plots distributed systematically in a selected grid (1 km^2) (P1 to P4 clockwise plot no.)

Table 1. Selected grids and number of sample plots in six study sites of mangrove coastal areas

Study sites	Area (km^2)	Selected grid (1 km^2)	Sampling plots (10 m x 10 m)
Haringhata EP	18.00	10	40
Tengragiri WS	27.08	15	60
Bara Baisdia CP	31.40	17	68
Charkukrimukri WS	34.48	17	68
Nijhum Dwip NP	21.33	11	44
Gulia Khali CP	6.91	6	24
Total	**139.2**	**76**	**304**

Note: EP = Eco-park, WS= Wildlife Sanctuary, CP= Coastal plantation, NP= National Park

Every alternate grid is selected to conduct the vegetation survey to ensure the heterogeneity as well as spatial distribution of structural vegetation composition. A cluster of four square-shaped plots (each plot size: 10 m x 10 m) was established at the center of each grid. In the case of constructing a cluster with four sample plots, every first plot (left lower one: south-west corner) is positioned on the 225° azimuth at a distance of 35.36m from the centroid point of the grid and then other three plots are systematically positioned on the lateral line of right side (south-east corner), upper right side (north-west corner) and upper left side (north-west corner) and a 50 m distance is spaced between two centers of two corresponding plots (Figure 3). So, each selected grid represents four sample plots. Using this systematic sampling technique, the selected 10 grids for HEP, 15 grids for TWS, 17 grids for BBCP, 17 grids for CKWS, 11 grids for NIPA, 6 grids (5 grids were initially selected but 1 additional grid was taken) for GCP produce 40, 60, 68, 68, 44, 24 sampling plots respectively (Figure 2 and Table 1). Therefore, a total of 304 sample plots will be selected from six coastal mangrove sites for collecting vegetation data, soil samples and garbage or plastic waste cover data.

3.2.2 Data collection

Field data was collected from Haringhata EP in November, 2022, Tengragiri WS in January, 2023, Bara Baisdia CP in November 2023, Char Kukrimukri WS in February, 2024, Gulia Khali in November 2024 and Nijhum Dwip National Park in December 2024 (Figures 4). All mangrove species including associate species were identified to species level. Girth at breast height (GBH) and height (H) of all trees (DBH ≥ 5 cm), sapling (DBH ≥ 2 cm to DBH <5 cm), the number of individuals of seedling (DBH < 2 cm and Height < 0.1 m) and cut-wood trunk were recorded from the plot (size: 10 m x 10 m). The GBH was measured with a measuring tape at 1.3 m above ground level or just above the buttress and height was measured by rangefinder/height measuring pole. Canopy coverage of plot was taken by camera. Plastic waste cover in the plot was qualitatively estimated and grouped into five categories. GPS data of all plots was also recorded. All these field data were collected by MonMang app and recorded on data sheet. Voucher specimen only collected from the mangrove trees and associates which could not be identified in situ.

During the periods of survey, we have established 40, 60, 68, 68, 44, and 24 sample plots (each plot size: 10 m x 10 m) in HEP, TWS BBCP, CKWS, NINP, and GCP, respectively (Figures 4). Necessary data were collected and recorded in data sheet.

3.3 Data Analysis

The field data of six coastal sites were collected at different feasible times (from October 2022 to December 2024), compiled, and analyzed to attain the study objectives by using the following parameters.

3.3.1 Site and vegetation data

The following parameters were used for site and vegetation data analysis.

3.3.1.1 Site Identity

Fieldwork data recording should provide the necessary information related to site and location, time, and geographic position.

3.3.1.2 Trunk Diameter at Breast-Height (GBH)

This is one of the main parameters to analyze the mangrove community structure. Girth at Breast-Height (GBH) was used for calculating frequency (F), density (D), dominancy (Do) of each species, their relative value, and important value index (IVI).

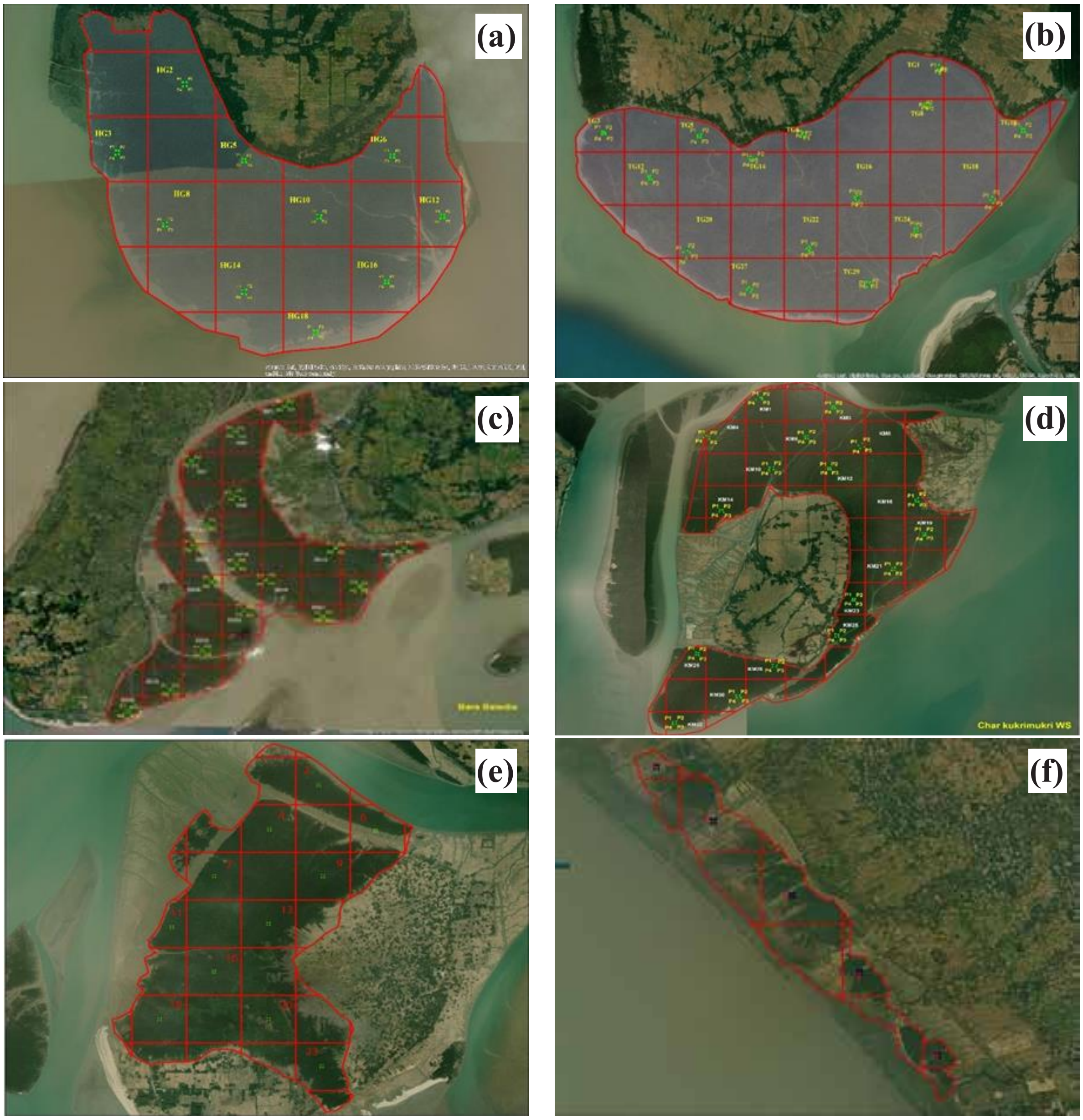


Figure 4. Maps of six study sites, where grids are systematically selected and each grid produces four sampling plots (a) Haringhata Eco Park (b) Tengragiri Wildlife Sanctuary (c) Bara Baisdia Coastal Plantation (d) Char Kukrimukri Wildlife Sanctuary (e) Nijhum Island National Park and (f) Guliakhali Coastal Plantation.

3.3.1.3 Relative Values (RF, RD, RDo)

Dharmawan and Ulumuddin (2020) reported that relative values are each percentage of frequency, density, and dominance of each species. Relative frequency (RF) describes the proportion of frequency and distribution of each species to all species' frequency on the plot measured. Relative density (RD) provides information on the number of species found compared to the total number of stands. Relative dominance (RDo) was calculated using the total basal area for each species divided by the total basal area of all stands and multiplied by 100%.

3.3.1.4 Important Value Index (IVI)

This index is a value obtained from all relative values of each type that summarizes the summary of each type's level of distribution, abundance, and dominance. This value also shows the amount of influence or importance of a tree in a measured community.

$$IVI = RF + RD + RDo$$

Where, RF is the relative frequency, RD is the relative density and RDo is the relative dominance.

3.3.1.5 Seedling Number (SD)

Mangrove seedling is an essential component in determining the mangrove community's regeneration rate, especially for mangroves that are damaged. MonMang facilitated this recording by including the type and number found in a single research plot.

3.3.1.6 Forest Height (H)

MonMang is also featured by a forest height estimation analysis. Dharmawan and Ulumuddin (2020) used the relationship among the measurement distance (d), the forest canopy tip angle (ϴ), and the height of the observer's eye (H_0). However, the height of trees was measured by rangefinder or height measuring pole depending on feasibility and applicability.

3.3.2 Diversity Indices

Three non-parametric indices were used to measure species diversity or equitability (evenness). Some other indices parameters were also used for diversity measurement.

3.3.2.1 Simpson's index D′ (Lande, 1996)

Simpson (1949) gave the probability of any two individuals drawn at random from an infinitely large community belonging to the same species as: $D' = \sum_{i=1}^{S} P_i^2$. Lande (1996) proposed Simpson's index in the following form:

$$1\text{-}D' = 1 - \sum_{i=1}^{S} P_i^2 \quad (P_i = n_i / N) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, n_i is the number of individuals of the ith species, N is the total number of individuals, and S is the total number of species.

3.3.2.2 Shannon's index H ′ (MacArthur and MacArthur, 1961)

Shannon and Wiener independently derived the function that is now generally known as the Shannon index or Shannon information index, though sometimes mistakenly referred (MacArthur and MacArthur, 1961) to as the Shannon-Weaver index. Shannon's index was calculated from the equation:

$$H' = \sum_{i=1}^{s} \frac{n_i}{N} \log_2 \frac{N}{n_i} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

3.3.2.3 Equitability index J' (Pielou, 1969)

The maximum diversity ($H'_{\max}$) that could occur in a situation where all species had equal abundances, in other words, if ($H' = H'_{max} = \log_2 S$). Therefore, the ratio of observed diversity to maximum diversity can be used to measure evenness (J'),

$$J' = \frac{H'}{H'_{max}} \quad (H'_{max} = \log_2 S) \quad \ldots\ldots (3)$$

The value of the equitability index is less than 1. The value would be 1 when the relative abundances of individuals of all species in a community are the same. This circumstance is naturally or biologically impossible.

3.3.3 Forest Canopy Coverage (C)

Hemispherical photography is one of the methods used in determining the percentage of mangrove canopy cover. The method would be done by taking a perpendicular photo of the substrate or vertically towards the sky to capture the canopy object in the hemisphere photo (Annex 3). All photos will be analyzed by ImageJ Software following equation.

Summary of the formula used to calculate the percent canopy coverage (C) based on the two scenarios of the function Histogram results in ImageJ,

C = P(255) /P (tot) x 100% : Histogram [Mode: 255] or

C = {(P(tot)- P0)}/P (tot) x 100%: Histogram [Mode: 0]

where C = Percent canopy cover (%), P255 = The number of pixels with 255 value representing the canopy, P0 = The number of pixels with 0 value representing the sky, Ptot = The total pixel number.

3.3.4 Threats: Garbage (G) and Cut-wood Trunk (CW)

Plastic waste cover in the plot was also qualitatively estimated and grouped into five categories which are 0% (no garbage cover); 1-25% (small area of the substrate covered by plastic waste); 25-50% (garbage covers proportion is equal to soil appearance); 50-75% (more garbage than substrate); and 75-100% (garbage covers the entire substrate) (Dharmawan and Ulumuddin, 2020).

Cut-wood event is a significant parameter in determining mangrove communities' health. The data was identified and the fresh stumps were counted in the entire plot. Data processing was conducted by dividing the number by the total live stands (trees and saplings) and multiplying by 100%.

3.3.5 Vegetation structure parameters

Through analysis of all the above parameters, the following parameters (Table 2) are summarized by plot. These parameters are used to generate the Field Mangrove Health Index (MHI_F). Principal component analysis (PCA) with these parameters is performed to find out the multicollinearity among the variables and the most significant variables responsible for higher degree of variation in different principal component axis. The important parameters are then used in various combinations to get the best index that describe the vegetation structure.

Table 2. Vegetation structure parameters

Sl No	Variables	Description
1	C	Canopy percentage
2	H	Dominant Forest Height
3	ntot	Total Density (Tree+Sapling)
4	Batot	Total Basal Area (Tree+Sapling)
5	Dmin	Minimum Diameter
6	Dmax	Maximum Diameter
7	Dtot_mean	Total Mean Diameter (Tree+Sapling)
8	nt	Tree Density
9	Bat	Tree Basal Area

Sl No	Variables	Description
10	Dt_mean	Tree Mean Diameter
11	nsp	Sapling Density
12	Basp	Sapling Basal Area
13	nsd	Seedling Density
14	G	Garbage Coverage
15	S	Stumps Proportion

3.3.6 Mangrove Vegetation Indices

Among the diverse remote sensing tools used in characterizing forests, spectral vegetation indices are widely adopted for monitoring forest states and canopy processes. These indices are fairly straightforward and quite efficient in forest resource management and for estimating forest biophysical properties (Huete, 2012). These indices have extensive implementation within remote sensing applications using different airborne and satellite platforms. One of the most used and implemented indices is the Normalized Difference Vegetation Index (NDVI), which is calculated from the ratio of | NIR-Red | and | NIR+Red |. It has the characteristics of analyzing canopy growth or vigor (Xue and Su, 2017).

$$\text{NDVI} = \frac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}} \text{ (Kriegler et al., 1969)}$$

Another important vegetation index is the Green Chlorophyll Index (GCI). This index is very useful in assessing chlorophyll content in leaves by analyzing the ratio of NIR and green bands. The increased reflectance of the NIR band from the leaf surface indicates increased leaf thickness. In addition, the increased reflectance in the visible range indicates decreasing pigment content of leaves (Steininger, 2000; Gitelson et al., 2003). In general, the chlorophyll value reflects vegetation.

$$\text{GCI} = \frac{\text{NIR}}{\text{Green}} - 1 \text{ (Gitelson et al., 2003)}$$

Vegetation indices can be utilized in various ecological issues like forest monitoring and sustainability requires the combination of optical-thermal remote sensing techniques, which have the potential to significantly improve and strengthen satellite-based monitoring systems.

Some others vegetation indices are also generated for the location where the plots were taken. The vegetation indices that were used in the study to evaluate the mangrove health index are listed in the Table 3. These most important vegetation indices that are not correlated with each other are selected by PCA analysis. The indices that have higher contribution in principal components are selected for further linear and non-linear regression model considering the field mangrove health index (MHI_F) as dependent variables to find out a meaningful and significant MHI model.

3.3.7 Mangrove Health Index (MHI)

MonMang can perform analysis and interpretation on mangrove health using Mangrove Health Index (MHI) equations introduced by Dharmawan and Ulumuddin, (2020). The MHI is a multivariate analysis product conducted to determine mangrove health's important parameters. The equation involves a combination of three selected parameters, namely: mangrove cover percentage (C), Diameter (DBH), and sapling density (Nsp). However, each parameter must be transformed before it is used to calculate the MHI value (Eq. 4). There are three categories used in determining mangrove quality based on the MHI value (Table 4).

MHI_F1 = $(S_C + S_{DBH} + S_{Nsp})$: 3 x 10………………………………………………………... (4)

Where, MHI = Mangrove health index, S = Score, C = Canopy coverage (%), DBH = Diameter at breast height (sapling+tree) (cm) and Nsp = Number of saplings per area

$S_C = 0.25\ C – 13.06$; but if $S_C < 0$ then $S_C = 0$ and $S_C > 10$; $S_C = 10$

$S_D = 0.45\ C + 1.42$; but if $S_D < 0$ then $S_D = 0$ and $S_D > 10$; $S_D = 10$

$S_{Nsp} = 0.13\ Nsp + 4.1$; but if $S_{Nsp} < 0$ then $S_{Nsp} = 0$ and $S_{Nsp} > 10$; $S_{Nsp} = 10$

Table 3. Different remote sensing vegetation indices used to develop the new MHI model

SL No	Index	Name	Formula	Bands Used	Purpose	Reference
1	NDVI	Normalized Difference Vegetation Index	(NIR - Red)/(NIR + Red)	NIR, Red	Vegetation greenness	Rouse et al. (1974)
2	EVI	Enhanced Vegetation Index	2.5 × (NIR - Red) / (NIR + 6×Red - 7.5×Blue + 1)	NIR, Red, Blue	Dense vegetation, atmospheric correction	Huete et al. (2002)
3	SAVI	Soil Adjusted Vegetation Index	((NIR - Red)/(NIR + Red + L)) × (1 + L), L=0.5	NIR, Red	Soil brightness correction	Huete (1988)
4	GNDVI	Green Normalized Difference Vegetation Index	(NIR - Green)/(NIR + Green)	NIR, Green	Chlorophyll concentration	Gitelson et al. (2001)
5	NDWI	Normalized Difference Water Index	(NIR – SWIR1)/(NIR + SWIR1)	NIR, SWIR	Vegetation water content	Gao (1996)
6	ARVI	Atmospherically Resistant Vegetation Index	NIR−(Red-y(Blue−Red))/NIR+(Red-y(Blue−Red)), y = quotient derived from the components of atmospheric reflectance in the blue and red channel (see literature, e.g. Bannari 1992, for details) y=1	NIR, Red, Blue or coastal aerosol	Atmospheric correction	Kaufman & Tanré (1992)
7	GCI	Green Chlorophyll Index	(NIR/Green)−1	NIR, Green	Chlorophyll content	Gitelson & Merzlyak (1997)
8	MI	Moisture Index	NIR/SWIR	NIR, SWIR	Vegetation moisture	Karnieli et al. (1996)
9	NBR2	Normalized Burn Ratio	(NIR−SWIR2)/(NIR+SWIR2)	NIR, SWIR2	Burn severity, fire detection	Key & Benson (2006)
10	SIPI	Structure Insensitive Pigment Index	(NIR−Blue)/(NIR−Red)	NIR, Blue, Red	Pigment ratios	Peñuelas & Filella (1998)
11	MSI	Moisture Stress Index	SWIR1/NIR	SWIR, NIR	Moisture stress	Hunt & Rock (1989)
12	MVI	Mangrove Vegetation Index	(NIR-Green)/(SWIR1-Green)	NIR, Green, SWIR1	Mangrove detection	Baloloy et al (2020)

Table 4. Three categories of mangrove health index (MHI).

Category	MHI
Poor	MHI ≤ 33.33%
Moderate	33.33 < MHI ≤ 66.67%
Excellent	MHI > 66.67%

Nurdiansah and Dharmawan (2021) developed an index for monitoring mangrove health based on remote sensing vegetation indices

$\mathrm{MHI\_1} = 102.12\ \mathrm{NBR} - 4.64\mathrm{GCI} + 178.15\mathrm{SIPI} + 159.53\mathrm{ARVI} - 252.39$ (Nurdiansah and Dharmawan, 2021)

Where, NBR (Normalized Burn Ratio) = $\frac{\mathrm{NIR-SWIR}}{\mathrm{NIR+SWIR}}$ (Key and Benson, 2006)

GCI (Green Chlorophyll Index) = $\frac{\mathrm{NIR}}{\mathrm{Green}} - 1$ (Gitelson et al., 2003)

SIPI (Structure Insensitive Pigment Index) = $\frac{\mathrm{NIR-Blue}}{\mathrm{NIR-Red}}$ (Pen Uelas et al., 1995)

ARVI (Atmospherically Resistant Vegetation Index) = $\frac{\mathrm{NIR-2\times Red+Blue}}{\mathrm{NIR+2\times Red+Blue}}$ (Tanre et al., 1992)

The equation was applied in the GEE to develop an MHI map of all sites. The three categories of mangroves, namely poor, moderate, and excellent, were visualized in red, yellow, and green colors, respectively. The area of these three categories of mangroves was estimated, and the final MHI map was exported using ArcMap version 10.8.

3.3.8 Satellite Image Analysis, Interpretation, and Visualization

3.3.8.1 Image Source

Harmonized Sentinel 2 MSI level-2A surface reflectance images were gathered for the period of October-2022 and December-2024 to produce a single cloud-free composite. Sentinel-2 is a wide-swath, high-resolution, multi-spectral imaging mission that supports Copernicus Land Monitoring investigations, including the monitoring of vegetation, soil, and water cover, as well as the observation of inland waterways and coastal areas. Level-0, Level-1A, and Level-1B products of Sentinel 2 MSI are not disseminated to users except the Level-1C and Level-2A products. The Level-2A operational processor creates atmospherically corrected Surface Reflectance (SR) products from Level-1C products using algorithms for scene recognition and atmospheric correction. Pixels that are damaged, nonexistent, or saturated are excluded at the Level-2A. Level-1C product provides orthorectified Top-Of-Atmosphere (TOA) reflectance, with sub-pixel multispectral registration. The product comes with cloud and land/water masks. On the other hand, various scene classification maps (cloud, cloud shadows, vegetation, soils/deserts, water, snow, etc.) are provided with the Level-2A product.

Depending on the band resolution (10, 20, or 60 m), the surface reflectance is performed at the resolution of the original products. Radiometry correction is usually done to revise the image's visual quality due to disturbances such as atmospheric disturbance, light illumination, and tool response inference (Lillesand et al., 2015). Solar radiation reflected by the Earth's surface to satellite sensors is modified by its interaction with the atmosphere. The objective of applying an atmospheric correction was to determine true surface reflectance values and to retrieve physical parameters of the Earth's surface, including surface reflectance, by removing atmospheric effects from satellite images. Atmospheric correction is arguably the most important part of the pre-processing of satellite remotely sensed data (Hadjimitsis et al., 2010).

The spectral bands of Sentinel-2 sensor used in the study with their central wavelength and bandwidth and the spatial resolution are presented in the following Table 5.

Table 5. Spectral bands for the Sentinel-2 sensors

Band	Sentinel-2 bands	Sentinel-2A		Sentinel-2B		Spatial resolution (m)
		Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)	
Band 1	Coastal aerosol	442.7	21	442.2	21	60
	Band 2 – Blue	492.4	66	492.1	66	10
Band 3	Green	559.8	36	559.0	36	10
Band 4	Red	664.6	31	664.9	31	10
Band 5	Vegetation red edge	704.1	15	703.8	16	20
Band 6	Vegetation red edge	740.5	15	739.1	15	20
Band 7	Vegetation red edge	782.8	20	779.7	20	20
Band 8	NIR	832.8	106	832.9	106	10
Band 8A	Narrow NIR	864.7	21	864.0	22	20
Band 9	Water vapour	945.1	20	943.2	21	60
Band 10	SWIR – Cirrus	1373.5	31	1376.9	30	60
Band 11	SWIR	1613.7	91	1610.4	94	20
Band 12	SWIR	2202.4	175	2185.7	185	20

3.3.8.2 Cloud Masking

Open-source satellite images from Sentinel-2 MSI level-2A from the USGS or Copernicus website were analyzed using the cloud computing platform, Google Earth Engine (GEE). The Sentinel image was classified as medium resolution since each pixel is approximately 10 m by 10 m in size. Level 2A-processing includes Scene Classification (SCL), which aims at detecting of clouds, snow and cloud shadows and generation of a classification map, which consists of three different classes for clouds (including cirrus), together with six different classifications for shadows, cloud shadows, vegetation, not vegetated, water and snow. During the atmospheric correction process, cloud screening is performed on the data to extract precise atmospheric and surface parameters. The SCL algorithm determines whether there are clouds in an image by looking at the reflecting qualities of scene features. The process is applied to Level-1C products (Top of Atmosphere reflectance) resampled at a spatial resolution of 60 m. A function was created in GEE to mask the pixels in images corresponding to cloud shadows, unclassified and thin cirrus, with no data in Sentinel-2 level-2A images according to the SCL product. It generates a probabilistic cloud mask quality indicator at the end of the processing chain. Median function as a reducer band was applied to aggregate the image collection.

3.3.8.3 Image Visualization

Google Earth Engine (GEE) has a default function Map.add Layer, to visualize a map. If any layer is added to the map without any additional parameters, by default, the Code Editor assigns the first three bands, i.e., red, green, and blue, to the map respectively. Cloud and water pixels were masked out to obtain an atmospherically corrected image. When the equation of MHI developed by Nurdiansah and Dharmawan (2021) was applied in GEE, a single band image appeared as the output image. Based on the pixel values, the output image was segregated in three categories using a split function (Table 4). These categories are used to indicate mangrove quality, like poor, moderate and excellent health state. To visualize the three categories, red, yellow, and green colors were used for poor, moderate and excellent pixel areas. This map was exported in .tiff format, and ArcMap version 10.8 was finally utilized to create a map, which is the final output of utilizing MHI.

4. Results and Discussion

4.1 Floristic composition in the study areas

A total of 304 sample plots has been established in six coastal mangrove sites spread across the coastal belt from the South-West part (Patharghata, Barguna) to the South-East part (Sitakundu, Chottogram) of Bangladesh. Forty-two plant species were identified (Table 6) from the sample plots and adjacent area examined in the coastal regions. A diverse array of 24 tree species, in conjunction with many plant species, is observed within the plots. Numerous major mangrove species, including Sundri (*Heritiera fomes*), Gewa (*Excoecaria agallocha*), Goran (*Ceriops decandra*), Keora (*Sonneratia apetala*), Baen (Avicennia officinalis), and Golpata (*Nypa fruticans*), alongside various herbs, shrub and climber were identified in these coastal regions, creating an environment akin to natural mangrove forests.

Study site wise floristic compositions with their Relative Frequency (RF), Relative Density (RD), Relative Dominance (RDo), and Importance Value Index (IVI) of three stand level, such as tree, sapling and seedling of six study sites are provided in Table 7. In Haringhata Eco-Park, a total of 9 species belonging to 4272 individuals from 40 sample plots has been captured through the systematic sampling design. Among the species, *E. agallocha* has the highest RF, RD, RDo and IVI at tree and sapling level, except second highest RDo at tree level. It has also the highest RF and RD at seedling level. *S. apetala* has the second highest RF, RD and IVI at tree level and has the highest RDo. Therefore, *E. agallocha* is the most dominant species in Haringhata EP.

In Tengragiri Wildlife Sanctuary, 15 speices belonging to 13805 individuals from 60 sample plots has been recorded. *E. agallocha* is the most dominant species in terms of the highest RF, RD, RDo and IVI at tree and sapling level, but has the second highest RF and RD at seedling level (Table 7). *Heritiera fomes* (Sundri) is the second dominant species at tree and sapling level in terms of RF, RD, RDo and IVI. It has the highest regeneration capacity in the sampling area because of the highest RF and RD in the seedling level. *Ceriops decandra* (Goran), *Xylocarpus mekongensis* (Passur), *Cynometra ramiflora* (Singra), *Pongamia pinnata* (Koromcha), *Avicennia officinalis* (Baen) and *S. apetala* are the other dominant species. A matured stand of Raintree (*Samanea saman*) plantation was also found in Tengragiri WS. It is worthy to mention that almost area of Tengragiri WS is densely covered by *Phoenix paludosa* (Hantal). Out-side the sampling plot, some species such as, *Casuarina equisetifolia* (Jhau), *Acacia nilotica* (Babla), *Albizia procera* (Sil koroi), *Sonneratia caseolaris* (Choila), *Erythrina variegata* (Mandar) and *Nypa fruticans* (Golpata) were found along the khals/rivers.

Table 6. List of plant species found in the coastal area of Bangladesh

SL No	Local Name	Scientific Name	Family
1	Amoor	*Aglaia cucullata* Pellegr.	Meliaceae
2	Baen	*Avicennia officinalis* L.	Acanthaceae
3	Bola	*Hibiscus tiliaceus* L.	Malvaceae
4	Bon Lebu	*Merope angulata* (Willd.) Swingle	Rutaceae
5	Choila	*Sonneratia caseolaris* (L.) Engl.	Lythraceae
6	Dakur	*Cerbera odollam* Gaertn.	Apocynaceae
7	Gewa	*Excoecaria agallocha* L.	Euphorbiaceae
8	Goran	*Ceriops decandra* (Griff.) W.Theob.	Rhizophoraceae
9	Holud Kakra	*Bruguiera sexangula* (Lour.) Poir.	Rhizophoraceae
10	Hurmoi/Batul	*Shirakiopsis indica* (Willd.) Esser	Euphorbiaceae
11	Karanj	*Pongamia pinnata* (L.) Pierre	Fabaceae
12	Keora	*Sonneratia apetala* Banks	Lythraceae
13	Khalshi	*Aegiceras corniculatum* (L.) Blanco	Primulaceae
14	Kripa	*Lumnitzera racemosa* Willd.	Combretaceae
15	Lal Kakra	*Bruguiera gymnorhiza* (L.) Lam. ex Savigny	Rhizophoraceae

SL No	Local Name	Scientific Name	Family
16	Nona Jhau	*Tamarix indica* Willd.	Tamaricaceae
17	Nuniya	*Aegialitis rotundifolia* Roxb.	Plumbaginaceae
18	Pani-Kapula	*Dolichandrone spathacea* (L.f.) K.Schum.	Bignoniaceae
19	Passur	*Xylocarpus moluccensis* M.Roem.	Meliaceae
20	Raintree	*Samanea saman* (Jacq.) Merr.	Fabaceae
21	Sada Baen	*Avicennia alba* Blume	Acanthaceae
22	Singra	*Cynometra ramiflora* L.	Fabaceae
23	Sonalu/Lahur	Unidentified	
24	Sundri	*Heritiera fomes* Buch.-Ham.	Malvaceae
25	Baoli lata	*Sarcolobus globosus* Wall.	Apocynaceae
26	Bonpiaz	*Crinum viviparum* (Lam.) R.Ansari & V.J.Nair	Amaryllidaceae
27	Chanda kata	*Dalbergia horrida* var. horrida	Fabaceae
28	Char Kachu	*Cryptocoryne ciliata* (Roxb.) Schott	Araceae
29	Gang Jhapa	*Volkameria inermis* L.	Lamiaceae
30	Gila Lata	*Entada phaseoloides* (L.) Merr.	Fabaceae
31	Golpata	*Nypa fruticans* Wurmb	Arecaceae
32	Hantal	*Phoenix paludosa* Roxb.	Arecaceae
33	Hargoza	*Acanthus ilicifolius* L.	Acanthaceae
34	Jhau	*Casuarina equisetifolia* L.	Casuarinaceae
35	Kalilata	*Brachypterum scandens* (Roxb.) Wight & Arn. ex Miq.	Fabaceae
36	Kewa kanta	*Benstonea foetida* (Roxb.) Callm. & Buerki	Pandanaceae
37	Kutum kanta	*Ticanto crista* (L.) R.Clark & Gagnon	Fabaceae
38	Lata Sundri	*Brownlowia tersa* (L.) Kosterm.	Malvaceae
39	Nicker Bean	*Guilandina bonduc* L.	Fabaceae
40	Pan-nata	*Aganope heptaphylla* (L.) Polhill	Fabaceae
41	Pitali	*Mallotus polycarpus* (Benth.) Kulju & Welzen	Euphorbiaceae
42	Tiger fern	*Acrostichum aureum* L.	Pteridaceae

In Bara Baisdia Coastal Plantation, a total of 11 species belonging to 3276 individuals from 68 sample plots has been enumerated. Among the species, *E. agallocha* has the highest RF, RD, RDo and IVI at sapling level, second highest RF, RD and IVI at tree level and also has the highest RF and RD value at seedling level (Table 7). *S. apetala* has the highest RF, RD and IVI at tree level and has the second highest DR in sapling level. *Sonneratia caseolaris* (Choila) has the third highest RF, RD, RDo and IVI at tree level, but low IVI and RF and RD values at sapling and seedling levels. Therefore, *E. agallocha* is the most dominant species in Bara Baisdia CP based on tree, sapling and seedling levels combinedly, whereas *S. apetala* is the most dominant species at tree level. A total of 14 speices belonging to 3745 individuals from 68 sample plots have been recorded in Char Kukrimukri Wildlife Sanctuary. *E. agallocha* is the most dominant species in terms of the highest RF, RD, RDo and IVI at sapling level, second highest RF, RD, RDo and IVI at tree level and also has the highest RF and RD value at seedling level (Table 7). *S. apetala* has the highest RF, RD and IVI value at tree level. But in sapling stages it has low IVI value and no seedling is found. *Sonneratia caseolaris* (Choila) has the third highest values of RF, RD, RDo and IVI at tree level but has no sapling and lowest RF and RD values. *Dolichandrone spathacea* (Pani Kapula) has the fourth highest RF, RD and IVI value at tree level, but low IVI and, RF and RD values respectively at sapling and seedling levels. *Heritiera fomes* has the third highest IVI value at sapling level, but has low IVI, and RF and RD values respectively at tree and seedling levels. Therefore, *E. agallocha* is also the most dominant species in Char Kukrimukri WS considereing tree, sapling and seedling levels, whereas *S. apetala* is the most dominant species at tree level (Table 7). In Guliakhali Coastal Plantation, a total of 6 species belonging to 529 individuals from 24 sample plots has been recorded. Among the species, *S. apetala* has the highest RF, RDo and IVI at tree level and has the second highest RD. It has no sapling and seedling. On the other hand, *E. agallocha* has the second highest RF, RDo and IVI at tree levels level, but has the highest RD.

Table 7. Relative frequency (RF), Relative Density (RD), Relative dominance (RDo) and Importance value index (IVI) of tree, sapling and Seedling in the coastal area of Bangladesh

Location	Local Name	Species name	Tree				Sapling				Seedling	
			RF	RD	RDo	IVI	RF	RD	RDo	IVI	RF	RD
Haringhata EP	Gewa	*Excoecaria agallocha*	52.70	86.32	29.71	168.73	88.89	99.50	99.62	288.01	63.49	96.15
	Keora	*Sonneratia apetala*	44.59	13.41	70.21	128.22	-	-	-	-	-	-
	Baen	*Avicennia officinalis*	1.35	0.13	0.06	1.55	-	-	-	-	-	-
	Sundri	*Heritiera fomes*	1.35	0.13	0.02	1.50	2.22	0.08	0.06	2.37	1.59	0.04
	Amoor	*Aglaia cucullata*	-	-	-	-	4.44	0.17	0.09	4.70	22.22	2.08
	Dakur	*Cerbera odollam*	-	-	-	-	2.22	0.17	0.09	2.48	4.76	0.65
	Hurmoi	*Shirakiopsis indica*	-	-	-	-	2.22	0.08	0.13	2.44	-	-
	Goran	*Ceriops decandra*	-	-	-	-	-	-	-	-	4.76	0.95
	Bon Lebu	*Merope angulata*	-	-	-	-	-	-	-	-	1.59	0.09
	Bola	*Hibiscus tiliaceus*	-	-	-	-	-	-	-	-	1.59	0.04
Tengragiri WS	Gewa	*Excoecaria agallocha*	31.82	59.79	52.07	143.68	24.29	33.53	37.51	95.32	17.31	11.55
	Sundri	*Heritiera fomes*	24.43	27.62	18.72	70.78	23.81	27.71	26.92	78.44	21.92	58.63
	Keora	*Sonneratia apetala*	4.55	1.19	9.37	15.11	-	-	-	-	0.38	0.20
	Passur	*Xylocarpus moluccensis*	8.52	1.86	3.20	13.59	5.24	1.73	1.94	8.90	6.92	1.14
	Baen	*Avicennia officinalis*	3.98	1.19	8.13	13.30	-	-	-	-	2.31	0.46
	Goran	*Ceriops decandra*	9.09	2.53	0.65	12.27	21.43	23.57	20.41	65.41	20.00	17.89
	Singra	*Cynometra ramiflora*	7.39	2.76	0.84	10.99	11.90	9.90	9.47	31.27	15.00	5.75
	Raintree	*Samanea saman*	1.14	0.60	6.07	7.81	-	-	-	-	-	-
	Karanj	*Pongamia pinnata*	5.11	1.41	0.62	7.14	9.52	2.04	2.33	13.90	5.38	2.17
	Lal Kakra	*Bruguiera gymnorhiza*	1.70	0.22	0.06	1.99	0.48	0.21	0.17	0.86	6.15	0.85
	Amoor	*Aglaia cucullata*	1.14	0.05	0.06	1.34	1.90	0.47	0.25	2.62	3.08	0.78

Location	Local Name	Species name	Tree				Sapling				Seedling	
			RF	RD	RDo	IVI	RF	RD	RDo	IVI	RF	RD
	Sonalu/Lahur	*A*	0.57	0.60	0.17	1.34	0.48	0.58	0.86	1.91	0.38	0.09
	Kripa	*Lumnitzera racemosa*	0.57	0.07	0.03	0.67	-	-	-	-	-	-
	Holud Kakra	*Bruguiera sexangula*	-	-	-	-	0.95	0.26	0.16	1.37	0.38	0.24
	Bon Lebu	*Merope angulata*	-	-	-	-	-	-	-	-	0.77	0.24
Bara-Baisdia CP	Keora	*Sonneratia apetala*	59.26	63.94	92.08	215.28	6.67	0.50	0.65	7.81	5.17	0.14
	Gewa	*Excoecaria agallocha*	23.15	23.00	1.78	47.93	73.33	90.26	91.16	254.76	68.97	96.44
	Choila	*Sonneratia caseolaris*	6.48	8.38	3.71	18.57	2.22	0.17	0.28	2.67	3.45	0.14
	Baen	*Avicennia officinalis*	5.56	1.75	1.08	8.39	-	-	-	-	5.17	0.14
	Lal Kakra	*Bruguiera gymnorhiza*	2.78	2.34	1.28	6.39	-	-	-	-	1.72	0.23
	Goran	*Ceriops decandra*	1.85	0.39	0.05	2.29	6.67	7.26	6.91	20.84	5.17	0.46
	Nona Jhau	*Tamarix indica*	0.93	0.19	0.03	1.15	4.44	0.50	0.07	5.00	3.45	0.14
	Pani-Kapula	*Dolichandrone spathacea*	-	-	-	-	2.22	0.99	0.55	3.76	3.45	2.14
	Khalshi	*Aegiceras corniculatum*	-	-	-	-	2.22	0.17	0.27	2.66	1.72	0.14
	Passur	*Xylocarpus moluccensis*	-	-	-	-	2.22	0.17	0.11	2.50	-	-
	Amoor	*Aglaia cucullata*	-	-	-	-	-	-	-	-	1.72	0.05
Char Kukri-Mukri NP	Gewa	*Excoecaria agallocha*	32.54	53.71	14.73	100.98	85.71	96.95	96.93	279.60	68.75	95.75
	Keora	*Sonneratia apetala*	48.41	28.34	77.91	154.66	2.04	0.12	0.09	2.25	-	-
	Amoor	*Aglaia cucullata*	0.79	1.14	0.10	2.04	2.04	2.23	2.11	6.38	4.69	1.37
	Lal Kakra	*Bruguiera gymnorhiza*	2.38	1.26	0.56	4.20	-	-	-	-	3.13	0.10
	Holud Kakra	*Bruguiera sexangula*	0.79	0.11	0.09	0.99	-	-	-	-	-	-
	Choila	*Sonneratia caseolaris*	7.94	10.63	5.71	24.28	-	-	-	-	1.56	0.05
	Sada Baen	*Avicennia alba*	0.79	0.46	0.29	1.54	2.04	0.12	0.10	2.26	1.56	0.05
	Sundri	*Heritiera fomes*	0.79	0.11	0.02	0.93	4.08	0.35	0.45	4.88	6.25	0.49

Location	Local Name	Species name	Tree				Sapling				Seedling	
			RF	RD	RDo	IVI	RF	RD	RDo	IVI	RF	RD
	Hurmoi	*Shirakiopsis indica*	0.79	0.11	0.02	0.92	2.04	0.12	0.07	2.22	1.56	0.05
	Passur	*Xylocarpus moluccensis*	0.79	0.11	0.08	0.99	-	-	-	-	-	-
	Pani-Kapula	*Dolichandrone spathacea*	3.17	3.89	0.49	7.55	2.04	0.12	0.24	2.40	7.81	1.51
	Karanj	*Pongamia pinnata*	-	-	-	-	-	-	-	-	1.56	0.15
	Nona Jhau	*Tamarix indica*	-	-	-	-	-	-	-	-	1.56	0.24
	Raintree	*Samanea saman*	-	-	-	-	-	-	-	-	1.56	0.24
	Bola	*Hibiscus tiliaceus*	0.79	0.11	0.01	0.92	-	-	-	-	-	-
Guliakhali CP	Keora	*Sonneratia apetala*	48.39	30.89	82.25	161.53	-	-	-	-	-	-
	Gewa	*Excoecaria agallocha*	32.26	52.85	9.63	94.73	66.67	97.29	96.87	260.83	52.63	85.25
	Baen	*Avicennia officinalis*	19.35	16.26	8.12	43.73	5.56	0.49	0.43	6.48	2.63	1.13
	Nona Jhau	*Tamarix indica*	-	-	-	-	16.67	0.74	1.02	18.42	15.79	5.77
	Goran	*Ceriops decandra*	-	-	-	-	5.56	0.99	0.76	7.30	18.42	7.56
	Holud Kakra	*Bruguiera sexangula*	-	-	-	-	5.56	0.49	0.92	6.97	-	-
	Lal Kakra	*Bruguiera gymnorhiza*	-	-	-	-	-	-	-	-	5.26	0.18
	Nuniya	*Aegialitis rotundifolia*	-	-	-	-	-	-	-	-	5.26	0.12
Nijhum Dwip NP	Gewa	*Excoecaria agallocha*	43.75	75.07	22.66	141.48	93.33	99.68	99.60	292.61	80.77	99.28
	Keora	*Sonneratia apetala*	41.67	19.73	67.49	128.89	-	-	-	-	-	-
	Baen	*Avicennia officinalis*	14.58	5.19	9.85	29.63	6.67	0.32	0.40	7.39	19.23	0.72

In Nijhum Dwip National Park, a total of 3 species belonging to 1602 individuals from 44 sample plots has been recorded. Among the species, *E. agallocha* has the highest RF, RD and IVI at tree and sapling levels and also the highest RF and RD at seedling level. *Sonneratia apetala* has the second highest RF, RD and IVI at tree level tree level but has the highest RDo at the same level. It has no individual in the sapling and seedling level (Table 7).

Upon evaluating RF, RD, RDo, and IVI values across three tree size classes (tree, sapling, and seedling) of coastal mangrove species, *Excoecaria agallocha* emerges as the most dominant and abundant species within the study sites. Conversely, *Sonneratia apetala* also ranks as the most dominant species in terms of the highest RDo (basal area) exclusively at the tree level in the majority of the sites. *S. apetala* is entirely absent in the understory at sapling and seedling stages. Among the six study locations, Tengragiri WS is entirely a natural patch akin to the Sundarbans mangrove forest, where *Heritiera fomes* ranks as the second most dominant species followed by *Excoecaria agallocha*. Similarly, the coexistence of *H. fomes* with other true mangrove and associated species among a dense proliferation of *Acanthus ilicifolius* (Hargaza) in Char Kukrimukri WS rendered the region natural. The dominance and abundance of *E. agallocha*, along with the absence of *Heritiera fomes*, categorizes some sites like Bara Baisdia CP as young forest. The Bangladesh Forest Department has utilized *Excoecaria agallocha* in conjunction with *Sonneratia apetala* in coastal plantations, which may contribute to their preeminence in these regions. The growing prevalence of *Excoecaria agallocha* in coastal regions, including the Sundarbans, may affect the whole ecology. It may surpass other mangrove species, such as *Heritiera fomes*, perhaps resulting in less biodiversity and impacting the extensive array of ecological services provided by mangroves.

4.2 Mangrove diversity indices

4.2.1 Species richness and diversity

Species richness has been a widely used parameter for diversity measurement, mostly because it is usually the straightforward assessment based on information available. Diversity depends on species richness and evenness (Magurran, 1988). Many ecologists listed values of Shannon's index (H'), the Equitability index (J'), and Simpson's Diversity Index (1-D') in the reports of tree species diversity. As shown in Table 8, the values of diversity indices for tree, sapling, seedling, and total stand are ranging from 0.16 to 0.60 for H', from 0.02 to 0.30 for J', and from 0.01 to 0.24 for 1-D' in Haringhata EP; from 1.71 to 2.20 for H', from 0.46 to 0.66 for J', and from 0.56 to 0.74 for 1-D' in Tengragiri WS; from 0.29 to 1.48 for H', from 0.46 to 0.66 for J', and from 0.09 to 0.53 for 1-D' in Bara Baisdia CP; from 0.24 to 1.77 for H', from 0.09 to 0.49 for J', and from 0.06 to 0.62 for 1-D' in Char Kukrimukri WS; from 0.03 to 0.99 for H', from 0.03 to 0.63 for J', and from 0.01 to 0.39 for 1-D' in Nijhum Dwip EP and from 0.23 to 2.201.44 for H', from 0.10 to 0.91 for J', and from 0.05 to 0.60 for 1-D' in Guliakhali CP.

Table 8. Diversity indices at different stand levels in coastal areas.

Study Sites	Stand level	Species Richness	H'	J'	1-D'
Haringhata EP	Tree	4	0.60	0.30	0.24
	Sapling	5	0.16	0.02	0.01
	Seedling	7	0.30	0.11	0.07
	Total	10	0.36	0.11	0.09
Tengragiri WS	Tree	13	1.71	0.46	0.56
	Sapling	10	2.20	0.66	0.74
	Seedling	13	1.90	0.51	0.61
	Total	15	2.05	0.53	0.67
Bara-Baisdia	Tree	7	1.48	0.53	0.53
	Sapling	8	0.60	0.20	0.18
	Seedling	10	0.29	0.09	0.07
	Total	11	0.93	0.27	0.28
Char Kukrimukri WS	Tree	12	1.77	0.49	0.62
	Sapling	7	0.24	0.09	0.06
	Seedling	11	0.36	0.10	0.08
	Total	15	0.89	0.23	0.25
Guliakhali	Tree	3	1.44	0.91	0.60
	Sapling	5	0.23	0.10	0.05
	Seedling	6	0.82	0.32	0.26
	Total	8	0.87	0.29	0.26
Nijhum Dwip EP	Tree	3	0.99	0.63	0.39
	Sapling	2	0.03	0.03	0.01
	Seedling	2	0.06	0.06	0.01
	Total	3	0.27	0.17	0.07

Note: H'= Shannon Diversity Index, J'= Pielou's Evenness Index, 1-D'= Simpson's Diversity

Species diversity (*H', J', and 1-D'*) of mangrove communities throughout the six study sites in the coastal region has been observed to be moderate and low respectively at the tree level, and at sapling and seedling levels, with the exception of Tengragiri WS, where species diversity is high at all stand levels (Table 8). Because low and moderate species richness and evenness values contribute low and moderate species diversity, and high species richness and evenness values contribute high species diversity.

It is well known that Simpson's index is heavily weighted towards the most abundant species in the sample, while it is less sensitive to species richness (Lande et al., 2000). Shannon's index is more sensitive to species richness than Simpson's index. It is found that Simpson's index produced values that have less variation when the sample size is small or species richness is low. Therefore, a satisfactory result can be obtained using Shannon's index for comparative

studies. As the study area is small and species richness is low (2 -15), the application of Shannon's index and Pielou's Equitability index is more appropriate than Simpson's index. Moreover, H' and J' are linked in the form: $H' = J' \times \log_2 S$. This form follows to the general concept of the measurement of species diversity where species diversity depends on the number of species and evenness. Therefore, low or medium species richness and low or moderate evenness value made low or moderate species diversity for all stand levels in the coastal mangrove areas. It may be stated that a trend of low to moderate mangrove species diversity is present in the coastal plantation forest, but high mangrove species diversity is observed in the natural forests of coastal areas, such as the Tengragiri Wildlife Sanctuary.

4.3 Stand dynamics of coastal mangroves

4.3.1 Density and Basal area of mangrove species for different size classes

The density and basal area of different tree forms are calculated for six coastal regions, shown in Table 9. A systematic sampling design has captured a total of 10 species belonging to 10650.00 individuals/ha from Haringhata EP, 15 species belonging to 22475.00 individuals/ha from Tengragiri WS, 11 species belonging to 4870.59 individuals/ha from Bara Baisdia CP, 14 species belonging to 5552.94 individuals/ha from Char Kukrimukri WS, 3 species belonging to 11815.91 individuals/ha from Nijhum Dwip National Park and 8 species belonging to 9208.33 individuals/ha from Gulia Khali Coastal Plantation.

Table 9. Density and Basal area of different tree forms in in coastal mangrove sites

Study Sites	Class	Density (Individuals/ha)	Basal Area (m^2/ha)
Haringhata EP	Tree	1882.50	38.44
	Sapling	2985.00	2.64
	Seedling	5782.50	
	Total	10650.00	41.08
Tengragiri WS	Tree	2238.33	28.59
	Sapling	3181.67	2.60
	Seedling	17055.00	
	Total	22475.00	31.19
Bara-Baisdia CP	Tree	754.41	40.06
	Sapling	891.18	0.71
	Seedling	3225.00	
	Total	4870.59	40.77
Char Kukrimukri WS	Tree	1286.76	42.51
	Sapling	1254.41	0.99
	Seedling	3011.76	
	Total	5552.94	43.50

Study Sites	Class	Density (Individuals/ha)	Basal Area (m^2/ha)
Guliakhali CP	Tree	512.50	10.38
	Sapling	1691.67	1.41
	Seedling	7004.17	
	Total	9208.33	11.78
Nijhum Dwip NP	Tree	1531.82	31.93
	Sapling	2109.09	1.83
	Seedling	8175.00	
	Total	11815.91	33.76

The density (Individuals/ha) of trees, saplings, seedlings, and overall stand is highest in Tengragiri WS compared to the other five study sites (Table 9). The density of seedlings surpasses that of the other two tree forms across the study locations, particularly exhibiting a significant increase in Tengragiri WS. The ecological niche at Tengragiri Wildlife Sanctuary sustains a greater diversity of mangrove plant species with a higher density (individuals/ha) compared to the other sites. The density trend progressively diminishes from the lower to the upper tree classes (seedling to tree) throughout six study locations, a typical characteristic of a stable forest.

The basal area varies from 10.38 to 42.51 m^2/ha for trees and from 0.71 to 2.64 m^2/ha for saplings in the study sites (Table 9). The maximum and minimum basal areas at both tree and whole stand levels were observed in Char Kukrimukri WS and Guliakhali CP, respectively (Table 9). The maximum and minimum basal areas at the sapling level were observed in Haringhata EP and Tengragiri WS, and in Bara Baisdia CP, respectively.

4.3.2 Diameter and height distributions of mangrove species

The diameter and height distribution of mangrove species across the six study sites were analyzed for species with a diameter of 2 cm or greater. In diameter distribution, *Sonneratia apetala* exhibits a greater median DBH relative to other species, while *Avicennia officinalis* demonstrates a significant variation in DBH (Figure 5). *Sonneratia apetala, Excoecaria agallocha, and Heritiera fomes* exhibit multiple potential outliers with high DBH.

The distribution of tree diameters for major species in the study locations is shown in Figure 6. The greatest quantity of *Excoecaria agallocha* was seen within the diameter class of 5-10 m throughout all coastal sites. The majority of *Sonneratia apetala* species had diameters ranging from 20 to 45 cm throughout the study sites. The highest number of *Heritiera fomes* was identified within the diameter class of 5-10 m in Tengragiri WS. A substantial quantity of *Sonneratia caseolaris* was identified in Bara Baisdia CP and Char Kukrimukri WS, namely within a diameter class range of 5-30 cm. A considerable quantity of *Avicennia officinalis* was identified within the diameter class of 20-30 cm in Nijhum Dwip EP and Guliakhali CP.

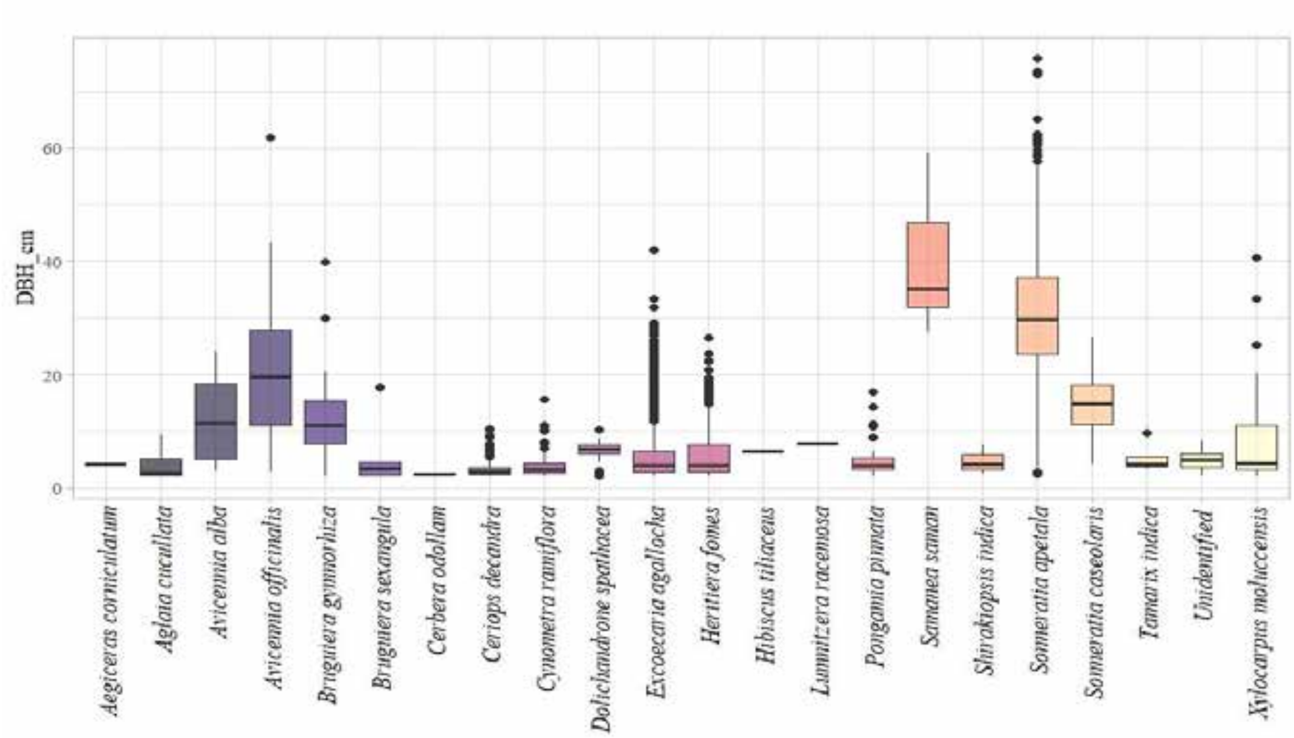


Figure 5. Diameter distribution of different species in coastal mangrove sites

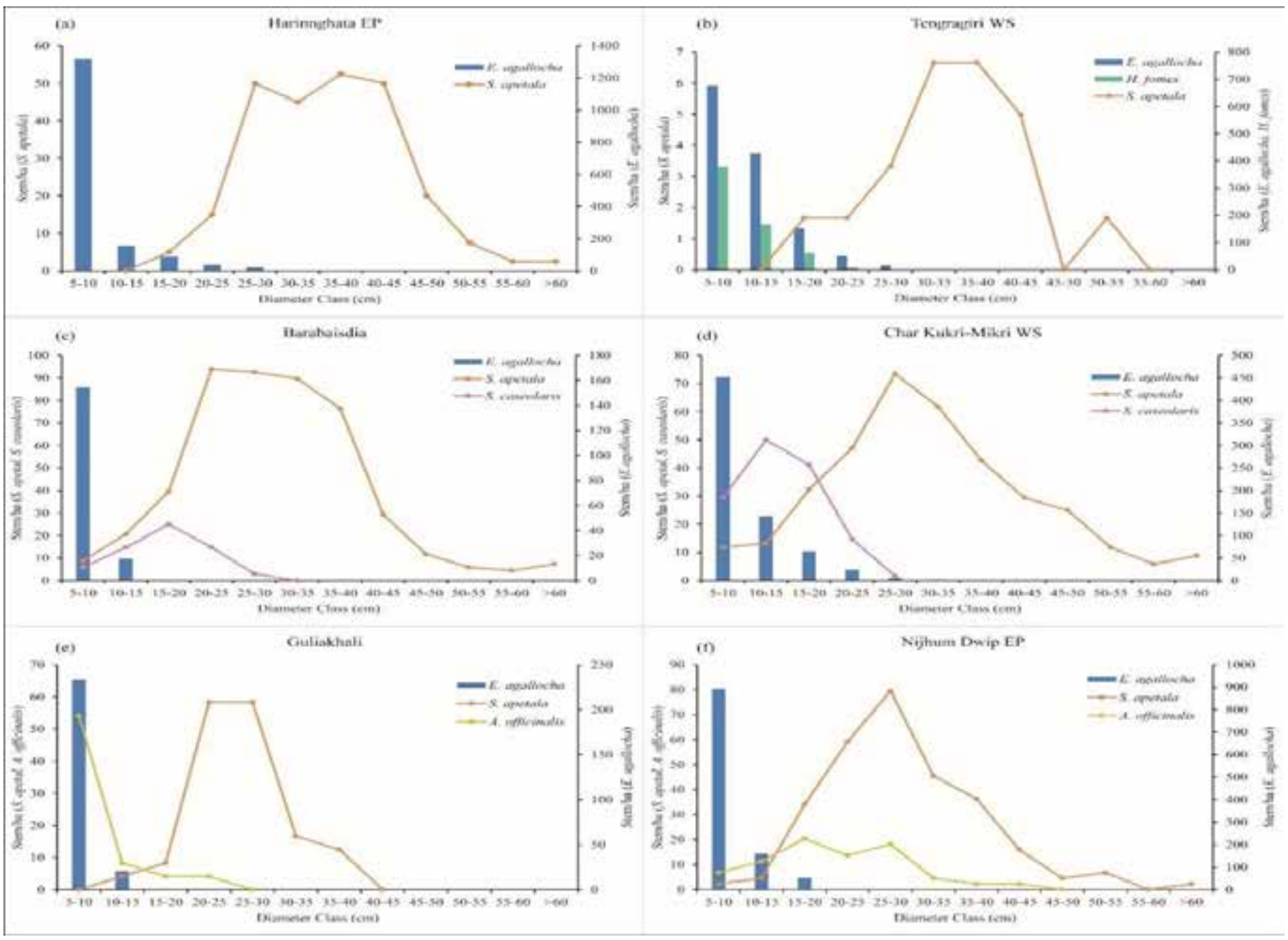


Figure 6. Tree diameter distribution of major species in coastal mangrove study sites (a) Haringhata EP, (b) Tengragiri WS, (c) Barabaisdia CP, (d) Char Kukri-Mukri WS, (e) Guliakhali CP and (f) Nijhum Dwip EP. In terms of height distribution, *Sonneratia apetala* appears to have a generally higher median height compared to other species, and it also shows a considerable spread in height (Figure 7). *Excoecaria agallocha,* and *Heritiera fomes* show several potential outliers with high height.

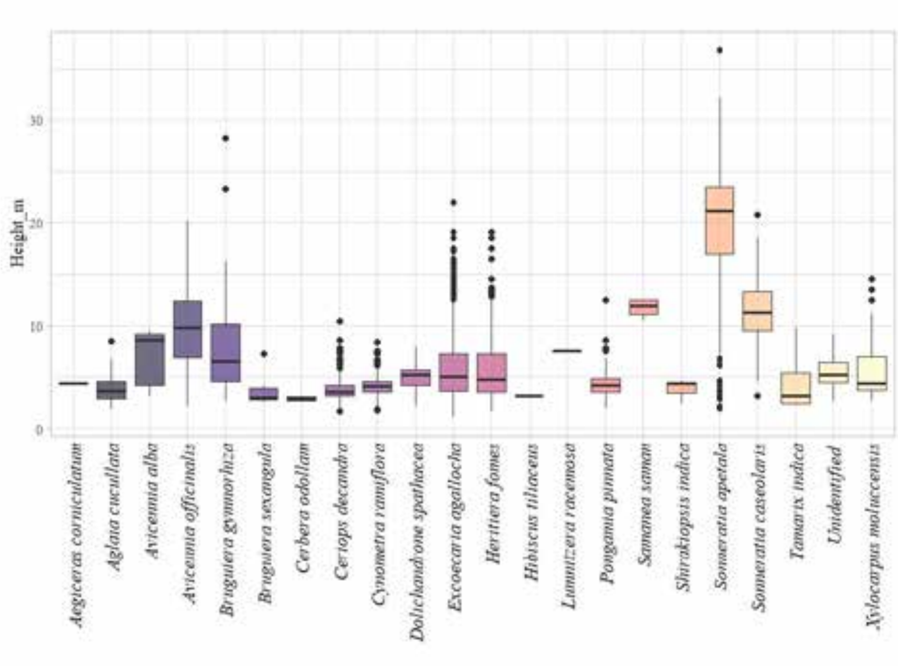


Figure 7. Height distribution of different species in coastal mangrove sites

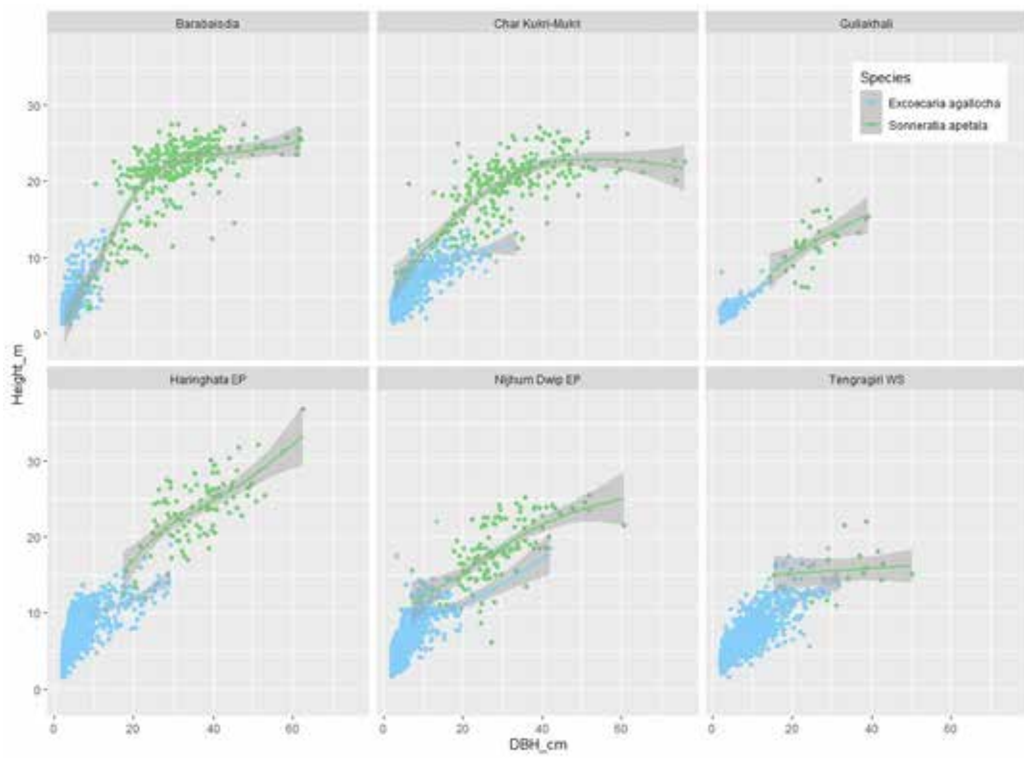


Figure 8. Diameter height relationship of *Sonneratia apetala* and *Excoecaria agallocha* in coastal mangrove sites

The diameter-height relationship of *Sonneratia apetala* and *Excoecaria agallocha* across six coastal sites reflects their distinct growth patterns in these environments (Figure 8). *Sonneratia apetala* typically exhibits a strong positive correlation between diameter and height, with taller trees associated with larger diameters, especially in nutrient-rich, waterlogged soils. In contrast, *Excoecaria agallocha* often shows a more variable relationship, with slower height growth relative to diameter, likely due to its adaptation to saline and stressful conditions. The variability in the diameter-height relationship across sites may be influenced by local factors such as soil salinity, tidal inundation, and competition, with *S. apetala* generally achieving greater heights in favorable conditions, while *E. agallocha* may prioritize lateral growth (diameter) as a survival strategy in harsher environments.

4.3.3 Canopy coverage

Analysis of the percent canopy coverage can represent the mangrove community's health (Dharmawan & Pramudji, 2017). As a foliage dominated structure, canopy coverage can also describe the productivity of mangrove community, light penetration level and forest gap that affects seedling growth in a certain area. The percentage of canopy cover is a two-dimensional projection of the canopy's length and width which has been categorized in to three states (Table 10).

Table 10. State of canopy coverage

Canopy coverage	State
< 50	Poor
50 - <75	Moderate
>= 75	Excellent

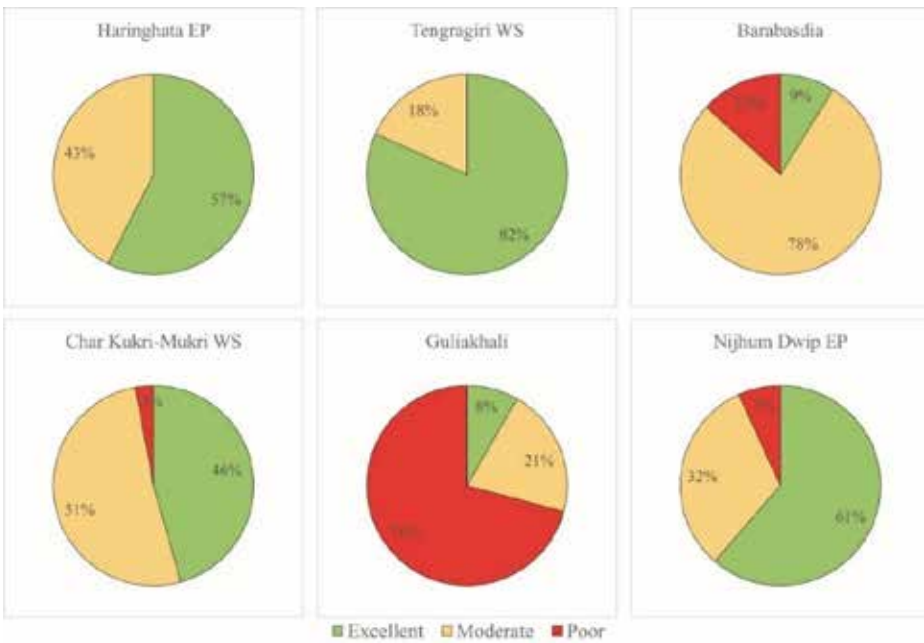


Figure 9. Status of Canopy coverage in six study sites of coastal plantation

Canopy coverage at six coastal locations has been categorized into three classifications: excellent, moderate, and poor, expressed in percentages (Figure 9). Exceptional canopy coverage was seen in Tengragiri WS (82%), succeeded by Nijhum Dwip EP (61%) and Haringhata EP (57%). A moderate level of canopy coverage was seen in Barabasdia (78%), followed by Charkukri-Mukri (51%) and Haringhata EP (43%). The poorest canopy coverage was recorded in Guliakhali CP, at 71%. No poor conditions in canopy covering were noted in Haringhata EP and Tengragiri WS. The Tengragiri Wildlife Sanctuary exhibited high species richness and diversity (Table 8). Consequently, it may be inferred that superior canopy covering may positively correlate with high species richness and diversity within the entire coastal mangrove community.

4.3.4 Above-Ground Biomass (Mg/ha) and Volume (m^3/ha) of different species

Among all the species found in six sites, *Sonneratia apetala* contains the highest Above-Ground Biomass (Mg/ha) and Volume (m^3/ha) in Haringhata EP, Bara Baisdia CP, Char Kukrimukri WS, Nijhum Dwip EP, and Guliakhali (Figures 10 and 11).

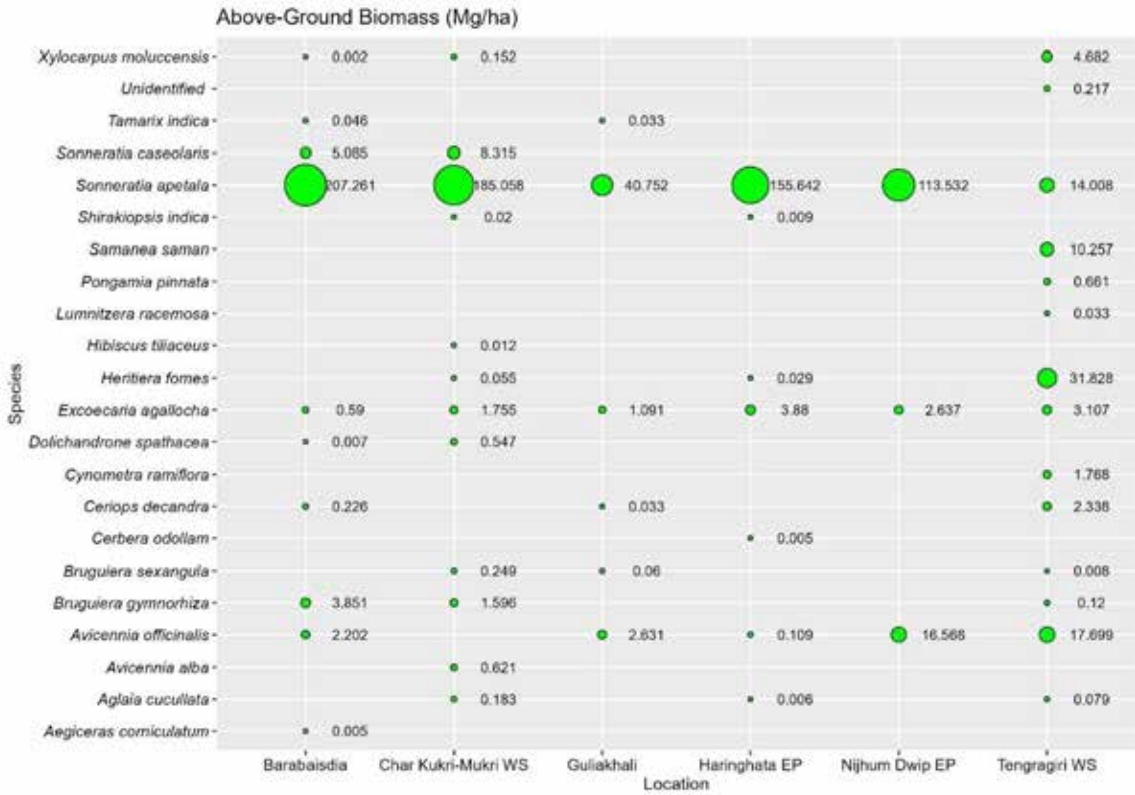


Figure 10. Above-Ground Biomass (Mg/ha) of different species in coastal mangrove sites

Sonneratia apetala typically exhibits very high above-ground biomass, especially in Barabaisdia CP, Char Kukri-Mukri WS, Haringhata EP, and Nijhum Dwip EP, with values of 207.26, 185.06, 155.64, and 113.53 Mg/ha, respectively (Figure 10). *Heritiera fomes* shows substantial above-ground biomass in Tengragiri WS, whereas *Avicennia officinalis* also has considerable above-ground biomass in both Tengragiri WS and Nijhum Dwip EP. Other species exhibit minimal or negligible above-ground biomass in specific places, as denoted by small circles or the lack thereof. The biomass distribution significantly varies among diverse places and species, underscoring the ecological disparities between various regions.

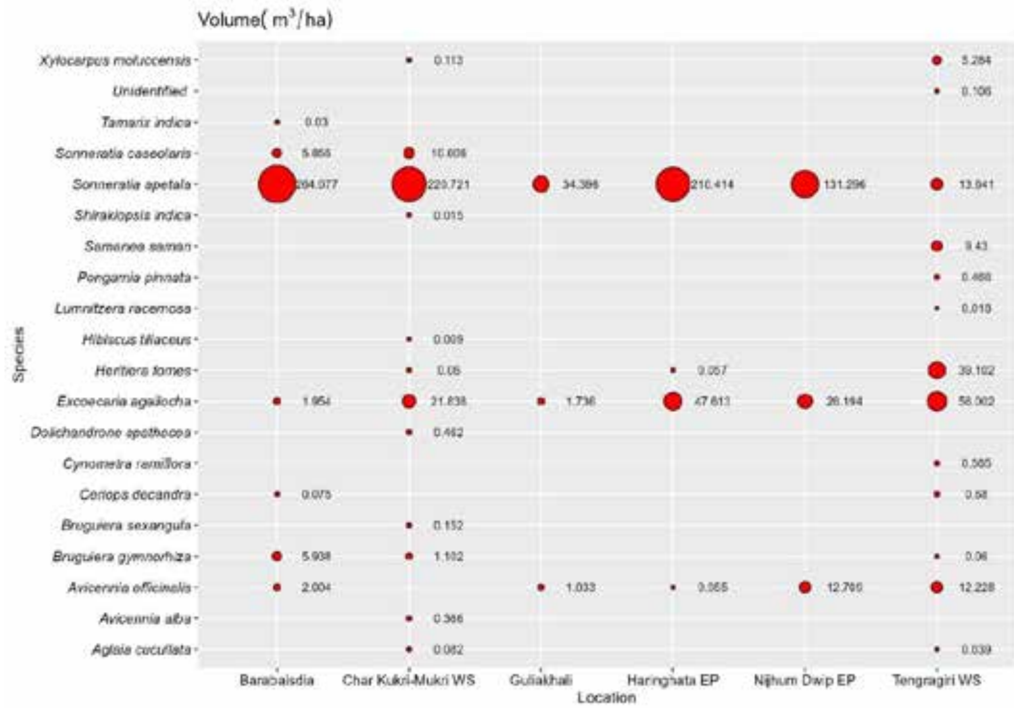


Figure 11. Volume (m^3/ha) of different species in coastal mangrove sites

Sonneratia apetala typically showed very high volume, especially in Barabaisdia CP, Char Kukri-Mukri WS, Haringhata EP, and Nijhum Dwip EP, with values of 264.08, 220.72, 210.41, and 131.30 m^3/ha, respectively (Figure 11). *Heritiera fomes* shows substantial volume in Tengragiri WS, whereas *Excoecaria agallocha* also has considerable volume in both Tengragiri WS and Haringhata EP. Many other species exhibit minimal or negligible volume in specific places, as denoted by small circles or the lack thereof. The volume distribution significantly varies among diverse places and species, underscoring the ecological disparities between various regions.

4.4 Mangrove Community Health

4.4.1 Mangrove Forest Healthiness in the coastal region

The android-based applications for mangrove monitoring system, MonMang can conduct analysis and interpretation of mangrove health utilizing the Mangrove Health Index (MHI) (eq. 4) established by Dharmawan and Ulumuddin (2020). Using the sample data of MHI_F1, Mangrove community health has been explained for six study sites into state 3 category (Table 4 and, Figures 12) and the results showed that 74 (24%), 213 (70%) and 17 (6%) plots out of 304 plots have excellent, moderate and poor mangrove health, respectively. Among the study sites, excellent mangrove health was found in 33 plots (55%) out of 60 plots in Tengragiri WS (Figure 12). Most of the plots (70%) across the six study sites were under Moderate health condition. Bara Baisdia CP, Char Kukri-Mukri WS and Guliakhali CP have very few plots containing poor health. Haringhata EP, Tengragiri WS and Nijhum Dwip NP have no plots having poor mangrove health. It can be concluded that mangrove community in Tengragiri WS is healthiest site in the study areas.

No. of Plots

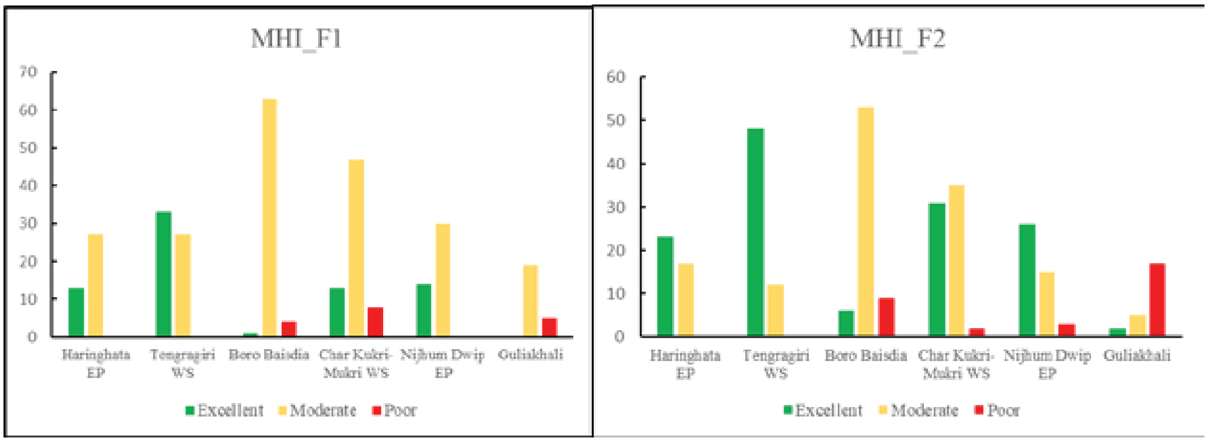


Figure 12. Mangrove Health Status in the six study sites using MHI_F1 and MHI_F2

Conversely, utilizing the sample data and the application of the created MHI_F2 (Equation 5) from this study, 136 (45%), 137 (45.5%), and 31 (10.5%) plots out of 304 exhibit excellent, moderate, and poor mangrove health, respectively, throughout the six study sites. Among the study locations, superior mangrove health was seen in 48 plots (67%) out of 60 in Tengragiri Wildlife Sanctuary, followed by Nijhum Dwip Ecological Park (59%) and Char Kukri-Mukri Wildlife Sanctuary (46%) (Figure 12). The majority of the plots at the six study sites exhibited intermediate health conditions. Guliakhali CP exhibited the lowest mangrove health at 71%, while other locations displayed minimal plots with poor health. Haringhata EP and Tengragiri WS lack plots exhibiting poor mangrove health. The mangrove community in Tengragiri WS is the healthiest site among the studied locations.

4.4.2 Development of Mangrove Health Index Model using Google Earth Engine

4.4.2.1 Mangrove Health Index

The Mangrove Health Index (MHI) is a widely recognized method for evaluating mangrove forest health. This index incorporates parameters such as canopy cover, stem diameter, and sapling density to determine the overall condition of mangrove ecosystems. MHI values can be derived through field data collection and estimated using remote sensing data, such as Sentinel-2A imagery (Schaduw et al., 2021). The assessment of mangrove health through satellite data involves vegetation indices, including the Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure-Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI) (Hidayah et al., 2023). The Mangrove Health Index developed by Dharmawan and Ulumuddin (2020) is described as MHI_1 where the field health index was estimated by MHI_F1.

In this study, the canopy, mean diameter of tree and sapling and sapling density were converted to MHI_F1. All the bands' values from Sentinel2 were used to estimate the NBR, GCI, SIPI and ARVI and finally MHI_1 were calculated. The linear regression model between these two does now show significant relation with $R^2 = 0.25$. The 1:1 plot between these two variables also explain poor relation between original and predicted value with model efficiency $R^2 = 0.13$ (Figure 13). Furthermore, the MHI_1 values were categorized into three classes i.e., Poor, Moderate and Excellent according to their value. The classes are then presented in the map in Google Earth Engine (GEE) platform (Figure 14). From the map, it was observed that all the sites are dominated by moderate class with fewer excellent and poor class. The presence of poor class at the edge of all site represents poor health condition of mangrove plantation. This might happen due to the high anthropological intervention at the edge because of its accessibility. This may be further accelerated with the effect of cyclone and high wind. From the vegetation structure, it was observed that the moderate class are not as much as observed in the map. There were high number of excellent area but not presented any one of the study sites. The result of accuracy assessment (Table 11) reveals the poor overall accuracy (66.12%) and very poor Kappa Coefficient (0.07) in comparison of field estimated mangrove health index class (MHI_F1) and mangrove health index class by model (MHI_1). That indicates the MHI_1 model is not suitable for the coastal mangrove vegetation of Bangladesh.

This model was developed with the data of Indonesian mangrove forest which are dominated by *Ceriops tagal*. Whereas, the coastal mangrove forest of Bangladesh is dominated by *Sonneratia apetala* and *Excoecaria agallocha*. The structure, canopy, undergrowth, sapling density, diameter distribution of coastal mangrove of Bangladesh are completely different from the mangrove of Indonesia. That may be the reason we did not have a good association between the MHI_1 model and the forest structure of Bangladesh. Furthermore, the differences in species composition may lead the differentiation of the reflectance value of Indonesian forest and Bangladesh forest and hence the NBR, GCI, SIPI and ARVI value.

In consideration of this, a new MHI model has been created to improve monitoring of Bangladesh's coastal mangrove forests. For field MHI several structural variables of vegetation were examined (Table 2) to fit with different vegetation index of satellite band composition of Sentinel 2. The vegetation indices and the band of the Sentinel2 satellite are presented in Table 3 and Table 5.

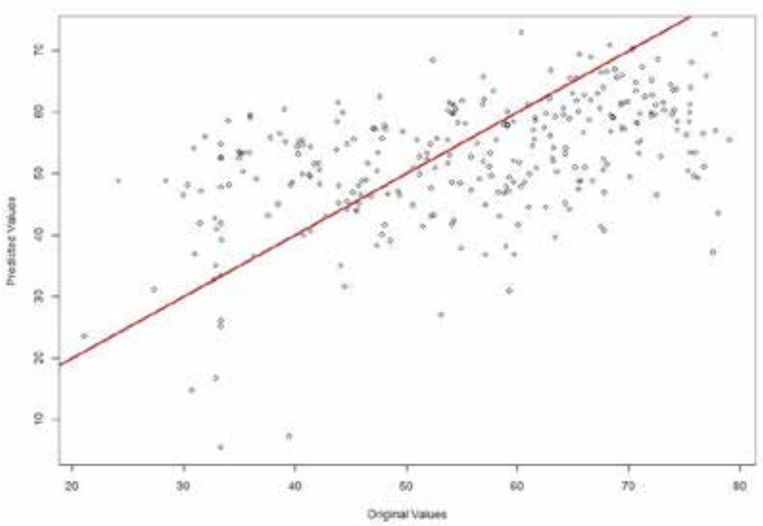


Figure 13. 1:1 plot of the original value estimated from field observation (MHI_F1) and Predicted value obtained from the model equation MHI_1

Here one thing is noticeable that among the equations used to fit MHI_1 NBR and ARVI are not same used to develop the new MHI model. The NBR = (NIR-SWIR)/(NIR+SWIR) used SWIR1 of sentinel2 Band-11 that is actually known as NDWI. In NBR the second SWIR2 is generally used that was named as NBR2 in this report. Another anomaly in Atmospherically Resistant Vegetation Index (ARVI) is that the equation was proposed by Kaufman and Tanre (1992) can be generalized as (NIR-2xRed+Blue)/(NIR+2xRed-Blue) but in most of the literature incorrectly use the formula generalized as (NIR-2xRed+Blue)/(NIR+2xRed+Blue). This small change in (+Blue) in denominator may lead a huge change in total model value. But in this study, we used NBR and ARVI in using MHI_1 as same as Nurdiansah and Dharmawan (2021) suggested and for the new MHI the vegetation indices of Table 3 were used.

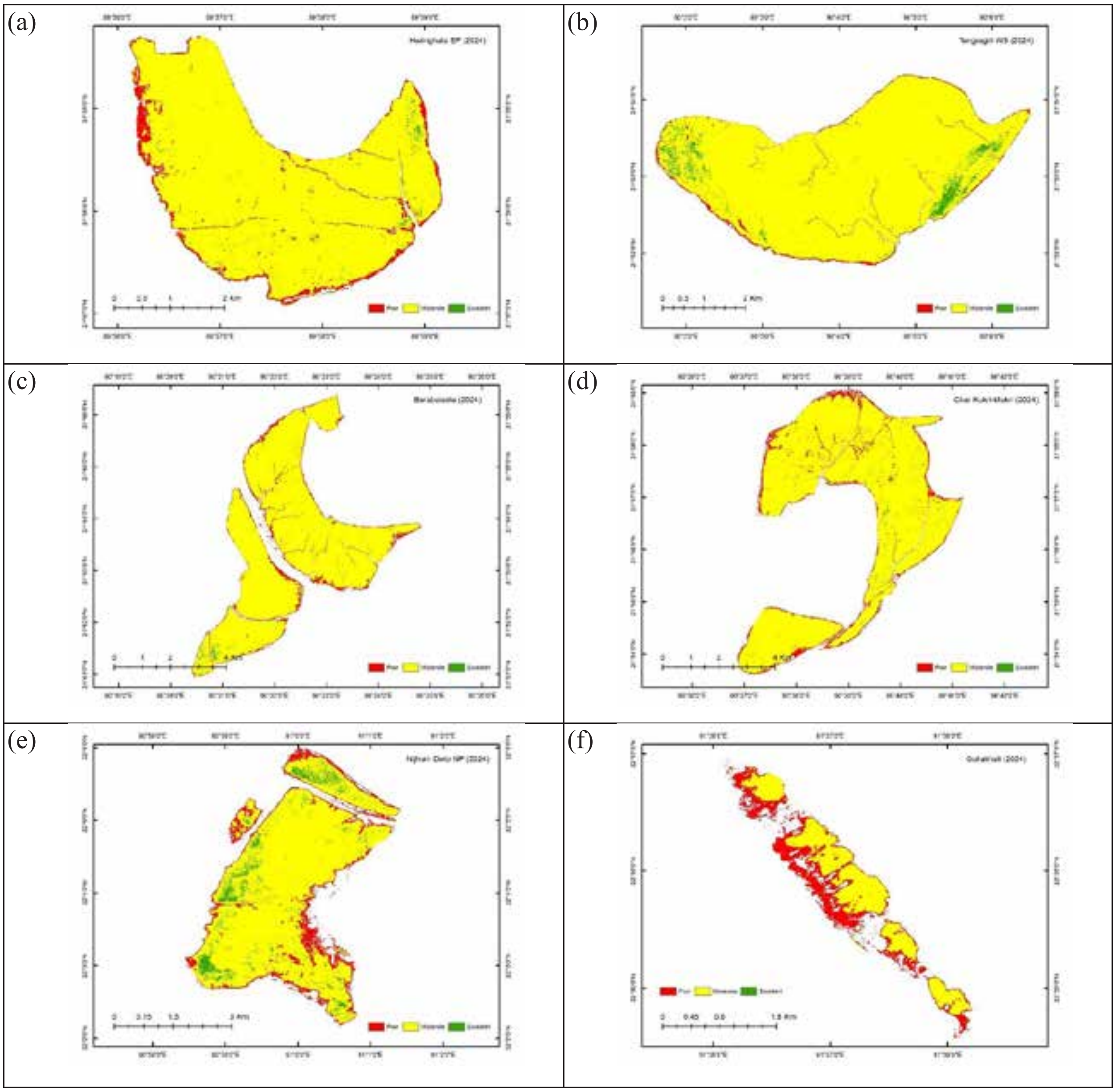


Figure 14. MHI_1 map with poor, moderate and excellent class in different coastal site of Bangladesh (a) Haringhata EP (b) Tengragiri WS (c) Barabaisdia (d) Char Kukri-Mukri WS (e) Nijhum Dwip NP and (f) Guliakhali.

Table 11. Error matrix of MHI_F1 and MHI_1 classification

	Poor	Moderate	Excellent	total	User's Accuracy%
Poor	5	12	0	17	29.41
Moderate	19	190	4	213	89.20
Excellent	0	68	6	74	8.11
total	24	270	10	304	
Producer Accuracy %	20.83	70.37	60		
Overall accuracy %	66.12				
Kappa Coefficient	0.07				

4.4.2.2 Selecting vegetation structure variables

Principal component analysis was performed with the variables described in Table 2 combined with all study sites (Haringhata EP, Tengragiri WS, Barabaisdia, Char Kukri-Mukri WS, Guliakhali and Nijhum Dwip EP) of coastal mangrove plantation of Bangladesh. The biplot of this first two dimensions describe at least three grouping of variables with high correlation (Figure 15). The scree plot of first 10 principal components of 15 variables showed 41.5% variability in first principal component and the second one can explain 19.7% variability (Figure 16). Combinedly, the first and second principal component can explain 61.2% variability of the data set. The ntot, Basp and nsp are highly correlated and show higher variability in dimension 1. Dt_mean and Dtot_mean are also correlated and show higher variability in dimension 1. Another grouping is also observed in dimension 2 with the Batot and Bat. Canopy percentage (C) is another important variable having higher variability in both the dimension 1 and dimension 2 and is not significantly correlated with other variables. Other variables e.g., Dmax, Dmin, nt, nsd, G and S do not show significant variability in first two dimensions. The correlation within the variables is observed in the correlation matrix (Figure 16).

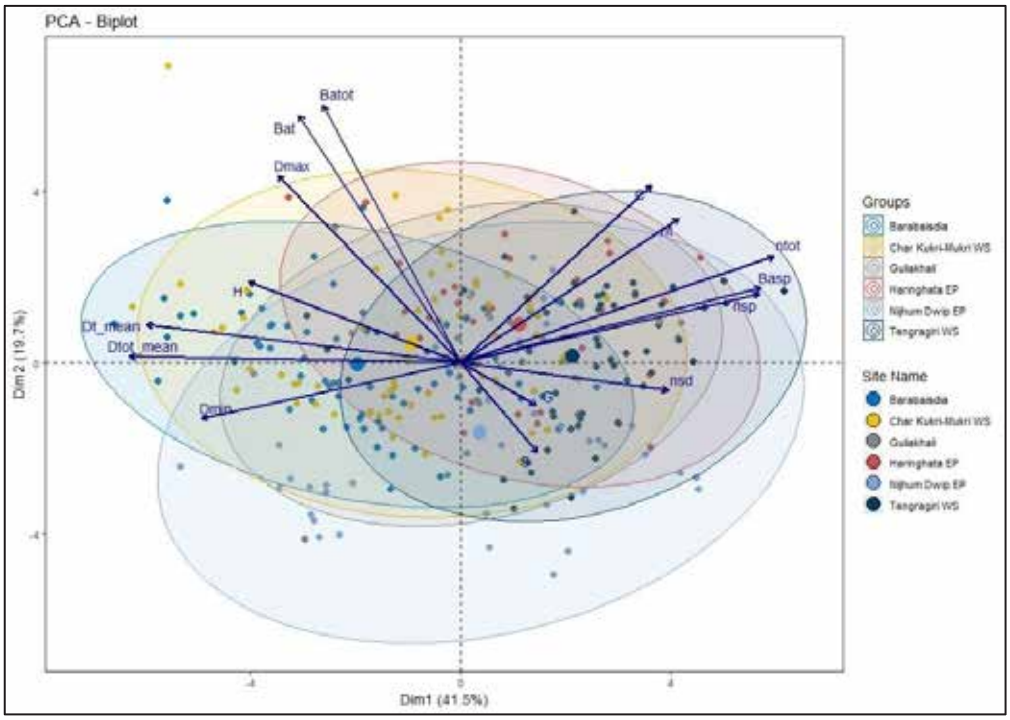


Figure 15. PCA biplot for Dim1 and Dim2 of vegetation structure variables

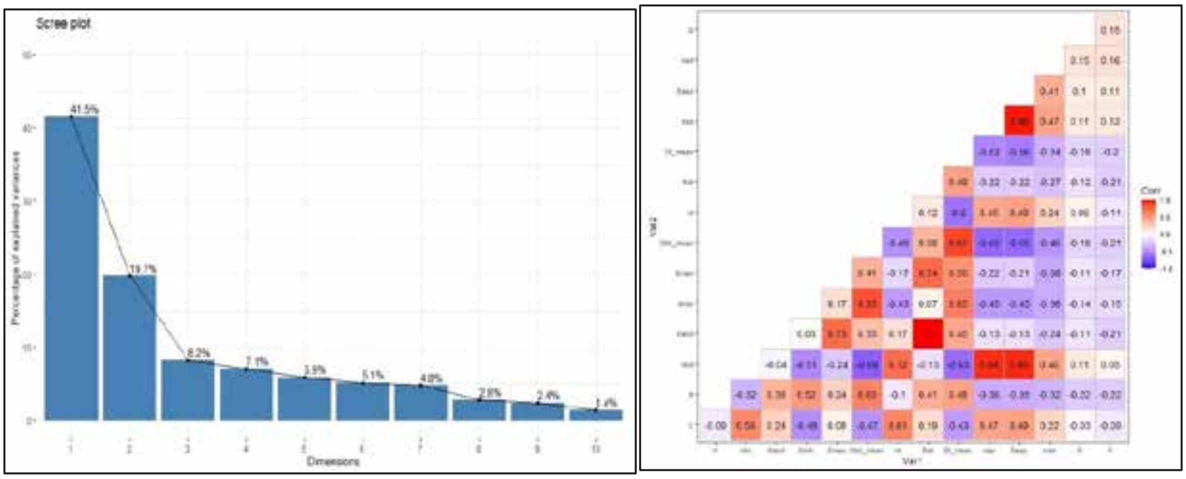


Figure 16. Scree plot of PCA and correlation matrix for vegetation structure variables

From each grouping of the variables one variable has been chosen. We have performed different combination of variables from the four grouping and finally chosen C, nsp, dt_mean and Batot as important variables to describe the vegetation structure as a single matrix. The four variables are same as the variables chosen for MHI_F1 except the inclusion of Batot. Unfortunately, the addition of Batot did not significantly improve the single matrix of field mangrove health index and finally the variable was dropped. The same matrix of MHI_F1 = SC+SD+Snsp was then adopted for determining the model MHI_2 with different vegetation indices of Table 3. Moreover, from the analysis of variables, we found only the score of canopy percentage with a different scoring algorithm (Figure 17) is highly associated with the vegetation indices and denoted as MHI_F2.

$MHI\_F2 = -0.0000888889C^3 + 0.02*C^2 - 0.1111111111C$ ……………………………….(5)

The model developed with the MHI_F2 and vegetation indices are named as MHI_3 model.

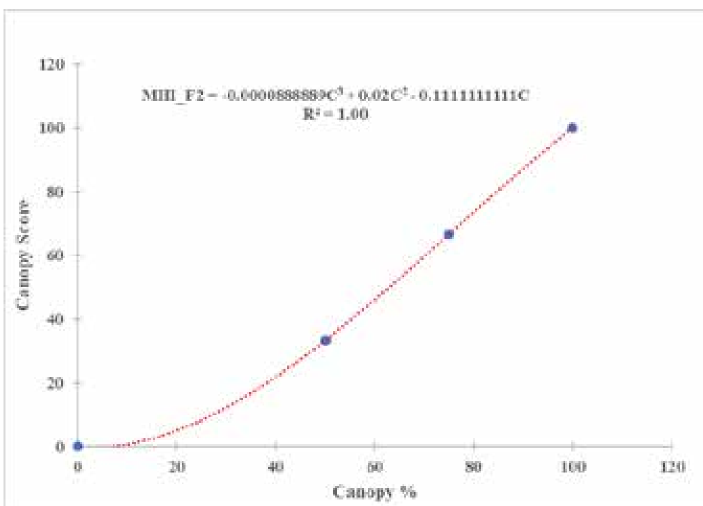


Figure 17. Canopy Score (MHI_F2) relationship with canopy percentage

4.4.2.3 Selecting vegetation indices for model development

Another principal component analysis was performed with the vegetation indices summarized in Table 3 for all the study sites of coastal mangrove plantation of Bangladesh. The biplot of the Principal Component Analysis (PCA) performed on 12 vegetation indices in remote sensing provides a clear visual representation of the relationships between these indices in terms of their contributions to two principal components (PC1 and PC2).

The first principal component (Dim1), which accounts for 75.3% of the total variance, primarily represents the most significant source of variability in the data, while the second principal component (Dim2), which explains 13.6% of the remaining variance, captures additional but secondary information (Figures 18 and 19). Indices such as NBR2, GNDVI, and GCI are closely aligned with Dim1, suggesting that they are heavily influential in explaining the primary variation in the dataset, likely reflecting vegetation cover and related attributes. On the other hand, indices like SIPI, MSI, and MI are positioned on the opposite side of Dim1, indicating a negative correlation with the first principal component. This suggests that these indices are more sensitive to different environmental variables than the indices on the positive side of Dim1. Dim2 provides an additional layer of complexity, with indices such as NDWI, MVI, SAVI and EVI contributing significantly to it, revealing secondary relationships that are not fully explained by Dim1. The overall structure of the biplot shows distinct groupings of indices, with those near each other on the plot being highly correlated, while those farther apart have less correlation. The correlation is further represented by the correlation matrix of Figure 19. All the vegetation indices are positively correlated except the SIPI and MSI that are negatively correlated with other indices. This complex relationship among the indices leads us to select all the indices for the model development in stepwise regression.

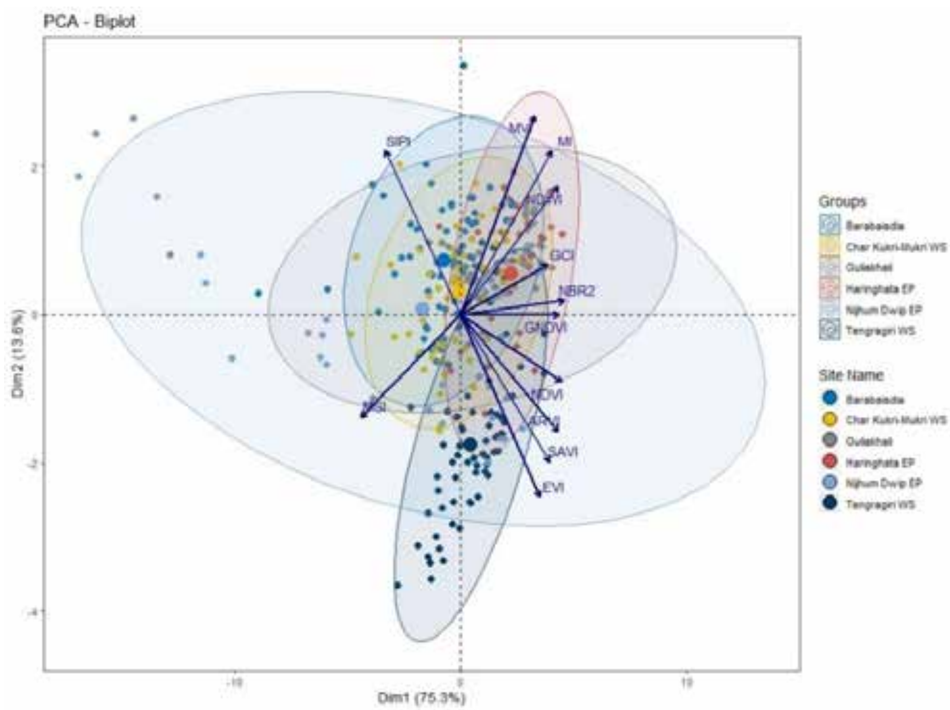


Figure 18. PCA biplot for Dim1 and Dim2 of vegetation indices

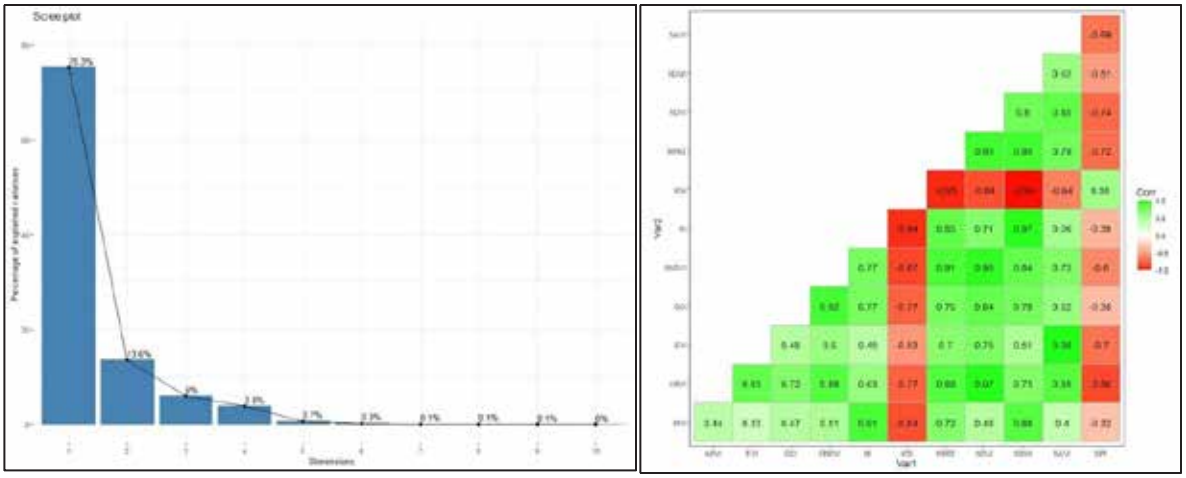


Figure 19. Scree plot of PCA and correlation matrix for vegetation indices

4.4.2.4 Model fit and validation with MHI_F1 and MHI_2

A stepwise regression analysis was performed to get a significant model with dependent variables MHI_F1 and all the indices as predictor variables. Both the forward and backward regression method was applied and the exclusion of indices was performed by examining the Variance Inflation Factor (VIF) that assess the multicollinearity among predictor variables. The final model expressed as MHI_2 is explained with NBR2, GCI, ARVI, GNDVI and NDWI. All the coefficients of these predictor variables are highly significance (Table 12). This regression model is significant ($p<0.01$) with an adjusted R^2 value 0.50, Residual standard error (RSE) 10.01 and Root Mean Square Error (RMSE) 9.91.

MHI_2 = 71.03 + 207.65*NBR2 + 15.36*GCI + 77.09*ARVI - 332.40*GNDVI - 134.84*NDWI...(6)

Table 12. Coefficients of regression equation MHI_2

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	71.033	9.551	7.437	1.10e-12 ***
NBR2	207.647	38.795	5.352	1.73e-07 ***
GCI	15.363	1.575	9.753	< 2e-16 ***
ARVI	77.085	17.908	4.305	2.27e-05 ***
GNDVI	-332.401	37.268	-8.919	< 2e-16 ***
NDWI	-134.842	28.344	-4.757	3.06e-06 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The 1:1 plot for the model MHI_2 between the original value and predicted value shows moderate fit (Figure 20). No significant irregularity was observed in the residual plots (Figure 20) except a little heteroscedasticity at the lower end of the residual plots.

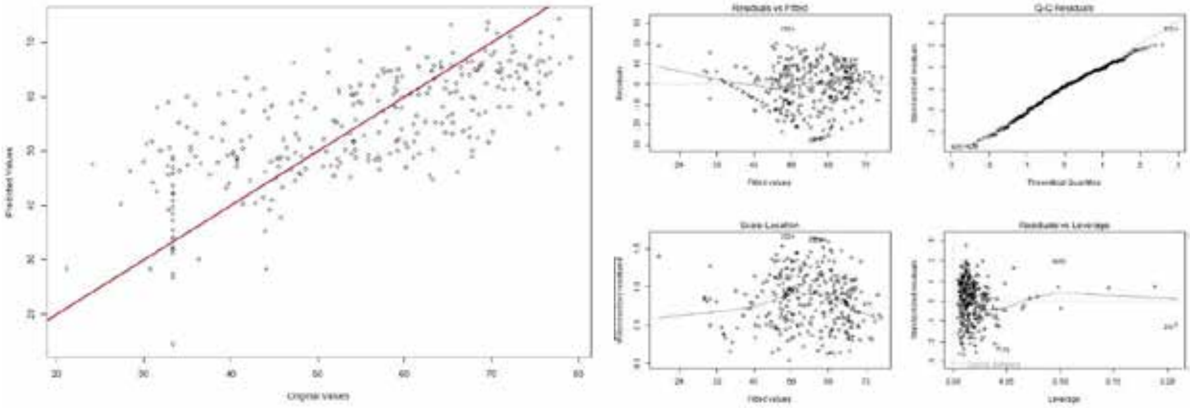


Figure 20. 1:1plot for original vs predicted values and residual plots of MHI_2 model

4.4.2.5 Model fit and validation with MHI_F2 and MHI_3

To improve the previous model MHI_2 and a new model was developed through stepwise regression equation between the MHI_F2 (dependent variable) and vegetation indices (predictor variables) that uses only the canopy percentage converted into a score. The model is finally presented as MHI_3 with only four vegetation indices i.e., NBR2, GCI, GNDVI and NDWI. All the coefficient of the predictor variables are highly significant ($p<0.001$) (Table 13). This regression model is significant ($p<0.01$) with an adjusted R^2 value 0.60, Residual standard error (RSE) 13.94 and Root Mean Square Error (RMSE) 13.82.

MHI_3 = 33.80 + 504.91*NBR2 + 22.42*GCI + -408.98*GNDVI + -332.04*NDWI…….(7)

Table 13. Coefficients of regression equation MHI_3

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	33.803	13.175	2.566	0.0108 *
NBR2	504.909	39.228	12.871	< 2e-16 ***
GCI	22.416	2.175	10.306	< 2e-16 ***
GNDVI	-408.981	51.539	-7.935	4.25e-14 ***
NDWI	-332.040	30.710	-10.812	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The 1:1 plot for the model MHI_3 between the original value and predicted value shows strong fit (Figure 21). No significant heteroscedasticity was observed in the residual plots (Figure 22).

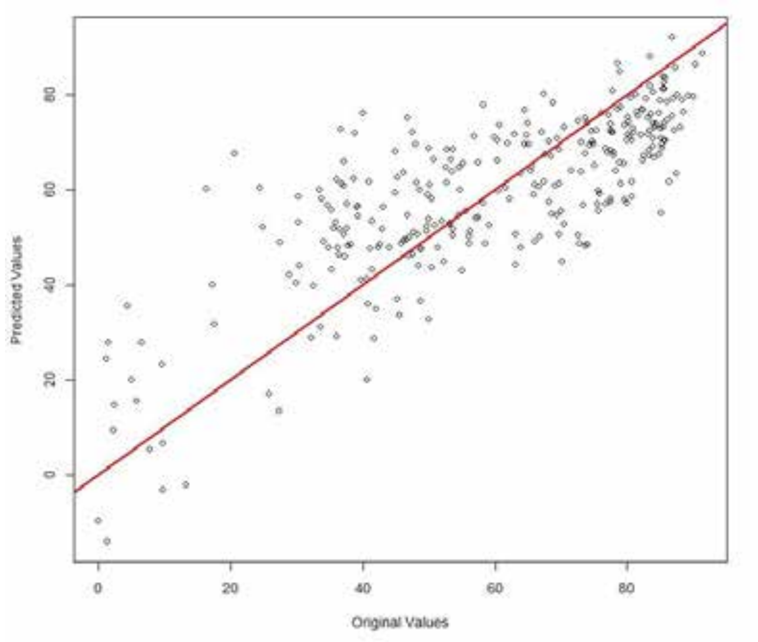


Figure 21. 1:1plot for original vs predicted values of MHI_3 model

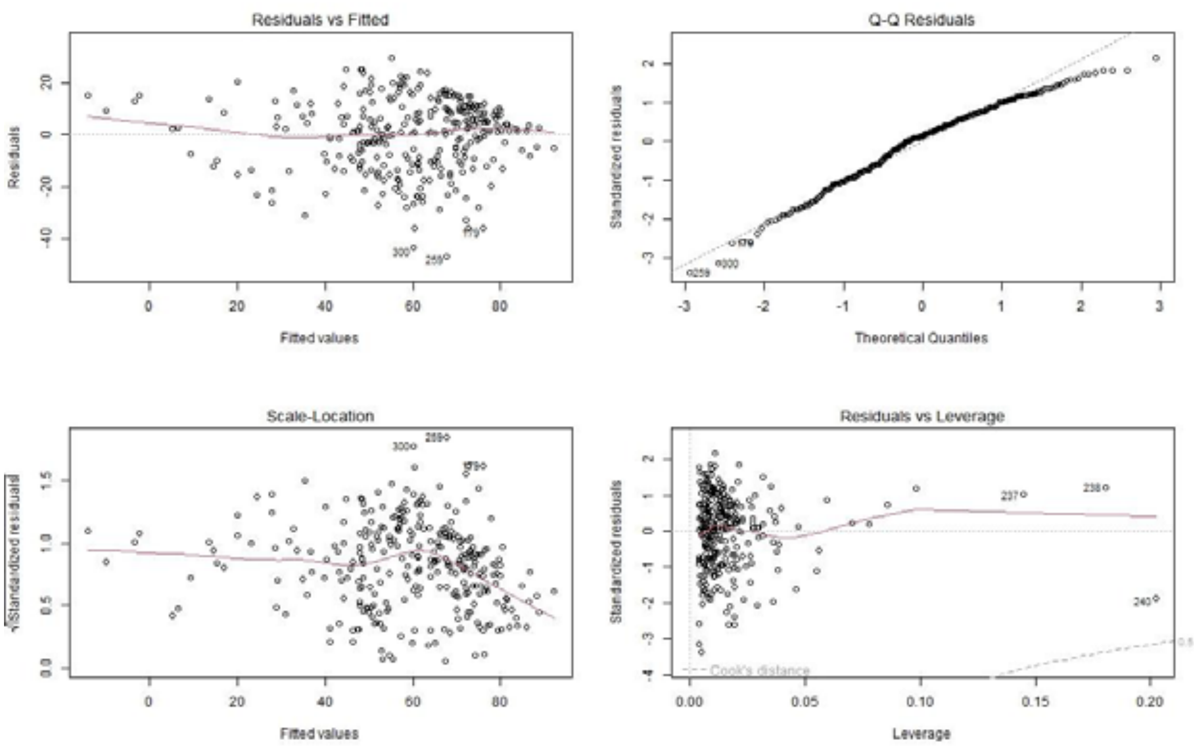


Figure 22. Residual plots of MHI_3 model

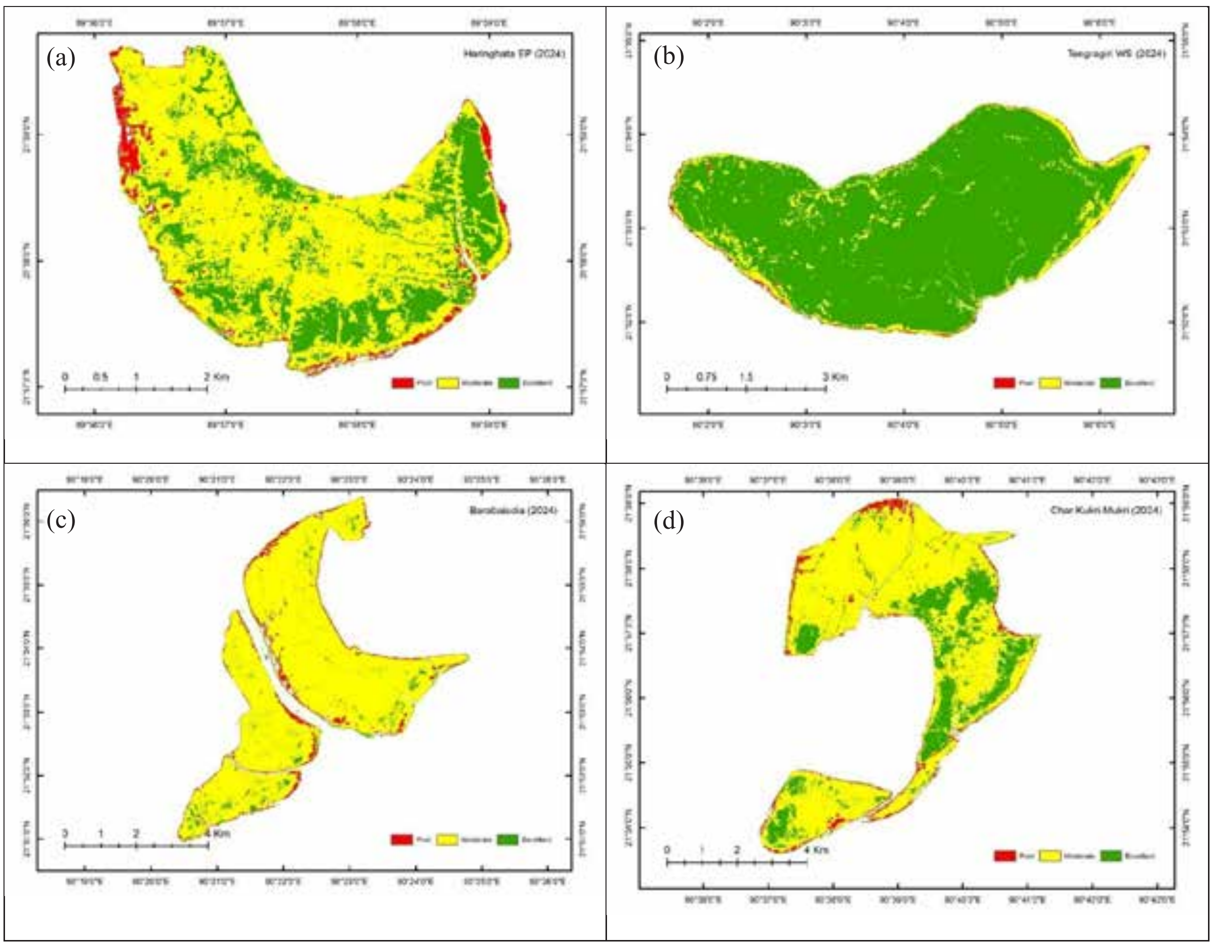
The classification error matrix of MHI_F2 and MHI_3 describe the overall accuracy 74% and a Kappa coefficient 0.56 that are much higher than the classification of MHI_1 model (Table 14). Furthermore, the model fitting of MHI_3 is better than the MHI_2 in respect to R^2 and residual plots, MHI_3 model has been selected as the best model for predicting the mangrove health of coastal mangrove plantation of Bangladesh.

Table 14. Error matrix of MHI_F2 and MHI_3 classification

	Poor	Moderate	Excellent	total	User's Accuracy
Poor	18	12	1	31	58.06
Moderate	5	110	22	137	80.29
Excellent	0	38	98	136	72.06
total	23	160	121	304	
Producer Accuracy	78.26	68.75	80.99		
Overall accuracy	74.34				
Kappa Coefficient	0.56				

4.4.2.6 Mapping mangrove health with MHI_3 model in Google Earth Engine

The MHI_3 model developed in this study for monitoring coastal mangrove plantation of Bangladesh was utilized in Google Earth Engine, which is the combination of a multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities. The equation for MHI_3 was applied to the obtained composite image in GEE and created an output map, which was then classified into three classes in state 3 condition, i.e., poor, moderate, and excellent (Table 4). The output map has been prepared for the year 2024 for all the study sites (Figures 23).



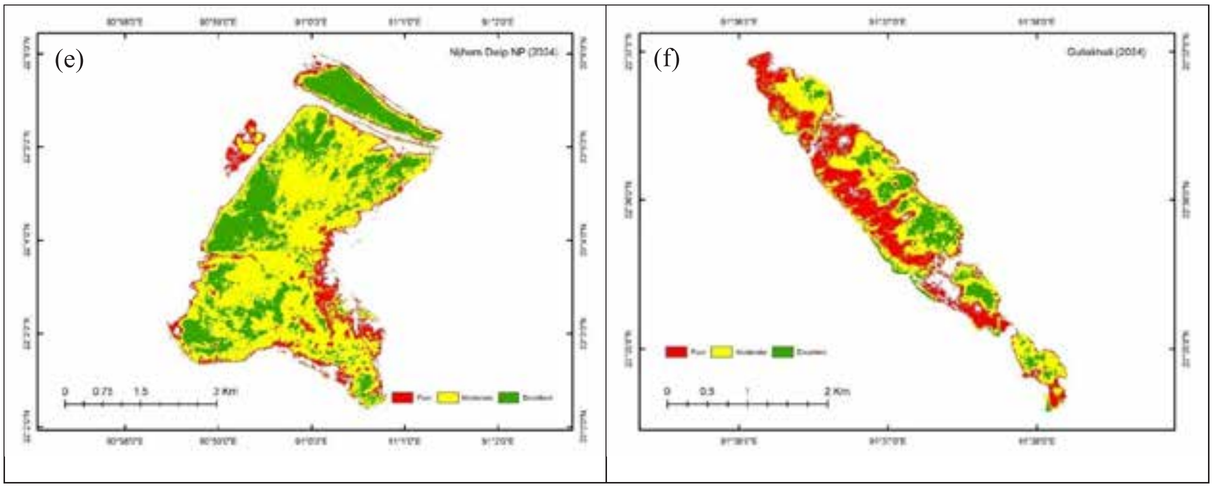


Figure 23. MHI map of (a) Haringhata EP (b) Tengragiri WS (c) Barabaisdia CP (d) Char Kukri-Mukri WS (e) Nijhum Dwip NP and (f) Guliakhali CP in 2024

In the maps (Figures 23) and Figure 24, it was observed that Tengragri WS had highest excellent area compared to other area. This is mostly a natural forest with high diversity and species density that may lead the area with best mangrove health condition. On contrary, Guliakhali had higher quantity of poor area than excellent area. Guliakhali is a sea beach and with high human intervention and due to lack of communication facility cause poor maintenance by forest department may be the reason for poor state of this forest. The main livelihood of the people of coastal area is depended on the fish collection from the river and sea. They often use saplings of various mangrove species as a fishing pole that are illegally harvested from the forest that are easily accessible. For this reason, the outer edge of the forest is in poor state in all the sites. The char Kukri-Mukri WS and Barabasidia forest are in moderate state.

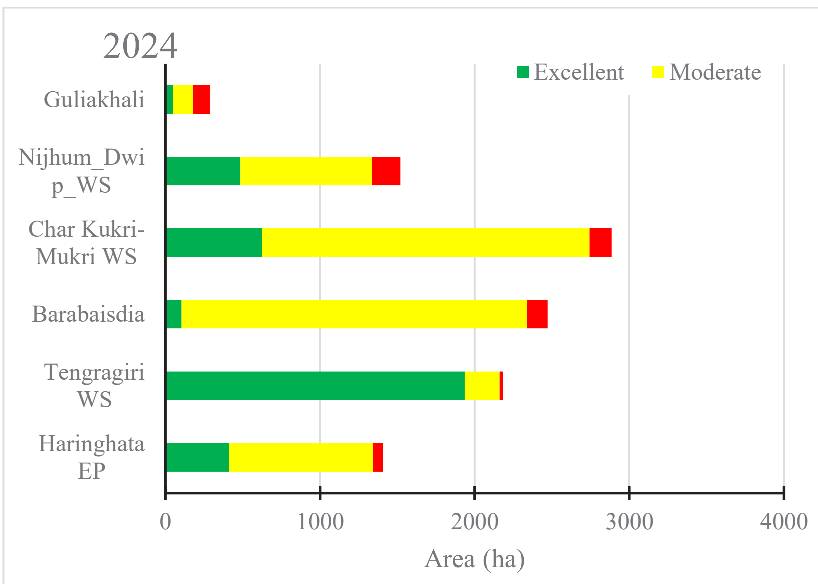


Figure 24. Area of poor, moderate and excellent class of all study sites for 2024

The model MHI_3 can be used in monitoring coastal mangrove forest for not only the 2024 but also the past and future year that can help in decision making process in forest management. This result provides a new strategy to obtain obvious understanding of current mangrove trends. Moreover, the obtained results can also be integrated with mangrove distribution data which may directly contribute to protected area management.

4.5 Mangrove threats in the coastal areas

4.5.1 Cut-wood

Cut-wood event is one of the mangrove threats and is a significant parameter in determining mangrove communities' health in the coastal areas (Figure 25). The data is identified and counted the fresh stumps number in the entire plot. Data processing is conducted by dividing the number by total live stands (trees and saplings) and multiplied by 100%. The frequency of occurrence of cut-wood is 32.50 % of the total plots in Haringhata EP, 48.33 % of the total plots in Tengragiri WS, 20.59 % of the total plots in Barabasdia CP, 38.24 % of the total plots in Char Kukri-Mukri WS, 68.18 % of the total plots in Nijhum Dwip NP and 54.17 % of the total plots in Guliakhali CP (Table 15). The density of the cut-wood stump was highest in Guliakhali (1204 stump/ha) and the lowest was in Barabasdia (63 stump/ha). In most cases, Gewa (*Excoecaria agallocha*) was found to be cut in the study areas. Small-sized Gewa saplings were illegally harvested by the adjacent villagers for fuelwood, and small trees (5-10 cm DBH) were harvested for fishing poles. Few Keora (*Sonneratia apetala*) were illegally harvested after being felled by tropical cyclones, claimed by the local people and forest department officials.

Figure 25. Pictures of cut-wood in the sampling areas.

Table 15. Garbage and Cut-wood status in six study sites of coastal plantation

Location	Garbage		Cut-wood		
	Frequency of occurrence in plots (%)	Coverage (%)	Frequency of occurrence in plots (%)	Proportion (%)	Density (stump/ha)
Haringhata EP	45.00	2.38	32.50	4.14	210
Tengragiri WS	26.67	1.58	48.33	3.19	178
Barabasdia CP	5.88	0.29	20.59	3.70	63
Char Kukri-Mukri WS	20.59	1.03	38.24	7.10	194
Guliakhali	62.50	3.13	54.17	35.33	1204
Nijhum Dwip NP	2.27	0.11	68.18	12.55	523

4.5.2 Forest Garbage

Mangrove threats in the coastal areas were measured by adopting a qualitative estimation of garbage contents in the plot in percentage (Table 15 and Figure 26). The garbage contents including plastic/inorganic waste, plastic bottles, glass, tin can, Styrofoam, fishing net, etc. and their pollution is a significant issue in coastal areas, causing harm to ecosystems and potentially impacting mangrove vegetation and human health. Normally people from ship, lunch, boat and other water vessels throw these garbage contents to water and these materials come to coastal forest floor by tide and wave action and finally deposited in the mangrove forest land. Additionally, the fisherman stores the fish in Styrofoam boxes, which frequently break and are dumped into the water, ending up on the forest floor. It has serious negative effect on mangroves health and growth. It is grouped into five categories which are 0% (no garbage cover); 1-25% (small area of the substrate covered by plastic waste); 25-

50% (garbage covers proportion is equal to soil appearance); 50-75% (more garbage than substrate); and 75-100% (garbage covers the entire substrate) (Dharmawan and Ulumuddin, 2020).

The result of mangrove threats by garbage contents showed that the frequency of occurrence of plastic waste cover or garbage and its coverage in the plots were respectively 2.38 % of the total plots (40) in Haringhata EP, 1.58 % of the total plots (60) in Tengragiri WS, 0.29 % of the total plots (68) in Barabasdia CP, 1.03 % of the total plots (68) in Char Kukri-Mukri WS, 0.11 % of the total plots (44) in Nijhum Dwip NP and 3.13 % of the total plots (24) in Guliakhali CP. It indicates that the highest amount of garbage coverage (3.13%) was found in Guliakhali CP, with the highest frequency of occurrence in plots (62.50%). Whereas, the lowest garbage coverage was found in Nijhum Dwip NP (0.11%), with the lowest frequency of occurrence in plots (2.27%).

Figure 26. Pictures of Garbage coverage in the sampling areas.

Considering the results of frequency of occurrence, coverage/proportion and density of cut-wood and garbage, it can be concluded that Bara Baisdia CP is less threatened as well as healthier than other coastal sites. It is observed that anthropogenic disturbances are higher in Guliakhali CP than in any other coastal area, which can lead to poor stand conditions in this area. Generally, garbage coverage and cut wood stumps are found higher along the coast. This zone often encounters natural and anthropogenic factors which cause severe damage to the mangrove community. Often the waves bring garbage as well as natural calamities cause serious damage to the coast. Sometimes people make fire and throw wastes in the forest as well as cut trees to use as fuelwood and for their other daily uses. High amount of garbage appearance in Guliakhali CP may be resulted from natural calamities and\or tidal inundation as well as illegal encroachment. Moreover, large and distinct coverage of *Acanthus ilicifolius* (Hargaza) in the study sites may restrict the forestry officials from extreme surveillance which sometimes facilitate illegal encroachment. Besides plastic/inorganic waste is one of the threats that cover the forest floor and negatively affects the community's regeneration ability in the area.

4.5.3 Forest Grazing

The grazing of domestic animals such as cattle and buffalo has a detrimental impact on forest ecosystems, particularly on seedlings and understory vegetation, which are crucial for forest regeneration. Additionally, these animals can act as vectors for zoonotic diseases, potentially transmitting harmful pathogens to wildlife populations. Grazing by livestock, especially buffalo and cattle, poses a significant threat to coastal forests, including the Wildlife Sanctuaries and other protected and non-protected areas. During the Bangla months of Bhadro to Kartik (July to November), the grazing of domestic animals in homestead forests or barren lands becomes less feasible due to the cultivation of Aman rice crops. As a result, extreme grazing pressure shifts to forested areas during this period, further endangering the delicate ecological balance of these habitats.

It was found during field visit that grazing occures more or less all over the areas of coastal region in the year-round (Figure 27) as the local people raise their livestock within the forest areas due to lack of fodder. Damage includes trampling or browsing of seedlings, and compacting, leading to reduced

Figure 27. Pictures of grazing in sampling areas.

vegetation and increased soil erosion. It poses a significant challenge to plants' growth and survival, and also create conflicts on forest management. Control or partial grazing may be permitted in the old mangrove plantation forest (over 15 yrs old), but it should be banned for 2 to 3 years in the areas where enrichment plantation implemented. Also, grazing must be banned in new char land because it increases soil compactness which hampers the performance of new mangrove plantation and regeneration. Permission of grazing in a designated areas may solve the conflict between FD and the local people for livestock rearing inside the forest.

5. Conclusion

Excoecaria agallocha emerges as the most dominant and abundant species within the study sites based on the importance value index across the tree size classes of coastal mangrove species. Conversely, *Sonneratia apetala* also ranks as the most dominant species in terms of the highest relative dominance (basal area) exclusively at the tree level in the majority of the sites. Among the six study sites, Tengragiri Wildlife Sanctuary was found to be the most diverse forest as it is completely a natural patch akin to the Sundarbans mangrove forest, where *Heritiera fomes* ranks as the second most dominant species. The greatest quantity of *E. agallocha* was seen within the diameter class of 5-10 m, whereas the majority of *S. apetala* species had diameters ranging from 20 to 45 cm throughout the study sites. Haringhata Eco-Park has the highest concentration of smaller trees (5-10 cm), suggesting it might be a younger stand or an area with good regeneration. Exceptional canopy coverage was seen in Tengragiri WS (82%), where high species richness and diversity exhibited. Superior canopy covering may positively correlate with high species richness and diversity within the entire coastal mangrove community. *S. apetala* contains the highest Above-Ground Biomass (Mg/ha) and Volume (m^3/ha) in the study sites.

The MHI_3 model with MHI_F2 has been developed in the present study and it is better suited for monitoring mangrove plantation in Bangladesh. This model can be used in monitoring coastal mangrove forest for not only the year of 2024 but also the past and future year that can help in decision making process in forest management. This result provides a new strategy to obtain obvious understanding of current mangrove trends. According to the MHI maps created by the model, Tengragiri Wildlife Sanctuary has the healthiest mangrove plantation as it has the highest excellent area compared to other areas. Guliakhali CP consists higher area of poor category that need to be addressed as this is a potential ecotourism spot. The results of frequency of occurrence, coverage/proportion and density of cut-wood and garbage, Bara Baisdia CP is less threatened than other coastal sites. It is observed that anthropogenic disturbances are higher in Guliakhali CP than in any other coastal areas, which can lead to poor stand conditions in this area. Grazing by buffalo and cattle poses a significant threat to the coastal forests because the local people raise their livestock inside the forest due to lack of fodder. To prevent illegal grazing and conflict between forest department and local people as well as to increase govt. revenue, FD can initiate grazing activities with a controlled way in designated areas, such as in the old mangrove plantation forest (over 15 yrs old), but it should be restricted for 2 to 3 years in the areas where enrichment plantation implemented.

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Distribution and growing stock of Agar populations (Aquilaria malaccensis lamk) in Bangladesh: Assessing for Non-detriment findings

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Chapter One: Introduction

1.1 Introduction

Agarwood, often referred to as the 'wood of the Gods', is a unique and highly valuable resinous heartwood derived primarily from the *Aquilaria malaccensis* tree. It holds profound cultural, religious, medicinal, and economic significance in Bangladesh and many parts of the world (Persoon et al., 2008). For centuries, agarwood has been used in religious rituals, traditional healing systems, perfumery, and aromatherapy. These multifaceted uses have turned agarwood into a globally coveted commodity, particularly in markets across the Middle East and Northeast Asia, including Japan, South Korea, and Taiwan (Abdin et al., 2014).

In Bangladesh, *Aquilaria malaccensis*—a species that naturally produces the resin upon stress or infection—is the main source of agarwood (Hashim et al., 2016). Historically, the rich forests of Sylhet, Chittagong, and the Chittagong Hill Tracts supported abundant wild populations of Aquilaria, driving a once-flourishing agarwood trade (Thompson, Teckwyn, et al., 2022). However, escalating global demand and lucrative prices—ranging from \$20 to \$6,000 per kilogram for agar chips and up to \$30,000 per kilogram for agar oil (Abdin et al., 2014)—have led to overharvesting and a sharp decline in natural stocks. Currently, the global market for agarwood is estimated at between \$6 billion and \$8 billion annually (Akter et al., 2020).

In Bangladesh, agarwood stands among the most valuable non-wood forest products, generating annual earnings between US\$0.05 million and US\$1.19 million (Chowdhury et al., 2018). Traditionally, two species—*A. agallocha* and *A. malaccensis*—were harvested primarily from the northeast. Initially, wild sources fulfilled market needs (Ador et al., 2021), but growing demand and depletion of natural populations have prompted large-scale plantation development, particularly in Chittagong, the Chittagong Hill Tracts, and Sylhet. As of 2016, over 3,009 hectares have been planted with agarwood trees (Talucder et al., 2016). The Sylhet division alone hosts 121 private agar plantations, with 111 located in Barlekha Upazila of Moulvi Bazar district.

This shift toward cultivation has made agarwood farming an increasingly profitable venture, offering a net return of approximately US\$0.022 million per acre over a 12-year cycle (Rahman et al., 2015). By 2015, the number of agar-related enterprises had grown to over 300, significantly contributing to rural employment and improving local livelihoods. These developments highlight agarwood's socio-economic potential, particularly in poverty alleviation and gender inclusion (Hossen & Hossain, 2016; Samiul et al., 2016). Furthermore, the rise of agarwood plantations supports multiple Sustainable Development Goals (SDGs) by promoting environmental conservation and sustainable resource use (Ali & Chowdhury, 2018).

Despite its promise, the sector remains largely informal, with minimal oversight from government or non-governmental organizations (Samsudin et al., 2008). This informality creates challenges in quality control, certification, and export regulation. Overharvesting, coupled with illegal and unsustainable practices, has critically endangered wild Aquilaria populations (Abdin, 2014; López-Sampson & Page, 2018; Iftekhar & Hoque, 2005). The severity of this decline prompted the inclusion of *A. malaccensis* in Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) in 1994 (Thompson, Teckwyn, et al., 2022). As a signatory, Bangladesh is now required to ensure that international trade in agarwood products is non-detrimental to the species' survival. This includes obtaining Non-Detriment Findings (NDF) certification—yet to date, no agarwood plantation in the country has achieved this.

The absence of formal certification has fueled illegal cross-border trade, especially through India, resulting in substantial economic losses and weakening regulatory mechanisms (CITES, 2010; Jensen, 2009). These challenges underscore the urgent need for a structured and data-driven management framework to sustain both the species and the agarwood industry.

A critical step in achieving this goal is the assessment of current biomass, growing stock, and ecological distribution of *Aquilaria malaccensis* in Bangladesh. However, data on the spatial distribution and condition of both wild and cultivated populations remain insufficient (Mahmood et al., 2020). Without such information, it is difficult to make sound policy decisions that align environmental sustainability with economic interests.

To address these gaps, Species Distribution Modelling (SDM) emerges as a powerful tool. SDMs analyze environmental factors such as temperature, rainfall, and soil properties—including pH, organic matter content, and moisture content—to predict suitable habitats for species like agarwood (Kumar et al., 2020). Advanced modeling techniques such as MaxEnt are especially valuable for identifying conservation priorities and guiding plantation development (Elith & Leathwick, 2009). Integrating SDMs with IUCN distribution data allows for more strategic conservation efforts and habitat management.

This study seeks to contribute to these objectives by mapping the current distribution and estimating the biomass of *Aquilaria malaccensis* in Bangladesh. The findings will provide essential insights into the status of both wild and plantation populations, helping to develop a scientifically informed Non-Detriment Findings (NDF) report. Ultimately, this research supports the sustainable development of the agarwood sector, aligning ecological protection with national economic goals, and paving the way for formalized international trade under CITES guidelines.

1.2 Study Objectives

1. To estimate the current volume stock and biomass of agarwood in Bangladesh.
2. To map the existing distribution of both wild and cultivated *Aquilaria malaccensis* populations across the country.
3. To prepare a Non-Detriment Findings (NDF) report to support the formalization and sustainable trade of agarwood.

Artificially Inoculated Agar Trees, (b) & (c) Infected Agarwood Core and (d) Fresh Agarwood Core Collected from Private Plantation in Barlekha

Chapter Two: Methodology

2.1 Study Site

The study was conducted across multiple regions of Bangladesh where Agarwood (locally known as agar) is cultivated, including Sylhet, Chittagong, the Chittagong Hill Tracts (CHT), and Tangail. These areas were selected for their ecological importance, climatic variation, and historical and contemporary relevance to agarwood plantation and trade. Each region contributes unique environmental factors that influence the survival, growth, and productivity of *Aquilaria malaccensis*—the primary species for agarwood production in Bangladesh.

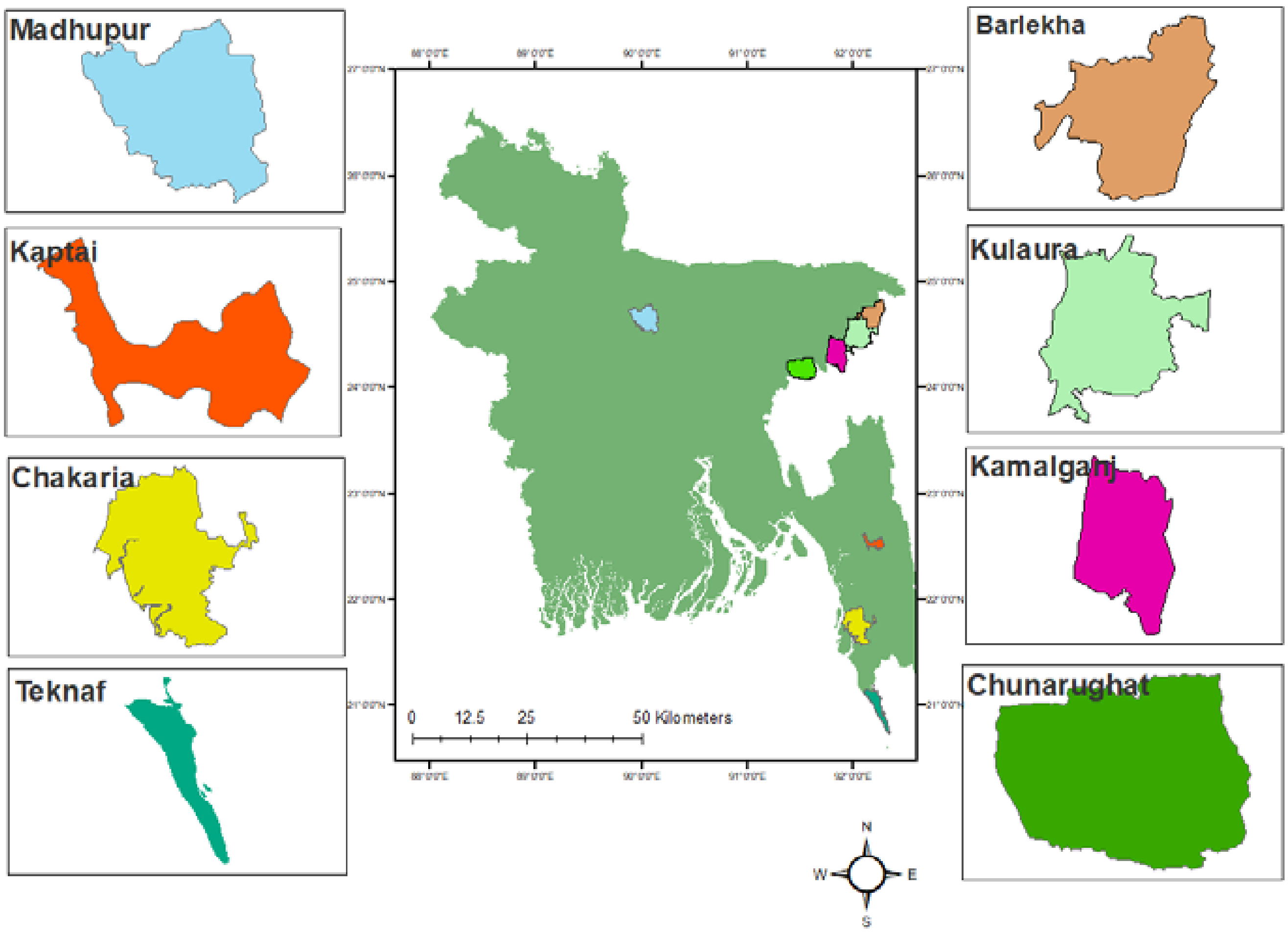

Figure 1. Map of study areas across Bangladesh showing selected districts with agarwood plantations.

2.1.1 Sylhet Forest Division

The Sylhet region plays a critical role in both natural conservation and commercial cultivation of agarwood. In this division, the study was conducted in government-managed natural forests as well as privately owned plantations.

Forest Department Plantations

Key sites included Rema-Kalenga Wildlife Sanctuary, Satchari National Park, Lawachara National Park, Juri Forest**, and** Madhobpur National Park**.**

- **Rema-Kalenga Wildlife Sanctuary**, located in Habiganj, spans approximately 1,795 hectares and supports tropical evergreen and semi-evergreen forests. Annual temperatures range from 15°C to 30°C, with rainfall between 3,500 mm and 4,500 mm. Agar plantations began in 1997–98, with later expansions in 2000–2009 across Rema and Rashidpur beats, totaling 40 hectares.

- **Satchari National Park**, also in Habiganj, spans 243 hectares. It receives similar climatic conditions to Rema-Kalenga, with 3,500–4,000 mm rainfall annually. Agar plantations began in 2007–08 (20 ha), followed by smaller expansions in subsequent years.
- **Lawachara National Park**, contains 60 ha of plantations in Chatoli beat and 13 ha in Lawachara beat. Eleven plots were sampled from this park for the study. Although less extensive, its role in preserving agarwood genetics is significant.
- **Juri Forest**, in Barlekha Upazila of MoulviBazar, consists of mixed evergreen-deciduous vegetation, with rainfall around 3,500–4,500 mm. Temperatures vary from 12°C in winter to 35°C in summer. The forest contains around 239 ha of agar plantations—mostly in Putichora (160 ha), Lathitila (55 ha), and other smaller beats.

Private Plantations in Barlekha

Barlekha Upazila in MoulviBazar district is a major commercial hub for agarwood enterprises, hosting over 300 businesses and 1,500+ hectares of private plantations (Talucder et al., 2019). The upazila lies in the Northern and Eastern Piedmont Plains and features grey Piedmont and non-calcareous floodplain soils. The region receives 3,500–4,500 mm rainfall annually, with pleasant winters (12–20°C) and hot, humid summers (28–35°C). The area is renowned for widespread agar cultivation, particularly in Sujanagar (also known as Bangladesh's "agar capital"), Kathaltoli, Bortol, Kalajura, and Gangkul (M. Chowdhury et al., 2017). A total of **62 systematic plots** were sampled from these private lands.

2.1.2 Chittagong Hill Tracts Forest Division

The Chittagong Hill Tracts (CHT) represent a high-rainfall, hilly region with complex topography and significant natural forest cover.

- **Kaptai National Park**, located in the Rangamati District, spans 5,464 hectares and features mixed evergreen and deciduous forests. It supports wildlife such as elephants and capped langurs. Agar plantations in this division cover about 283 hectares across beats like Suknachari, Kamaillachari, and Preyongkhong.
- **BFRI Keuchia Station** in Chittagong hosts around 7 hectares of experimental agar plantations. This station contributes to research on agar propagation and sustainability. A total of five plots were sampled from here for this study.

Table 1. Area and status of the Agar plantation in the forest divisions of Bangladesh

Ecological zones / Forest Division	Plantation Type	Forest/Location	Total Area (Ha)	Current Status
Sylhet	Natural Forests (63)	• Rema Kalenga Wildlife Sanctuary • Satchari National Park • Jury Forest • Lawachara National Park	442	Abundance is low in Rema Kalenga. Lawachara (Chatoli beat). Satchari has high abundance. In Jury, almost half of plantation were failed, but existing plantations are in good condition.
	Private Owned (63)	Borolekha (Homestead)	>1500	Mostly in good condition.

Tangail	Natural Forests (29)	Modhupur National Park	50	In abundant condition, planted with agro-crops like pineapple, banana, lemon etc.
Chittagong Hill Tracts	Plantation in Natural Forests (74)	BFRI Kaptai National Park	290	In good condition. Good growth, abundant.
Cox's Bazar	Plantation in Natural Forests (30)	Dulahazra National Park Teknaf National Park	210	In good condition, Good growth, abundant.

Figure . *Aquilaria malaccensis* habitat across four distinct regions: (A) Sylhet Natural Forests, (B) Cox's Bazar, (C) Tangail and (D) Chittagong Hill Tracts

2.1.3 Cox's Bazar Forest Division

Two major protected areas—Teknaf Wildlife Sanctuary **and** Dulahazra National Park—were selected in this coastal district.

- **Teknaf Wildlife Sanctuary**, located on the southernmost peninsula of Bangladesh, spans 11,615 hectares. Rainfall averages 3,000–4,000 mm/year, with temperatures between 15°C (winter) and 35°C (summer). Agar plantations established in 2002–03 and 2008–09 cover about 60 hectares under the management of the Forest Depatment.

- **Dulahazra National Park**, receives 3,000–3,500 mm rainfall annually. Soil textures are sandy loam to loamy. Agar plantations span 60 hectares, with 20 ha in Kakara beat (20% survival) and the rest in Fasiakhali beat.

2.1.4 Tangail Forest Division

- **Madhupur National Park**, covering 8,436 hectares in Tangail and Mymensingh, represents the heart of the Madhupur Sal Forest ecosystem. Agar plantations in Madhupur span 50 hectares across Rosulpur and Madhupur Sadar beats.

2.2 Quantitative Data Collection

Key morphometric parameters including tree height, diameter at breast height (DBH), canopy cover, and evidence of disturbances were meticulously recorded within each designated plot. Tree height was measured using a Range Finder (Model: BKA094YA, NIKON), which provided accurate readings even in densely vegetated areas. DBH was measured at 1.3 meters above ground level (standard breast height) using a diameter tape. Additionally, precise geographic coordinates and elevation data were documented using GPS technology. Within each delineated plot, a systematic sampling approach was employed to select three representative Agar trees. Subsequently, wood cores were extracted from these selected trees to facilitate the estimation of volume and above-ground biomass. This investigative process aimed not only to quantify the growth metrics of Agar trees but also to discern potential inter-regional variations in their growth patterns in different regions.

Figure 2. Photos during field data collection in different sites. a) Soil sample collection in Tangail, b) Measurement of DBH in Tangail, c) Sample tagging in Rema Kalenga Wildlife Sanctuary, d) Soil sample collection in Chatoli beat of Sreemangal range.

2.3 Qualitative data collection

2.3.1 Focus Group Discussion

In order to gain insights into the agar industry in Bangladesh, 9 focus group discussions (FGD)s were conducted with the beneficiaries of the Agar plantation across different parts of the country.

Each FGD involved 6 to 14 participants representing diverse stakeholder groups connected to the agarwood sector. Most of the participants were agar beneficiaries, including plantation workers and small-scale traders, while others included forest officials, private plantation owners, and members of local conservation and community patrolling groups. Efforts were made to ensure the presence of at least three female participants in each FGD wherever possible.

Table 2. Location, region and details of respondents of the FGD

Location	Region	No. of participants	Details of participants
Chatoli Beat	Sreemangal	10	All males, beat officer, 2 forest guards, rest were agar beneficiaries
Shomonbaag Beat	Barlekha	7	All males, 1 forest guard, 1 private owner, rest were agar beneficiaries
Rosulpur Beat	Tangail Forest Division	14	3 female, 11 male members. All were agar beneficiaries
Rajabari Beat	Madhupur Forest Division	13	4 female, 9 male. 2 forest guards, rest were agar beneficiaries
Satchari Beat	Habiganj	12	All males, Headman, 9 VCF/CPG members, 2 forest guards
BFRI Station	Chattogram	6	All males, BFRI officials
Phreyongkhong	Karnaphuli Range	11	9 male, 2 female, all were agar beneficiaries
Teknaf Sadar	Cox's Bazar	12	All males, all were CPG members and agar beneficiaries
Agar Association	Azimgar Bazar, Barlekha, Moulvibazar	6	All male members, private plantation and factory owners

2.3.2 Interview with forest official

Regulation In relation to the non-detrimental findings (NDF) and the status of wild populations of Aquilaria (agarwood), we also engaged in discussions with two senior forest officials. Based on their guidance, the assessment placed greater emphasis on reviewing the existing Agarwood Policy "Agar brikkho nitimala 2012" of Bangladesh. The officials highlighted the need to shift the focus from identifying wild populations—given their scarcity or near absence in natural forests—to improving regulatory and institutional mechanisms that support sustainable cultivation and trade. As a result, the core of the recommendations chapter in this report centres on strategies to streamline the processes of agarwood inoculation, harvesting, processing, and trade, particularly from the perspective of private sector investors. These recommendations aim to reduce bureaucratic hurdles, enhance traceability and

transparency, and create a more enabling environment for sustainable and legal agarwood production and export in Bangladesh.

2.3.3 Procedure

The Focus group discussion (FGDs) followed a semi-structured format, utilizing open- ended questions (Semi-structured questionnaire of FGD) to facilitate discussion and encourage participants to freely share their experiences and perspectives. Each discussion lasted approximately 1 hour and 30 minutes and covered key areas such as cultivation and harvesting practices for agar, processing and trade of agar products, challenges faced by the agar industry, and recommendations for its improvement in Bangladesh. Each discussion was moderated by a facilitator, who ensured that all participants had the opportunity to contribute, and that the conversation remained focused on the topic.

Figure 3. A photo of team members with the range officer of Chunarughat, Habiganj which host vast amount of Agar plantation.

Chapter Three: Volume and Biomass

3.1 Introduction

Biomass estimation is a critical aspect of forest management and ecological sustainability, particularly in the case of valuable species like Aquilaria spp., known for producing Agarwood. Estimating the biomass of these trees provides essential data for understanding their role in carbon sequestration, contributing to climate change mitigation efforts. As Bangladesh faces increasing environmental challenges, sustainable forest management becomes crucial for maintaining ecological balance. Accurate biomass estimation of Aquilaria spp. in different ecological zones—such as Sylhet, Chittagong Hill, Cox's Bazar, and Tangail Forest Divisions—will help determine the overall forest productivity and health. It can also aid in assessing the impact of plantation practices, forest conservation policies, and private land management. This data provides a baseline for the sustainable utilization of Agarwood and its derived products while ensuring long-term forest resilience. In addition, understanding biomass distribution across various ecological zones offers insight into the environmental adaptability of Aquilaria spp. This knowledge can enhance agroforestry practices, improve the carbon stock management system, and support future reforestation projects that balance economic growth with environmental preservation.

3.2 Structural Characteristics of Agarwood Populations Across Ecological Zones

A total of 3,820 *Aquilaria malaccensis* individuals were recorded across all study plots, with notable variation in abundance and structure across ecological zones and plantation types. Sylhet's privately owned plantations showed the highest tree count (1,527 individuals), followed by the Chittagong Hill Tracts with 1,205 individuals. Lower abundance was recorded in Cox's Bazar (608 trees) and Tangail (480 trees)**.**

In terms of height distribution, most agar trees in all zones ranged between 7–15 meters, with very few under 7 meters. The natural forests of Sylhet had the tallest trees, with many exceeding 15 meters, unlike private plantations in Barlekha, where few reached that height. In Tangail, all trees were confined to the 7–15 meter range. Regarding diameter at breast height (DBH), the majority of trees fell within the 10–20 cm class. Trees with DBH over 20 cm were moderately present, especially in the Chittagong Hill Tracts, while Sylhet's homestead plantations recorded the most trees in the <10 cm DBH class. These structural differences reflect varying plantation ages, management practices, and ecological conditions across zones.

Table 3. Summary of the total number of *Aquilaria malaccensis* individuals recorded in Four ecological zones.

Ecological Zones	Plantation Type	Plot	Abundance
Sylhet Forest Division	Plantation	63	1214
	Private Plantation	63	1527
Chittagong Hill Tracts Forest	Plantation	74	1205
Cox's Bazar Forest Division	Plantation	30	608
Tangail Forest Division	Plantation	29	480

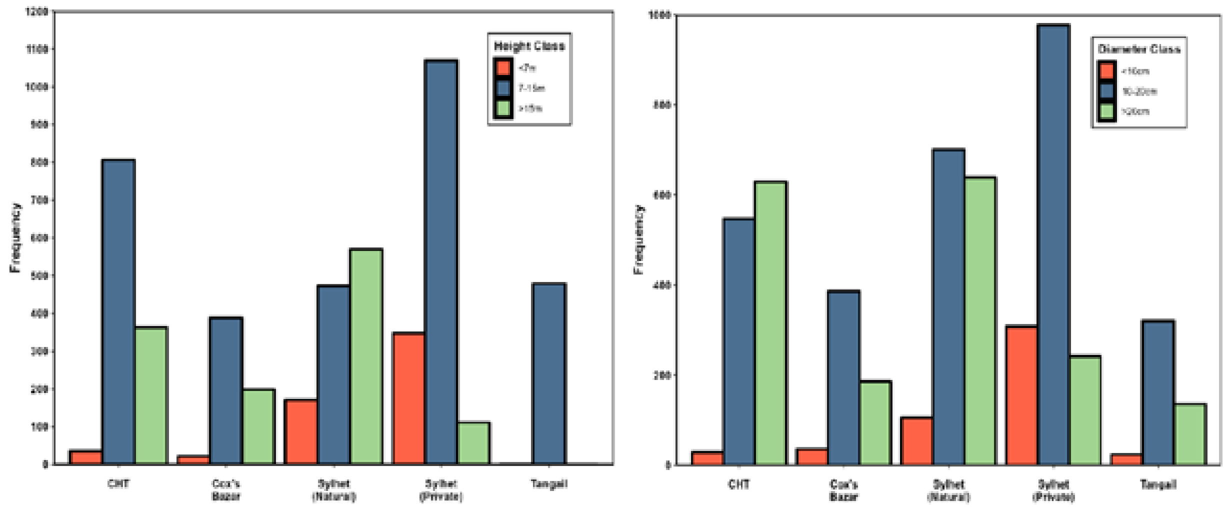

Figure 4. Distribution of agar trees based on their height classes & Dia classes among different ecological zones - Tangail (29 plots), Sylhet private forest (63 plots), Sylhet Natural Forest (63 plots), Cox's Bazar (30 plots), Chittagong hill tracts (CHT, 74 plots).

The distribution and structure of *Aquilaria malaccensis* trees vary significantly across different ecological zones in Bangladesh due to differences in plantation type, environmental conditions, and management practices. Sylhet Forest Division shows the highest abundance, particularly in privately-owned plantations (1,527 trees), followed by natural forests in Sylhet and the Chittagong Hill Tracts. Cox's Bazar and Tangail report lower tree counts, likely due to limited focus or environmental constraints.

In terms of height, most trees range between 7–15 meters, but natural forests in Sylhet have more trees exceeding 15 meters, indicating mature growth and less human interference. In contrast, Barlekha's private plantations have shorter trees, likely due to early harvesting. Tangail plantations show uniform tree height, suggesting recent establishment or slow growth.

DBH distribution reveals that most trees fall within the 10–20 cm range, showing moderate maturity. Larger trees (>20 cm DBH) are most common in Chittagong Hill Tracts, while Sylhet homesteads have the younger trees (<10 cm DBH), reflecting ongoing planting and rotation cycles.

These findings align with global trends, where natural forests support taller and more mature agarwood trees, as seen in India and Malaysia. The results highlight the adaptability of *A. malaccensis* and underscore the need for zone-specific management to balance sustainability with economic benefit.

3.4 Volume calculation Procedure

To determine the volume of Agar trees, we measured key parameters such as the diameter at breast height (DBH), total height (TH), and the form factor of sampled trees with a diameter greater than 7 centimeters. Careful consideration was given to selecting potential sample trees, excluding those with broken tops, abnormal stems, or signs of decay.

The volume of each individual log section of Agar trees was calculated using the volume equation provided by Islam and Chowdhury (2017), represented as:

$V = a + bD + cH + dD^2H$ (Islam & Chowdhury, 2017)

Where V= Total volume over bark in cubic meters; D= Diameter at breast height in centimeters; H= Total height in meters; a = Regression constant; b, c, d= Regression coefficients and the logarithmic functions are to the base.

3.5 Biomass calculation Procedure

The biomass of the stem of sampled trees was determined by estimating the volume and mean wood density values. Wood cores were collected from a minimum of three trees in each plot to estimate wood density, thereby capturing variations in wood density 31 among the study zones. The above-ground biomass of Agar was calculated using the equation provided by Mahmood, Siddique, et al. (2020), expressed as:

Ln (Stem) = - 10.7248+1.604*Ln (D)+1.323*Ln(H)+1.1469*Ln(W), (Mahmood, Siddique, et al., 2020)

where, D = Diameter at Breast Height; H = Total Height; W = Wood density

3.6 Volume and Biomass Estimation Across Ecological Zones

Significant variation was observed in both per plot volume and biomass of *Aquilaria malaccensis* across different ecological zones in Bangladesh. Statistical analyses using one-way ANOVA followed by Tukey's HSD test (conducted in R version 4.4.1) confirmed these differences, with the ANOVA results showing a significant effect of ecological zone on biomass ($F = 3.38$, $p < 0.001$).

The Sylhet natural forests and Chittagong Hill Tracts (CHT) consistently exhibited the highest mean values for both volume and biomass per plot, with no statistically significant difference between them. In contrast, other regions—particularly the privately owned plantations in Barlekha—recorded significantly lower mean values for both metrics.

While Cox's Bazar and Tangail zones also showed lower volume and biomass per plot, their distributions were statistically similar to each other but distinct from Sylhet and CHT. These results highlight the impact of ecological conditions, management practices, and plantation maturity on the growth performance of agarwood trees across regions.

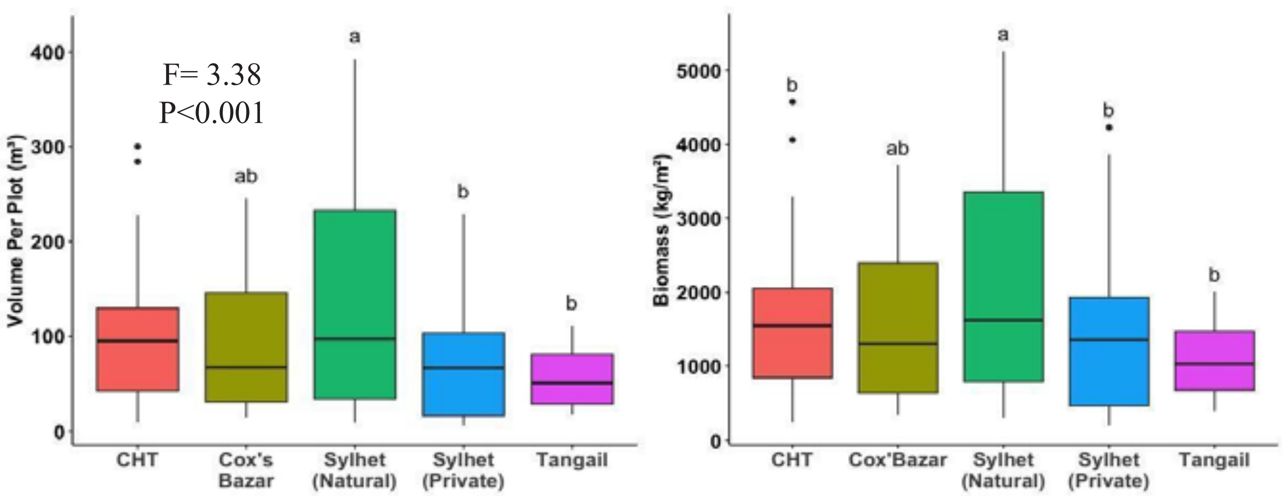

Figure 5. Boxplots showing per plot volume & Biomass in different ecological zones

The volume and biomass of *Aquilaria malaccensis* plantations in Bangladesh vary significantly across ecological zones due to differences in environmental conditions and management practices. Sylhet natural forests and the Chittagong Hill Tracts (CHT) consistently show the highest per plot volume and biomass, attributed to favorable conditions such as high rainfall, fertile soils, and minimal human disturbance. These zones support mature trees with greater growth potential, reflecting patterns seen in countries like Vietnam and Malaysia, where natural forest conservation enhances agarwood productivity. In contrast, Barlekha's privately-owned plantations exhibit the lowest mean volume and biomass, primarily due to intensive harvesting, shorter rotation cycles, and limited soil management. Similar outcomes have been observed in Thailand and Indonesia, where economic-driven plantation practices result in lower biomass accumulation. Cox's Bazar and Tangail fall in the intermediate range, with moderate volume and biomass per plot. These areas likely reflect a balance of ecological constraints and moderate management intensity.

Overall, the findings emphasize the need for zone-specific management strategies. High-yield zones like Sylhet and CHT should focus on conservation and sustainable harvesting, while areas like Barlekha could benefit from improved practices—such as longer rotation cycles and enhanced soil management—to boost productivity without harming the environment. Learning from global best practices could help Bangladesh enhance agarwood yield while preserving ecological integrity.

Picture During meeting with (a) Beat officer, Kakara Beat, (b) Beat officer, Madhobkunda Beat, (c) Beat officer, Shomonbagh Beat, (d) Agar Association, Suzanagar

The images illustrate various stages of field and laboratory data collection related to agarwood research.

Images (a) and (b) represent field data collection activities conducted across selected agarwood plots. Image (c) shows soil being sieved in preparation for pH and texture analysis. In image (d), wood core samples are being measured for biometric data. Image (e) depicts the initial reading of soil texture, while image (f) indicates the two-hour waiting period required before taking the second texture reading.

Chapter Four: Spatial Distribution Modelling

4.1 Introduction

Agarwood, a fragrant resinous wood derived primarily from trees of the genus *Aquilaria*, is highly valued across Asia for its use in traditional medicine, incense, and perfumes. Bangladesh, with its favorable subtropical climate and extensive hilly terrain, also suitable environmental conditions for agarwood cultivation and natural propagation. However, the wild populations of *Aquilaria* species are under severe threat due to overexploitation, habitat degradation, and climate variability. *Aquilaria malaccensis*, the most commercially valuable species in the region, is listed under Appendix II of the Convention on International Trade in Endangered Species (CITES), reflecting its threatened status due to unsustainable harvesting practices and habitat destruction (Chen et al., 2011). Moreover, stress-induced conditions such as wounding or fungal infection—crucial for resin production—are becoming less prevalent due to diminishing forest cover and environmental degradation, further threatening the natural production of agarwood (Nasser et al., 2021).

Species distribution modeling (SDM) is a powerful tool in conservation planning, allowing researchers to model the ecological niche of species and predict potential habitats under current and future environmental scenarios. By analyzing relationships between species occurrence and environmental variables—including temperature, rainfall, soil pH, organic matter, and canopy cover—SDM facilitates spatial planning for biodiversity conservation, ecological restoration, and sustainable resource management (Elith & Leathwick, 2009; Kumar et al., 2020). This chapter details the methodology and results of an SDM study for *A. malaccensis* in Bangladesh, aiming to map current suitable habitats and inform future conservation strategies.

4.2 Data Collection and Preparation

4.2.1 Field Sampling and Study Area

To build a reliable predictive model, data collection focused exclusively on regions known to contain naturally growing agar trees. A comprehensive reconnaissance survey, aided by historical records from the Forest Department and relevant literature, guided the identification of survey zones. A total of 259 sample plots, each measuring 20 × 20 meters, were established across different ecological zones.

The spatial distribution of plots was as follows: 127 plots in the Sylhet region, 73 in Chattogram, 20 in Cox's Bazar, 10 in Teknaf, and 29 in Tangail. Plots were separated by a minimum distance of 100 meters to ensure spatial independence. This spatial design allowed a broad ecological representation and minimized sampling bias.

4.2.2 Species Occurrence Data

Species occurrence data was gathered using both transect walks and fixed-area plot sampling. For each observation, GPS coordinates (latitude and longitude) and elevation data were recorded. These georeferenced points provided the foundation for spatial modelling.

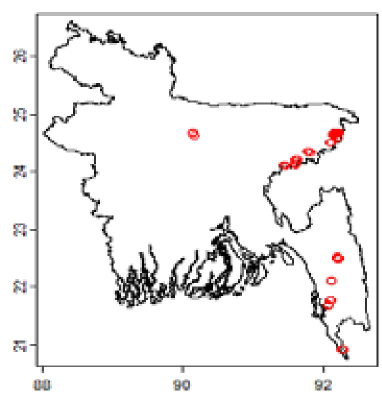

Figure 6. Sampling sites of *Aquilaria malaccensis* in Bangladesh

4.2.3 Soil Analysis

Soil samples were collected at five randomly chosen points within each plot at a depth of 0–15 cm. These were composited into a single sample per plot. Laboratory analyses measured key physicochemical properties:

- Soil pH using the 1:1 water-soil slurry method (Hanna HI2211 pH meter)
- Organic Matter (OM) and Soil Organic Carbon (SOC) via Loss-on-Ignition method
- Soil texture (sand, silt, clay percentages) using the hydrometer method
- Soil moisture content (MC) by gravimetric analysis (dried at 105°C for 24 hours)

4.2.4 Canopy Openness

Canopy openness, which affects light availability and microclimate, was measured using hemispherical photographs at five points per plot. The images were processed using ImageJ software to estimate the percentage of open sky, providing insight into the forest structure.

4.2.5 Bioclimatic Variables

Bioclimatic variables were sourced from WorldClim (Fick & Hijmans, 2017), a global repository offering high-resolution climatic datasets. Nineteen variables were used, representing annual trends, seasonality, and extreme environmental conditions (Cui et al., 2021).

- Temperature-based variables included annual mean temperature (BIO1), temperature seasonality (BIO4), and extremes such as max temperature of warmest month (BIO5).
- Precipitation variables included annual precipitation (BIO12), precipitation of driest month (BIO14), and precipitation seasonality (BIO15), among others.

These variables offer comprehensive climatic characterization, which is critical for modeling plant-environment interactions.

4.2.6 Variable Selection and Multicollinearity Control

Multicollinearity among predictor variables can distort model outputs. To mitigate this, the Variance Inflation Factor (VIF) was applied following the methodology of Naimi & Araújo (2016). A stepwise selection approach using the vifstep() function in the usdm R package (version 4.2.1) was adopted. A VIF threshold of 10 was used, resulting in the retention of 11 variables with minimal collinearity: soil characteristics (clay, silt, organic matter, moisture content), topographic elevation, canopy openness, and climatic variables including BIO1, BIO4, BIO12, BIO14, and BIO15.

4.2.7 Species Distribution Modeling Approach

The modeling framework included five algorithms: MaxEnt, Random Forest (RF), Generalized Linear Model (GLM), Multivariate Adaptive Regression Splines (MARS), and Boosted Regression Trees (BRT). These models were trained using the occurrence and environmental data, with 10-fold cross-validation.

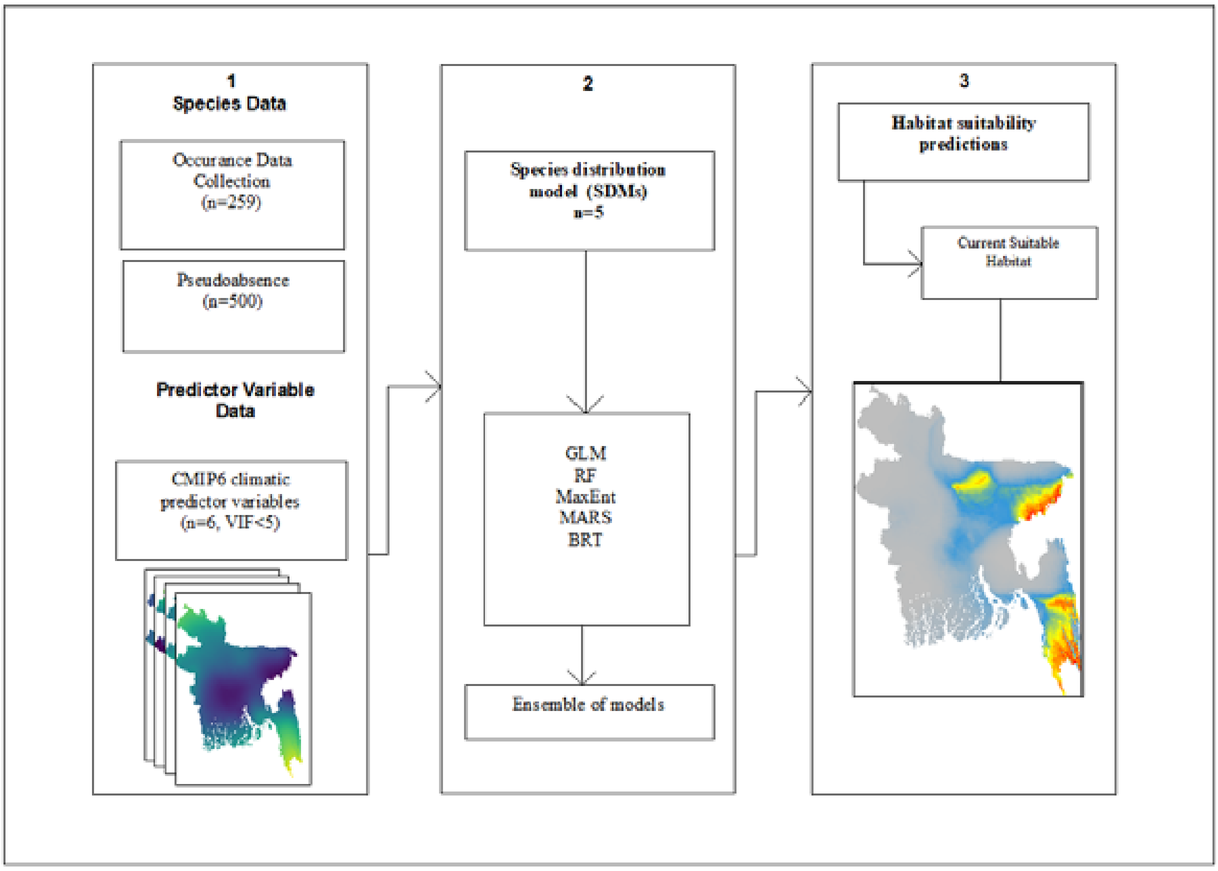

Figure 7. Workflow of species distribution modelling using environmental and occurrence data.

4.2.8 Threshold-Based Presence-Absence Mapping

To convert the continuous habitat suitability output of the ensemble model into binary presence–absence maps, a thresholding approach was applied, which is critical in transforming probabilistic predictions into ecologically interpretable outcomes. Specifically, the Maximization of Sensitivity and Specificity (MaxSe+Sp) method was employed, where the optimal threshold is determined by maximizing the sum of sensitivity (true positive rate) and specificity (true negative rate). This method is widely recommended in ecological modeling due to its balance between omission and commission errors (Liu et al., 2005; Jiménez-Valverde & Lobo, 2007).

All raster grid cells with predicted suitability values greater than or equal to this threshold were classified as presence (1), while those below were assigned as absence (0). This binary classification not only simplifies interpretation but also facilitates the development of distributional range maps, enabling spatial comparisons across time (e.g., between current and future climate scenarios). In the context of *Aquilaria malaccensis*, such maps are essential for identifying zones of potential habitat contraction, expansion, and fragmentation, which are vital for climate-adaptive conservation planning.

Additionally, presence–absence conversion allows integration with landscape metrics (e.g., patch connectivity or fragmentation indices) and enables quantification of habitat stability or gain/loss between temporal layers. The use of thresholding is particularly relevant for communicating SDM outcomes to non-specialist stakeholders and policymakers by translating complex probabilistic models into actionable binary maps (Pearson et al., 2007). This approach is consistent with SDM best practices, especially when model evaluation metrics such as AUC, TSS, and Kappa are used in combination with threshold optimization to validate predictive performance.

4.3 Model Performance

The current potential distribution of Agarwood was predicted accurately with the models. The models demonstrated notable differences in predictive performance, as reflected in their evaluation metrics. AUC scores ranged from 0.81 to 1.00, indicating varying abilities to distinguish between presence and absence, with several models displaying excellent discriminatory power. Similarly, correlation coefficients (COR) spanned from 0.54 to 0.96, underscoring variations in the strength of association between predicted and observed values. Deviance values, which ranged between 0.13 and 0.98, provided insight into model fit, with lower values denoting a better fit to the data. In terms of classification accuracy, TSS values varied from 0.65 to 0.97, where higher scores indicated more accurate predictions.

Table 4. Results of the Model

Model	AUC	COR	TSS	Deviance
Maxent	0.98	0.86	0.94	0.49
RF	0.99	0.96	0.97	0.13
GLM	0.81	0.54	0.65	0.98
MARS	0.98	0.91	0.93	0.4
BRT	0.98	0.87	0.91	0.64

Among the tested algorithms, the Random Forest (RF) model consistently yielded the best performance, attaining perfect AUC (0.99), a high correlation (0.96), very low deviance (0.13), and the highest TSS (0.97). The MARS and Maxent models also performed strongly, both achieving AUC values of 0.98 and TSS above 0.93. In contrast, the Generalized Linear Model (GLM) showed relatively weaker results across all metrics, particularly with a higher deviance (0.98) and lower COR (0.54). The BRT model, while still strong, showed slightly lower classification metrics compared to RF and MARS. These findings highlight the superiority of ensemble and tree-based methods for species distribution modelling in this context.

4.4 Result

4.4.1 Habitat suitability Under Present climate scenarios

The habitat suitability map for *Aquilaria malaccensis* in Bangladesh, generated through ensemble modelling, shows clear spatial variation in potential growth areas.

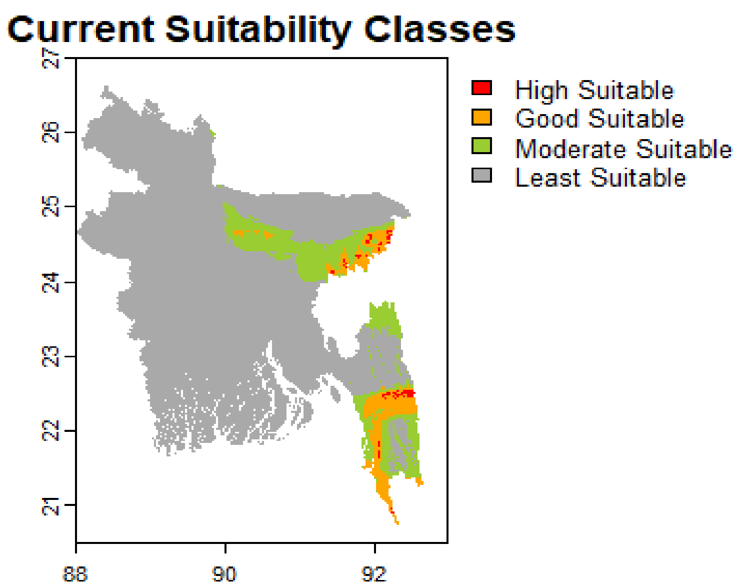

Figure 8. Current habitat suitability map of *Aquilaria malaccensis* categorized into four suitability levels.

Most of the country (approximately 79.92% or 118,593 km²) is classified as least suitable, mainly due to unfavourable climatic and soil factors like temperature extremes and low soil moisture. Moderately suitable areas cover 10.36% (15,368 km²), located mainly in Tangail, parts of the northeast (e.g., Habiganj), and hill tracts, where improved management could support cultivation. Good suitability zones (4.28% or 6,345 km²) are found mainly in Chattogram, Cox's Bazar, and nearby southeastern districts, featuring moderate seasonality and adequate rainfall. Only a small fraction (0.47% or 701 km²) is highly suitable, characterized by stable climate and fertile soils, representing prime areas for conservation and plantation expansion. Overall, about 15% of Bangladesh's land shows moderate to high suitability, highlighting significant potential for targeted agarwood cultivation and ecosystem restoration.

Table 5. Area of the suitable habitat of Agar across the country

	Least (km2)	**Moderate (km2)**	**Good Suitable**	**High (km2)**
Current Area	**118593**	**15368**	**6345**	**701**

4.5 Discussion

This section discusses the significance of species distribution modeling (SDM) using the MaxEnt model for identifying the current and potential habitats of *Aquilaria malaccensis* (agarwood) in Bangladesh. The model revealed that only a small portion of land (701 km²) is highly suitable for cultivation, with an additional 6,345 km² considered good—highlighting the species' narrow ecological niche and stressing the need for urgent conservation measures. Key areas for agarwood cultivation include Sylhet, Chattogram, and Teknaf.

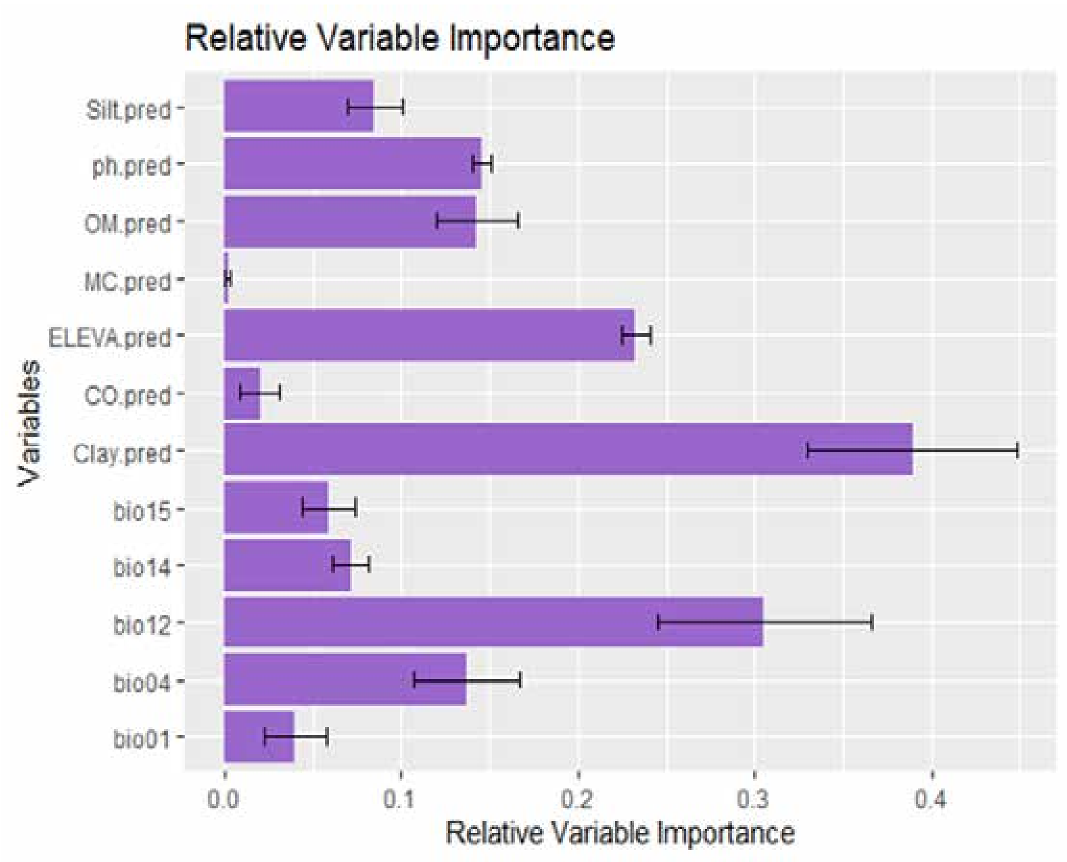

Figure 9. Relative Variable Importance for habitat suitability

The model's strong performance (AUC = 0.98, TSS = 0.92, COR = 0.85) confirms its reliability for ecological niche modelling, even with presence-only data. Threshold-based presence–absence mapping improved result interpretability and policy applicability. The discussion also identifies crucial environmental drivers—particularly clay content, elevation, and climatic variables like annual precipitation (BIO12) and temperature seasonality (BIO4)—as key determinants of habitat suitability. These findings emphasize the need for site-specific conservation, adaptive climate-resilient strategies, and prioritization of ecologically suitable zones for sustainable agarwood cultivation.

4.6 Implications of Policies and Good Practices

This section emphasizes the need for targeted conservation and sustainable land-use policies to protect *Aquilaria malaccensis* in Bangladesh. With only 180 km^2 of land classified as highly suitable for agarwood cultivation, urgent action is needed to prevent habitat loss from deforestation and urbanization. Conservation strategies should align with international conventions like CITES and enforce stricter controls on illegal trade. Policies should prioritize areas with clay-rich soils and optimal elevations, as these conditions are crucial for agarwood growth.

Best practices must also incorporate adaptive land-use planning that responds to climatic needs—particularly stable rainfall and minimal temperature fluctuations—essential for resin production. Integrating climate monitoring and adaptation strategies into policy frameworks will support the resilience of agarwood habitats and enhance the economic potential of sustainable cultivation across Bangladesh.

Figure 10: Nursery of Agar trees at Shomonbagh Beat, Juri Range

Chapter Five: Non-Detrimental Findings of Agar in Bangladesh

5.1 Introduction

Agarwood, mainly from *Aquilaria malaccensis*, is one of the world's most valuable natural products, widely used in perfumes, incense, and traditional medicine. However, high global demand has led to overharvesting, illegal trade, and declining wild populations, including in Bangladesh. To address this, *A. malaccensis* is listed in CITES Appendix II, which requires Non-Detriment Findings (NDF) to ensure that trade is sustainable and does not threaten the species' survival.

This study aims to develop a comprehensive NDF report for agarwood in Bangladesh, providing a science-based framework to assess population status, harvesting practices, and trade impacts. The goal is to promote legal, sustainable trade aligned with CITES guidelines. Key agarwood-producing regions include Sylhet, Chittagong Hill Tracts, Cox's Bazar, and Tangail, where both natural forests and private plantations exist. Currently, much of the agarwood trade is informal and of degraded quality, making it hard for Bangladeshi traders to compete internationally. A formal NDF process can improve quality control, ensure legal compliance, support biodiversity conservation, and open legal export opportunities, benefiting local

5.2 Private-Owned Plantations

Private plantation owners in Bangladesh have developed a well-established system for the cultivation, processing, and trading of agarwood. Private owned agar plantations are mostly prominent in Barlekha, MoulviBazar region. Sujanagar in Barlekha is called the capital of agar in Bangladesh. However, there are few private plantations in Rangamati, Chittagong, and Sylhet sadar upazila. Of the 121 registered agar-based factories nationally, 111 are located within this region, making a major contribution to regional employment and gross domestic product. The following outlines the different stages involved in the private sector's participation in agarwood trade:

5.2.1 Sourcing of Seedlings and Plantation Establishment

Private owners are proactive in sourcing seedlings, which are often acquired from local nurseries specializing in agarwood or directly from their own plantations. They invest in plantation establishment, ensuring that the trees are grown under conditions conducive to resin production. Typically, private plantations range in size, but larger operations span across several hectares, with owners carefully managing the growth of agar trees for optimal resin yield. One of the nursery owners stated that there are three large nurseries in Barlekha from which most of the plantation owners source seedlings if needed. He also told us that he produces almost 1 lakh seedlings every year.

5.2.2 Harvesting Process

Agarwood harvesting in private plantations occurs when the trees reach maturity, which is typically between 7 to 10 years, though some may wait longer for increased resin accumulation. The harvesting process involves:

5.2.3 Inoculation method

In many cases, plantation owners use artificial methods to speed up the resin production in agarwood trees, which improves the quality of the final product. In areas like Moulvibazar and Barlekha Upazila, a common technique involves driving nails (locally called "Perek") into the trees about 4-5 years before harvesting. This method, known as the "nailing method," is popular because waiting for resin to form naturally takes too long, which isn't practical for business. By using this approach, plantation owners can harvest earlier. Nailing is usually done when the trees are around 7-8 years old, and after another 4-5 years, the trees are harvested. The cut trees are then taken to factories for further processing.

5.2.4 Selective Harvesting:

Instead of cutting down all the trees at once, plantation owners carefully choose only the trees with a high amount of resin for harvesting. This is also common in Moulvibazar. Businessmen, using their experience, can often tell by looking at the tree which ones have good resin levels. They select these trees, agree on a price with the owner, and then cut them down for sale or processing in their own factories.

5.2.5 Processing of Agarwood

A factory owner and a member of the Agar Samity Bangladesh described the whole process of agar goods production to us, and we visited his factory in person. After the agarwood is harvested, it undergoes a detailed processing procedure, typically at specialized facilities owned or contracted by the plantation operators. The goal of processing is to extract and refine two main products from the resin-rich parts of the tree: agar oil (also known as oud oil) and agarwood chips or powder. These products are highly valued in global markets, especially in regions such as the Middle East and Southeast Asia. The processing stages are as follows:

> ***"We have been doing agar business for generation after generation. We can easily tell you which tree has better resin produced and which has less. It's all about experience. Same goes for other agar businessmen. Sometimes they come, observe some trees and ask for one or more which they think might have resin produced well''***
>
> ***- One small factory owner said.***

5.2.6 Agar Oil (Oud Oil):

Agar oil is considered the most valuable and sought-after product derived from agarwood. The process begins by carefully selecting the resinous sections of the tree, which are known for their aromatic properties. These sections are subjected to a steam distillation process. During this method, the wood is soaked in water for several days to soften it, after which it is placed into distillation apparatuses. The heat causes the resin to separate from the wood, producing the highly fragrant oil. Oud oil is prized for its unique, complex scent and is widely used in high-end perfumes and traditional incense. Due to its rarity and the intricate processing involved, agar oil commands extremely high prices in international markets, particularly in the luxury perfume industry in the Middle East, where it is regarded as a symbol of prestige and status.

5.2.7Agarwood Chips and Powder

The solid parts of the processed agarwood are also valuable and are converted into chips or powder. Agarwood chips are typically created by cutting or shaving the resinous wood into small pieces. These chips are highly coveted for their potent aroma when burned and are commonly used in cultural and religious practices as incense. In many parts of Southeast Asia, these chips are burned during ceremonies to create a fragrant environment. In addition to chips, agarwood is sometimes ground into powder, which is then used in the creation of traditional incense sticks, cones, and other aromatic products. Both chips and powder serve as key ingredients in the perfume and incense industries, where they are appreciated for their strong, long-lasting fragrance.

5.2.8 Marketing and Trade

Private plantation owners employ a variety of strategies to sell their products:

- Direct Export: Many private owners have established networks with international buyers, particularly from countries like Saudi Arabia, UAE, Singapore, Malaysia, and Japan etc, where agar products are in high demand.

- Use of Middlemen: In some cases, owners sell their products to middlemen, who either export the products or sell them domestically. These middlemen play a crucial role in connecting small-scale producers to the larger market.

- Local Market: While most high-value agar products are exported, some lower-grade agarwood is sold in local markets for domestic use as direct wood chips, or as locally made "Agar Bati".

This well-integrated supply chain allows private owners to manage everything from seedling procurement to the export of finished products.

5.2.9 Drawbacks of Private Plantation and Trading

Private Agarwood plantation owners in Bangladesh face several challenges that hinder their growth and competitiveness in the global market. One of the most significant issues is the lack of formal registration and certification, as most trades occur informally. This informal trade leads to unregulated pricing, reduced profitability for traders, and missed opportunities for contributing to national revenue. Without proper certification and traceability, Agarwood products from Bangladesh struggle to gain acceptance in international markets, limiting their global reach and reputation. One plantation owner from Shomonbagh remarked:

> *"We trade mostly informally, so we can't charge the expected price. Again, in recent times the buyers are doubting our quality due to lack of traceability and certification."*
>
> *-Plantation owner in Shomonbagh*

Another major issue is the lack of technical knowledge and training on sustainable cultivation and resin extraction methods. This gap reduces the quality and yield of the products. The absence of public-private cooperation further exacerbates the problem, with little support available to improve cultivation practices, establish pricing standards, or promote the industry. In Vietnam and Malaysia, several inoculation methods are used to induce agarwood resin production in Aquilaria trees, each tailored to balance production speed and quality. Chemical inoculation, where chemical mixtures are injected into the tree to trigger resin formation, is widely used for its efficiency and cost-effectiveness, though it may leave residues affecting resin purity. Biological inoculation, using fungi to naturally stimulate resin, produces high-quality agarwood but is slower. Mechanical wounding involves making cuts to the tree to stimulate resin, often combined with chemical or biological methods for better results. Hybrid techniques, blending these approaches, offer a balanced solution, while microbial inoculation—injecting bacteria or fungi—provides a sustainable, eco-friendly option. Vietnam tends to focus more on biological methods for quality, whereas Malaysia emphasizes chemical and hybrid techniques for faster production, supported by advanced research.

A pressing concern highlighted by many respondents in Sujanagar is the unavailability of gas lines and the high price of gas necessary to run their factories. Despite Agarwood being a prominent industry, plantation owners are not provided industrial gas lines, unlike other industries, which significantly increases their production costs. As a result, profitability is severely impacted. The President of the Agar Samity expressed the frustrations of plantation owners:

> *"We have been trying for a long time to get access to industrial gas privilege for our factories, as our factories are mostly run by gas. But we haven't got any green signal from the government yet. If we are provided industrial gas lines, it will reduce our production cost a lot."*

Limited financial resources, poor access to international markets, and reliance on intermediaries further restrict growers' ability to maximize profits. In the past, industry owners could secure loans on fixed terms from the Agar Samity, but this has been restricted in recent years due to a capital crisis. No formal bank loan facility is available specifically for Agarwood plantation owners. Another concern in recent times is the sharp decline in exports due to a lack of quality control measures and insufficient promotion. Agarwood oil or wood produced from nailed trees has been identified as lacking the quality demanded by international buyers.

Meanwhile, countries like India and Malaysia are using modern inoculation tools to enhance resin production, leading to an increase in their exports.

> *"There is no research on inoculation in Bangladesh. We only know about nailing. But nailing these days no longer produces good quality agar due to harvesting too early. We are gradually losing our position in the global market. We have heard about research on inoculation in BFRI, we are eagerly waiting for the outcome."*
>
> -Mr Kabir Hossain, General Secretary, Agar Samity

Moreover, there is little investment in research and development (R&D) aimed at improving Agarwood production, leaving plantation owners without access to improved genetic varieties or modern processing techniques. Environmental concerns, such as deforestation and unsustainable practices, remain unchecked due to inadequate government oversight. Additionally, competition from well-established Agarwood-producing countries like India and Vietnam intensifies the challenges, making it increasingly difficult for Bangladeshi producers to compete globally.

5.3 Government-Owned Agar Plantations

Government-owned plantations, despite having vast areas under agarwood cultivation, have not yet entered the trade of agarwood products. According to the register of Bangladesh Forest Department, 992 hectares of agar plantation were developed in different ecological zones of the country which were all planted in a rotation age of 20 years. Due to adverse climatic conditions and human interventions, a good portion of plantations failed.

Despite that, government plantations in Sylhet, Chittagong, Cox's Bazar, Kaptai, Tangail, and Dinajpur have a great abundance of agarwood trees. There have been nurseries dedicated to produce agar seedlings in several forest areas, especially in Shomonbag forest under Jury Range in MoulviBazar District. Many of the plantations, especially in Teknaf and Habiganj, have reached their rotation age. However, they haven't yet been brought under any harvesting or any other management. These mature plantations represent a significant untapped economic resource. In the below we have listed the key challenges of government owned agar plantations include.

5.3.1 Bureaucratic Delays

One of the primary reasons for the inactivity in government-owned plantations is the complex bureaucracy involved in decision-making. Various government departments, including the Forest Department, Ministry of Environment, and Ministry of Trade, have overlapping responsibilities, which leads to delays in decisions regarding:

5.3.2 Lack of Clear Harvesting guidelines for Agarwood

There is currently no clear or systematic plan in place for the harvesting of mature Agarwood trees in government-owned forests, despite the fact that many of these trees have reached maturity. While harvesting Agarwood is part of the government's broader plan and national policy, the implementation details remain vague and uncertain.

Field-level staff, who are directly involved with the forests, have limited knowledge about when or how the harvesting will take place. Although they are aware that such a plan exists as part of national policy, they lack concrete information on the specifics. Senior officers within the forestry sector are more aware of the plan's existence but remain unsure about the precise timing or the approach to be taken. As per one of the forest officials in MoulviBazar, a collaborative approach of the Department of Environment, Department of Agriculture Extension and Forest Department is needed to take further action regarding agar which is still unclear to many officials. As a result, even the higher authorities are unable to provide clear guidance on when the plan will move forward or how it will be carried out in a systematic manner. This lack of coordination and clarity is delaying the harvesting process, leaving valuable Agarwood resources underutilized, and causing concern among stakeholders who are eager for a more efficient approach to managing these forests.

> *"Most of the agar plantations were done as a part of restoration of denuded lands in different forests. Though benefit sharing was initially addressed, there has been no approach from the department regarding harvesting of matured agar trees."*
>
> - A range officer in Habiganj

The beneficiaries of government-owned Agarwood plantations have shown remarkable patience over the years, but recent delays in harvesting and trade activities have left many feeling uncertain about their future prospects. Despite their long-standing commitment to maintaining the plantations, they are losing interest day by day due to the lack of any concrete plans regarding the harvesting and trade of Agarwood. This growing sense of doubt reflects the wider issue of beneficiaries feeling disconnected from the decision-making process and the forest department's long-term plans for these plantations.

> *"We've been caring for the plantation for the past 20 years, but it's disheartening that our hope in the benefit-sharing agreement is fading, and our trust in the forest department is being questioned.*

We're uncertain whether we will ever receive our share. Despite this, we remain patient and hopeful that the forest department has a plan in place."

-A beneficiary in Kaptai said.

5.3.3 Trade Authorizations

In addition to concerns about benefit-sharing, the process for exporting Agarwood products from government plantations adds further complications. Multiple layers of approval from different government bodies are required to obtain the necessary permissions, and there is no streamlined or efficient process in place for securing these trade authorizations. This bureaucratic complexity further frustrates beneficiaries and slows down any potential commercial gains from the plantations.

Without a clear, well-defined process for both the harvesting and trading of Agarwood, beneficiaries are left in a state of uncertainty, unsure of when or if they will see the fruits of their decades-long labor.

5.3.4 Absence of a Well-Defined Legal Framework for Agarwood Trade

A critical obstacle hindering the growth of the Agarwood industry in Bangladesh is the lack of a comprehensive legal framework governing the trade of Agarwood products from government-owned forests. This regulatory vacuum creates multiple challenges for plantation managers, beneficiaries, and stakeholders involved in the Agarwood sector.

5.3.5 Lack of Clear Policies on Harvesting:

One of the most pressing issues is the absence of clear regulations on when and how to harvest Agarwood trees from government plantations. Despite the maturity of many Agarwood trees, there are no formal guidelines to ensure a systematic and sustainable approach to harvesting. Without clear policies, there is a risk of either over-harvesting, which could deplete resources, or delayed harvesting, leaving valuable trees underutilized. The absence of harvesting plans not only affects the profitability of the plantations but also causes frustration among beneficiaries, who have been waiting for years to see returns on their investment in the care and maintenance of the trees.

Figure 12. Photos taken during meeting or conducting FGDs in different locations, a) FGD in Tangail, b) FGD in Teknaf Sadar, c) Agar beneficiaries of Preyongkhong beat, Kaptai, d) FGD in Satchari National Park

In addition, the lack of standardized harvesting methods impacts the quality of Agarwood, as improper harvesting techniques can reduce the resin yield or damage the trees, making the final product less competitive in global markets. This policy gap further undermines the potential of Bangladesh’s Agarwood industry to establish a strong foothold in international trade.

5.3.6 Uncertainty Regarding Trade Permissions

Another significant challenge is the ambiguity surrounding who holds the rights to trade Agarwood products from government plantations. There is no clear designation of authority when it comes to issuing trade permissions, leading to confusion and hesitancy among potential traders. Multiple government bodies may be involved in the decision-making process, but their roles and responsibilities are poorly defined, resulting in delays and bureaucratic hurdles.

For stakeholders interested in exporting Agarwood, the uncertainty regarding trade permissions creates significant risks. They may invest in cultivating and processing Agarwood, only to face difficulties in obtaining the necessary approvals for export. This not only discourages private-sector investment but also restricts the ability of government plantations to tap into the lucrative international market.

Together, these gaps in the legal framework make it difficult for the Agarwood industry in Bangladesh to grow and compete globally. Clear, well-defined policies on harvesting and trade are crucial for ensuring the sustainable development of this sector and for maximizing the economic benefits for all stakeholders involved.

5.3.7 Conservation Concerns and Lack of Coordination

Government officials are often concerned with the conservation of forest resources, and the potential environmental impact of agarwood harvesting may be viewed as a reason for inaction. Furthermore, the lack of coordination between different government agencies has resulted in a failure to develop a cohesive strategy for the sustainable trade of agarwood.

5.3.8 Lack of research and development tools and investments

In Bangladesh, research on Agarwood (agar) development and production has primarily focused on its economic contribution, with limited attention given to other critical aspects. Areas such as the genetic diversity of Agarwood species, genetic improvement, scientific methods for inoculation, and sustainable harvesting and management practices remain under-researched. The lack of studies in these areas has hindered the optimization of cultivation techniques and the long-term sustainability of Agarwood production in the country.

While the Bangladesh Forest Research Institute (BFRI) has made notable strides in recent years by conducting extensive research on artificial resin induction in Agarwood, these efforts primarily aim to improve the productivity and quality of Agarwood products. However, there is still a significant need for more comprehensive research. For instance, scientific inoculation methods could be further refined to ensure more consistent resin production, and studies on genetic diversity could lead to the identification of superior Agarwood strains that offer higher yields or better-quality resin.

Additionally, research into sustainable harvesting and management practices is critical to ensuring the long-term viability of Agarwood plantations. Without proper management, unsustainable practices could lead to resource depletion and environmental degradation. More focused research in these areas would provide valuable insights into improving the efficiency, quality, and sustainability of Agarwood cultivation in Bangladesh, thereby enhancing the industry's overall contribution to the economy and the environment.

5.3.9 Conclusion

The Agarwood sector in Bangladesh faces significant legal and institutional challenges. Unclear trade permissions create uncertainty for investors and discourage private-sector participation. The absence of a designated authority for issuing export licenses results in bureaucratic delays. Conservation concerns, while important, often hinder progress due to lack of coordination among government bodies. Additionally, there is a serious research gap in areas critical to sustainable Agarwood development. Key issues such as genetic diversity, scientific inoculation, and sustainable harvesting remain underexplored. Although BFRI has made progress, efforts remain limited in scope. Comprehensive R&D is essential to improve yield, quality, and ecological sustainability. Without policy clarity and targeted research, the sector cannot compete in global markets. To ensure long-term growth, Bangladesh must streamline trade regulations and invest in scientific innovation.

Remarks on the Status of Naturally growing Agarwood Trees and Non-Detrimental Findings

In the course of our research on Agarwood (Aquilaria spp.) in Bangladesh, a key observation has been the absence of naturally growing agar trees within natural forest ecosystems. Despite concerted efforts to locate such populations using snowball sampling and focus group discussions, we were unable to confirm the presence of any natural individuals in government-managed or community forests. These methods included consulting local forest users, indigenous communities, experienced harvesters, and plantation owners with generational knowledge of agar in the region. The findings were consistent across multiple study sites, strongly indicating that naturally occurring agarwood trees are either functionally extinct or extremely rare in the wild in Bangladesh.

As a result, our analysis does not propose any decision or claim regarding detrimental findings based on naturally growing populations. Rather, the focus of our assessment is on cultivated agarwood trees—those that have been planted and managed within private and institutional plantations across different ecological zones. The abundance and biomass data used in this study were collected from these cultivated stands. Additionally, perspectives from stakeholders were captured through structured focus group discussions that shed light on various aspects of the supply chain, management practices, and ecological dynamics.

Despite the absence of natural individuals, our study undertook a comprehensive exploration of the nine critical steps required for establishing detrimental findings as outlined in international guidelines. These include propagation, conservation status, inoculation methods, harvesting practices, trade volumes, regeneration capacity, management strategies, legal frameworks, and sustainability assessments. In each of these steps, we collected empirical evidence through field visits, measurements of above-ground biomass, and interviews with relevant stakeholders such as growers, traders, forest officials, and researchers.

Propagation techniques in Bangladesh are now largely dependent on nursery-based saplings and vegetative propagation. Conservation efforts remain largely limited to plantation-scale initiatives, and there is no targeted program for in situ conservation of wild agar trees, primarily due to their apparent absence in natural ecosystems. Inoculation practices vary, with artificial methods becoming increasingly popular, though not yet standardized. Harvesting typically occurs in privately owned plots, and is largely driven by market demand, without formal monitoring or certification systems in place.

In conclusion, while the absence of wild agar populations precludes a traditional detrimental finding, our findings underscore the need for a plantation-based sustainability model. Policymakers and international agencies must recognize the cultivated nature of Bangladesh's agarwood sector and tailor their regulatory and conservation frameworks accordingly. Our study provides a baseline for such efforts by documenting current practices, biomass potential, and management challenges. Going forward, investments in research, policy clarity, and coordinated conservation strategies will be crucial to ensuring the ecological and economic sustainability of the agarwood industry in Bangladesh.

Chapter Six: Recommendations

Based on fieldwork conducted across five publicly and privately owned Aquilaria (agarwood) cultivation sites in Bangladesh, this study presents a set of critical recommendations to enhance the sustainability and economic potential of the agarwood sector. Through the estimation of standing volume and biomass stock, combined with insights from focus group discussions (FGDs) and an in-depth analysis of the Agar Brikkho Bikroy Nitimala-2012, the findings highlight several key policy gaps and practical challenges. While the existing Nitimala prioritizes government-owned plantations in the procurement and trade of agarwood, our study reveals a contrasting ground reality. Privately managed plantations were found to exhibit significantly higher biomass and tree density compared to their government-owned counterparts. This suggests that private cultivators, often operating with greater flexibility and care, may contribute more substantially to the national agarwood stock than currently recognized by policy. Accordingly, the study recommends a recalibration of the current regulatory framework to ensure fair market access for private growers, encourage best cultivation practices, promote sustainable harvesting, and establish a transparent, CITES-compliant product traceability system. Strengthening institutional coordination and revising outdated rules will be essential steps toward unlocking the full economic and ecological potential of agarwood in Bangladesh.

Recommendation for both Government and Private Plantations

1. **National Agarwood Management Strategy**

- **Establish a Coordinated Cultivation and Marketing Plan**: Develop region-specific plans through community-private partnerships to boost production and income opportunities.
- **Standardize Quality and Certification Systems**: Implement national standards for grading and certifying agarwood products to improve market transparency and meet export requirements.
- **Strengthen Institutional Coordination**: Ensure effective collaboration between government agencies, research institutions, and private stakeholders for policy alignment and implementation.

2. **Create Agar board**

Establishing a national-level Agar board is essential to streamline and regulate the agarwood industry in Bangladesh. This board would act as a central authority responsible for overseeing policy implementation, quality control, certification, trade facilitation, and coordination among stakeholders including government agencies, private growers, exporters, and researchers. It would ensure that both private and public sector activities align with national and international legal standards such as CITES, promote sustainable practices, and help address issues like illegal trade, adulteration, and lack of technical guidance. Additionally, the Agar board could facilitate research, training, and innovation, enhancing the global competitiveness of Bangladesh's agarwood industry.

3. **Formation of an Agarwood Price Evaluation Committee:**

To eliminate disputes over pricing and bring transparency in trade:

- Establish a multi-stakeholder committee including FD officials, local beneficiaries, registered processors, and academic forestry experts under the Agar Board.
- This committee will regularly assess resin quality and issue standard reference prices for government auctioned agarwood.
- Use scientific grading systems for resin-based products (e.g., oil grades, chip grades) to determine market value fairly.

4. Revise Harvesting Guidelines and Recognize Resin Induction Legally

There is a longstanding policy vacuum regarding the legality of wounded or nailed trees. To address this:

- Legally define nailed trees as harvestable under regulated and verified conditions.
- Allow monitored harvesting by community-based groups based on plantation maturity, health, and registered inventory.
- Include protocols for periodic verification of tree condition, resin formation, and ownership updates.

5. International Trade Promotion

To maximize the economic potential of agarwood trade in Bangladesh, efforts should be made to promote Bangladeshi agarwood products in the global market.

- **Trade Fairs and Expos:**

Encourage participation in international trade fairs and expos to showcase Bangladeshi agarwood products and establish connections with global buyers.

- **Branding and Marketing:**

Develop a national brand for Bangladeshi agarwood products, emphasizing quality, sustainability, and legality, which will appeal to high-end international markets like the Middle East, Europe, and Southeast Asia.

- **Export Facilitation:**

Simplify export procedures for certified agarwood products, ensuring a smooth process for enterprises wishing to sell their products abroad.

Recommendation for Private Plantations

1. Develop Agarwood trade centre in Barlekha under the Agar Board:

The Agarwood Trade Centre in Barlekha will serve as a key hub for promoting and expanding the agarwood trade, with a strong focus on facilitating international market access. It will offer essential facilities such as spaces for buyer-seller meetings, video conferencing, trade information services, educational support, and exhibition areas. This center will create significant opportunities for attracting foreign investment while providing substantial benefits to agarwood farmers and traders through enhanced exposure and market connectivity.

2. Establish a Legal Policy Framework for Agarwood Trading

A standardized regulatory framework should be established to enable private plantations to participate in the agarwood trade, covering all steps from cultivation to export. This framework must include clear guidelines for sustainable production, such as approved resin induction methods, effective pest control, and proper plantation management practices. Legal provisions should also be enforced to ensure that agarwood is harvested only from certified and legitimate sources, promoting traceability and compliance with national and international trade regulations.

3. Registration and Certification of Enterprises and Traders:

To formalize and standardize the agarwood trade, every enterprise and trader involved in the agarwood supply chain must be registered, and their activities legally regulated.

✓ Enterprise Registration:

Require all agarwood-related enterprises (plantations, processors, traders) to register with the government or an authorized body. Create an online registry for transparency, where each enterprise’s registration status is publicly accessible.

✓ **Certification of Legality:**

Mandate that all agarwood products be certified by the government or a government-authorized body before they are marketed or exported. Introduce certification requirements that ensure the agarwood was cultivated, harvested, processed, and traded in accordance with national and international standards (such as CITES).

✓ **Trade Compliance:**

Ensure that every agarwood trade transaction is conducted legally, with proper documentation and licensing. Trading agarwood without legal registration and certification should be penalized to discourage illegal practices.

4. Strengthen Legal Traceability through Certificate of Ownership:

To eliminate the risk of illegal sourcing and ensure compliance:

- Require the Certificate of Ownership of Agarwood Cultivation at every node—cultivation, harvesting, transport, trade, and export.
- Link this certificate to plantation registration records and resin output logs.
- Integrate with digital systems to ensure CITES compliance for all exports.

5. Provide Incentives for Sustainable Practices:

Our study found that most agarwood plantations are located in privately-owned areas, where both the biomass and tree density are significantly higher than in government plantations. This shows how important private growers are in agarwood production. To support their efforts, proper incentives should be provided—especially for raising high-quality seedlings, better cultivation practices, artificial resin induction, and sustainable harvesting and processing. With the right support, these growers can improve the quality and quantity of their agarwood, which will benefit not only their livelihoods but also strengthen the agarwood industry as a whole.

6. Training and Awareness Generation

Proper training is essential to engage unemployed and underemployed youth in the growing agarwood sector. Specific training programs should be designed to support different stages of the value chain. This includes training for farmers and small growers on nursery management and plantation techniques, guidance on artificial resin induction, methods for cutting agarwood chips, chemical evaluation of agarwood oil, and digital marketing of agarwood products. These trainings can be conducted by recognized institutions like BFRI, as well as by qualified private agencies, NGOs, or training institutes. In addition, district-level workshops and seminars should be regularly organized, and the participation of traders in national and international trade fairs and exhibitions should be encouraged to boost market access and overall growth of the agarwood industry.

For Govt. own plantations

1. Establish a Legal Policy Framework for Agarwood Trading

To ensure sustainable agarwood harvesting in mature government forests, clear policies should guide selective harvesting to prevent overexploitation. Harvest quotas must be set to allow for natural regeneration. Technology developed by BFRI should be used to assess agarwood availability and guide informed harvesting decisions. These measures will help protect biodiversity while supporting responsible resource use.

2. Support for Sustainable Practices:

Research and Development:

Invest in research through institutions like BFRI and academic organizations to enhance resin yield and improve the quality of agarwood. This includes the development of efficient resin-induction techniques and disease-resistant cultivars.

Capacity Building and Training:

Implement specialized training programs for forestry officials and plantation managers on sustainable cultivation, proper harvesting age, and eco-friendly processing techniques.

Resource Allocation:

Ensure access to necessary resources, including skilled manpower, proper infrastructure, and environmentally sound technologies for sustainable management of public agarwood plantations.

3. Rising of quality seedling in Nursery:

High-quality agarwood seedlings and saplings should be produced in Forest Department nurseries using certified seeds or advanced tissue culture techniques. Dedicated funding must be allocated annually for the maintenance and development of these nurseries to ensure consistent seedling quality.

4. Opportunity For New Plantation:

There is significant potential to expand agarwood (*Aquilaria malaccensis*) plantations by utilizing underused or strategically located lands across Bangladesh. Notably, Sylhet's tea gardens offer a promising opportunity, where agarwood trees can be introduced as complementary species. Instead of conventional shade trees like *Acacia auriculiformis* (Akashmoni), *Albizia lebbeck* (Koroi), or *Melia azedarach* (Mingium), agarwood can be strategically planted along boundaries, roadsides, and buffer zones within tea estates. This approach, facilitated through collaboration between the Forest Department and tea estate owners, would promote agroforestry diversification and offer an additional income stream for estate managers and workers. Beyond tea estates, agarwood plantations can be extended to government-owned barren lands, roadsides, and railway embankments, which remain largely unused but suitable for long-term tree cultivation.

5. Develop Agarwood Processing Unit under the Forest department:

Setting up agarwood processing units under the Forest Department will help ensure standardized, high-quality production of resin, oil, and chips. These units will improve value addition, promote legal and traceable trade, and reduce reliance on unregulated private processors. They can also serve as training and demonstration centers for sustainable harvesting and processing. Government oversight will enhance product credibility in global markets, attract better prices, and generate revenue from public plantations. Additionally, it will strengthen monitoring and compliance with national and international trade regulations.

6. Control and Regulation of Illegal or Informal Trade

A major challenge in the agarwood trade is the existence of illegal or informal trade networks, which undermine the sustainability of the industry and deprive the government of tax revenues. Steps to control illegal activities include:

Strengthen enforcement by empowering officials with monitoring authority and conducting regular inspections of plantations, processing units, and trade centers.

Enforce strict penalties such as fines, license cancellations, and imprisonment for illegal harvesting, unregistered plantations, and uncertified exports.

Raise awareness through targeted campaigns and community involvement to curb illegal trade and promote sustainable Agarwood practices.

7. Institutionalize Transparent and Fair Auction Mechanisms

Government plantations currently lack structured auction systems. The recommendation would be to establish regular, transparent auctions for mature agarwood trees from government plantations using digital platforms with real-time bidding and independent valuation. Participation should prioritize licensed local stakeholders to ensure inclusivity and prevent monopolization.

Conclusions

This study highlights the urgent need for a more coordinated and sustainable approach to managing Bangladesh's precious agarwood resources. Once commonly found in regions like Sylhet and Tangail, wild agarwood trees have now become rare due to years of overharvesting and habitat loss.

Our fieldwork—spanning 259 plots across key ecological zones—provided valuable baseline data on tree volume and biomass. The results show that natural forests in Sylhet and the Chittagong Hill Tracts have the highest productivity, making them strong candidates for both conservation and sustainable use. In contrast, private plantations in Barlekha are producing lower yields, likely due to shorter rotation periods and more intensive harvesting.

To guide future cultivation efforts, we developed a Species Distribution Model (SDM) using climate, soil, and environmental data. The model shows that only 0.47% of the country (701 km^2) is currently highly suitable for agarwood growth, with an additional 4.28% (6,345 km^2) falling into the moderately suitable category—mainly in areas like Chattogram, Cox's Bazar, and parts of Sylhet. This underscores how selective and climate-sensitive agarwood cultivation must be, reinforcing the need for location-specific, resilient planning.

Consultations with local stakeholders and Forest Department officials have revealed major challenges, including difficulties in plantation establishment, community-level conflicts affecting management decisions, and limited understanding of agarwood commercialization. Addressing these issues requires a comprehensive, multi-stakeholder approach. Key recommendations include incentivizing the domestic agarwood industry, establishing transparent auction systems for mature plantations, and building the capacity of local communities through training in sustainable harvesting, value addition, and entrepreneurship. Furthermore, promoting public-private partnerships and engaging research institutions will help facilitate knowledge exchange, technological advancement, and the adoption of industry best practices, ultimately ensuring ecological sustainability and socio-economic benefits.

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Identification, Assessment and Verification of Potential OECMs (Other Effective Area based Conservation Measures) with In-situ Biodiversity Conservation Importance in Bangladesh

by

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1. INTRODUCTION

1.1. Context

The Sustainable Forest and Livelihood (SUFAL) Project of the Bangladesh Forest Department (BFD) awarded an “innovation grant” to the Arannayk Foundation for identification, assessment and verification of potential OECMs (Other Effective Area based Conservation Measures) in Bangladesh on 6 September 2022.

An OECM is ‘a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values (CBD CoP decision 14/8).’

Parties to the CBD included “other effective area-based conservation measures” (OECMs) in the Aichi Biodiversity Targets (Target 11) because some areas outside the recognized protected area networks also result in the effective in-situ conservation of biodiversity (CBD 2010). These can include territories and conserved areas governed by any of four governance types, i.e., by governments, private actors, Indigenous Peoples and local communities, and shared governance arrangements (IUCN-WCPA Task Force on OECMs, 2019).

OECMs offer a significant opportunity to recognize de facto conservation that is taking place outside currently designated protected areas and implemented by a diverse set of actors, including by governments, the private sector, Indigenous peoples and local communities. OECMs can contribute to ecologically representative and well-connected conservation systems, integrated within wider landscapes and seascapes. Thus, they can generate a range of positive conservation outcomes, such as: conserving important ecosystems, habitats and wildlife corridors; supporting the recovery of threatened species; maintaining ecosystem functions and securing ecosystem services; enhancing resilience against threats; and retaining and connecting remnants of fragmented ecosystems within developed landscapes.

The UNEP World Conservation Monitoring Center (WCMC) maintains the World Database on OECMs (WD-OECM) alongside the World Database on Protected Areas (WDPA) that are accessible at the Protected Planet website (thttps://www.protectedplanet.net). UNEP-WCMC (2019) has published a User Manual for the WDPA and WD-OECM that provides guidelines for submission of information for inclusion in these databases. On behalf of Parties to the CBD, the IUCN-WCPA developed technical guidelines for the identification and reporting of OECMs (Jonas et al. 2023).

Aside from protected areas, the CBD has put enormous importance on OECMs for effective in-situ conservation of biological diversity and ecosystem functions since 2010 through a decision made at the 10th meeting of the Conference of the Parties (CoP) to the CBD. The CBD Strategic Plan for Biodiversity 2011-2020 targeted that (Aichi target 11): “By 2020, at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscape and seascape” (CBD 2010).

The subsequent Kunming-Montreal Global Biodiversity Framework aims to “ensure and enable that by 2030 at least 30 per cent of terrestrial and inland water areas, and of marine and coastal areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas and OECMs, recognizing indigenous and traditional territories, where applicable, and integrated into wider landscapes, seascapes and the ocean (Target 3)”. It emphasizes ensuring that any sustainable use, where appropriate in such areas, is fully consistent with conservation outcomes, recognizing and respecting the rights of indigenous peoples and local communities, including over their traditional territories” (CBD 2022).

As of November 2022, the WD-OECM listed 827 sites globally, including 632 terrestrial and inland water OECMs and 195 marine OECMs, covering 1,587,466 km² and 359,105 km², respectively. These areas represent approximately 1.18% of the world's terrestrial and inland waters and 0.1% of its marine areas. Canada has registered the highest number of OECMs (230), followed by the Philippines (178) (UNEP-WCMC & IUCN, 2022). India and Malaysia are actively identifying and assessing potential OECM sites, though neither has yet registered any in the global database (UNDP and NBA, 2022; SEARRP, 2019). India has selected 14 sites across ten provinces. These encompass a wide range of ecosystems, including lakes, floodplains, nature reserves, bird sanctuaries, mangrove forests, and unique agricultural systems under public, private, and community ownership. Their sizes vary considerably, from the 0.4 km² Jagatpur Lake in Bihar to the 30 km² Saffron Heritage System in Kashmir (UNDP and NBA, 2022).

According to IUCN-WCPA guidelines, no fixed minimum size exists for an OECM. Instead, an area must be of "sufficient size" to achieve long-term biodiversity conservation. This critical threshold is context-dependent, determined by the ecological requirements necessary for the persistence of the species and ecosystems the site is intended to protect (IUCN-WCPA Task Force on OECMs, 2019).

OECM is of immense importance for Bangladesh. As a party to the United Nation’s Convention of Biological Diversity (CBD), Bangladesh is committed to scale up its biodiversity conservation programs aligning its targets with the CBD’s global targets. During the 2011-2021 plan period, Bangladesh performed quite well in relation to Aichi Biodiversity Target 11, when the target was to bring the country’s 3% area under terrestrial ecosystem (forests), 3% area under inland wetlands and coastal ecosystems and 5% of total marine area under PAs or ECAs with development and implementation of management plan for these areas by 2021 (Department of Environment, n.d.; GOB 2019). But achieving an increased target, that has to be planned for the next period (up to 2030) in connection with the Kunming-Montreal Global Biodiversity Framework target of brining 30% of the total land, wetlands, and oceans under effective conservation measures (PAs and OECMs) will be very challenging for Bangladesh due to its limited scope for increasing area of PAs.

Under this circumstance, it is important to include OECMs in the CBD target of Bangladesh. There are at least 385 village common forests (VCFs) and considerable number of Buddhist religious institutions having forested lands with rich biodiversity in Chittagong Hill Tracts (GOB 2019, UNDP 2021) as well as biodiversity rich areas under private (corporate) and institutional possession throughout the country that may qualify as OECMs. But so far there has been no initiative to initiate a process to identify, assess, enlist and report such sites as OECMs.

In this context, Arannayk Foundation undertook this study to initiate the process of identification of OECMs (terrestrial) in Bangladesh for eventual reporting to the WD-OECM by the Government of Bangladesh.

1.2. Objectives

The goal of the project is to establish Other Effective Area-based Conservation Measures (OECM) as a mechanism of biodiversity conservation in Bangladesh to contribute to achieving the country’s biodiversity conservation targets.

The specific objectives of the study are:

a) to establish a national mechanism for identification, assessment, selection, and documentation of OECMs; and
b) to identify and document at least 45 OECMs in Bangladesh that meet the criteria set up by the IUCN World Commission on Protected Areas (WCPA).

2. METHODOLOGY

We followed the IUCN-WCPA guidelines (Jonas et al. 203) for OECM identification for this study. The objective and methodology of the study were shared with high-level stakeholders including the Secretary, Ministry of Environment, Forest and Climate Change (MoEFCC) by organizing a workshop (16 March 2023) at BFD, which was chaired by the Chief Conservator of Forests (CCF). Senior officers of BFD and Department of Environment (DoE), experts from forestry research and academic institutions, IUCN Bangladesh, Wildlife Conservation Society (WCS) Bangladesh and Center for Natural Resource Studies (CNRS), and representatives from the Ministry of Chittagong Hill Tracts Affairs (MoCHTA), World Bank, USAID, US Forest Service, attended the event. The suggestions of the learned participants of the workshop were addressed in finalizing the methodology and list of potential sites to survey.

Subsequently, we identified and collected necessary information on 60 potential terrestrial OECM sites through key informant interviews (KII), focus group discussions (FGD), literature review, and direct observation for subsequent assessment by technical experts (Assessors) endorsed by the National Technical Advisory Committee (NTAC) on OECM. The documentation on the sites included an overview of the site (location, area, ownership, natural/cultural history, biodiversity and ecological importance, current designation, etc.); bio-geographic significance; governance and management systems; biodiversity and other values; conservation initiatives and effectiveness; map and images; and contact information.

Based on a proposal developed jointly by Arannayk Foundation and BFD, the MoEFCC established the NTAC on 18 December 2023 vide memo no. 22.00.0000.067.06.002.23.279 to perform the following functions:

a) Provide guidance on the identification, assessment, evaluation, and documentation of OECM sites in Bangladesh;
b) Form “Verification Team(s)” as needed to assess potential sites for OECM recognition;
c) Prepare a standard assessment methodology for evaluating selected sites in consultation with relevant stakeholders, using the CBD guidelines and global best practices; and
d) Present the findings and recommendations on OECMs to the National Committee for further decision-making.

The 16-member NTAC is headed by the Additional Secretary (Admin) as Convenor, with the Deputy Chief Conservator of Forests (Forest Management) serving as Member Secretary. The committee includes senior representatives from key government agencies such as the MoEFCC, Ministry of Land, Ministry of Chittagong Hill Tracts Affairs, Forest Department, Department of Environment, Department of Fisheries, Bangladesh Haor and Wetland Development Board. It also involves representatives from IUCN Bangladesh and Arannayk Foundation, and two renowned technical experts (Botanist, Wildlife specialist). committee may co-opt one or more experts or members as required.

In its first meeting held on 4th March 2024 at MoEFCC, the NTAC reviewed and endorsed a list of technical experts (Assessors) for the assessment of the candidate OECM sites identified by the Arannayk Foundation OECM research team and provided directives to finalize the list of assessors for all categories (terrestrial, freshwater wetlands, marine and coastal) based on nominations to be sent by the heads of the respective organizations. The NTAC meeting also established a Verification Team, composed of senior technical experts, for the verification of the candidate OECM sites that would be confirmed by the Assessors to qualify as OECMs as per IUCN WCPA criteria.

In April 2024, Arannayk Foundation organized a day-long training program on the IUCN WCPA criteria and methodology of assessing potential OECM sites for the technical experts selected as OECM Assessors at Bana Bhaban, Agargaon, Dhaka. A total of 16 technical experts (Assessors and members of Verification Team) took part in this training program. Subsequently, seven of the trained experts assessed 48 candidate OECM sites proposed by Arannayk Foundation.

2.1. Site Selection

Potential sites were identified based on prior knowledge of the members of the study team and other colleagues of Arannayk Foundation, and information gathering through internet browsing, review of literature (relevant project reports, journals, newspaper articles), and personal communication with relevant professionals including those in Arannayk Foundations network of partner organizations. The main source of information was a UNDP (2021) report that provided a list of 385 village common forests (VCFs) in the Chittagong Hill Tracts (CHT) with the names and telephone numbers of the contact persons of those VCFs. The VCFs are community conserved areas.

Fifty VCFs from Khagrachari, Bandarban and Rangamati districts were selected for assessment in consultation with the leaders of the VCF network of the respective district by organizing a consultation meeting at each district. The consultation meeting in Khagrachari was held on 02-June-2023 at Hotel Gairing, Khagrachari. In Bandarban, this meeting was held on 24-July-2023 at the Arannayk Foundation Office at Bandarban, and, in Rangamati, it was held on 17-August-2023 at Kalyanpur Hill Resort, Kalyanpur, Rangamati. A total of 39 VCF network representatives participated in these meetings: 21 in Khagrachari, 7 in Bandarban and 12 in Rangamati from the respective districts.

In these meetings, OECM concept was shared with the VCF network leaders to obtain their informed consent for collecting information about their VCFs following the principle of "free, prior, and informed consent (FPIC)" and the sites were selected based on IUCN-WCPA criteria (Jonas et al., 2023) for screening of potential sites. The criteria were:

1) The site is not a Protected Area (PA)
2) There is a reasonable likelihood that the site supports important biodiversity values i.e., at least one of the following important biodiversity values:
    a) Rare, threatened or endangered species and ecosystems
    b) Natural ecosystems that are under-represented in protected area networks
    c) High level of ecological integrity or intactness
    d) Significant populations/extent of endemic or range-restricted species or ecosystems
    e) Important species aggregations, such as spawning, breeding or feeding areas

Ten other sites that were selected based on the above criteria, included institutional lands of three public universities (Chittagong University, Shahjalal Science and Technology University, Sylhet, and Jahangirnagar University, Savar, Dhaka), two government institutions (Forestry Science and Technology Institute, Sylhet and Citrus Research Station of BARI at Jointapur, Sylhet) and a Buddhist religious institution (Taraban Bhabona Kendrea) in Panchari, Khagrachari, and four private lands.

The selected private lands were Pittachhara private forest in Khagrachari, Phulbari Tea Estate in Moulvibazar, Nuhash Palli resort in Gazipur and Sharifpur cane (rattan) garden in Derai, Sunamganj.

2.2. Getting consent of site authorities

For collection of necessary information on a selected site and for listing and reporting it by the government as an OECM, the AF research team sought written consent of the authorized representative(s) of the site in a prescribed form.

In the VCF Network meetings and subsequent site visits in Khagrachari and Bandarban, the VCF representatives gave written consent (on the 'consent form') for recognizing their VCFs as OECMs and for visiting the sites and collecting necessary information through direct observation and by interviewing their fellow community members. They also assigned local guides from their respective communities to accompany the research team on the site and to act as the key informant.

In the meeting at Rangamati, the VCF leaders of Rangamati district also expressed their willingness to have their VCFs recognized as OECMs and extended their cooperation to us in surveying the selected VCFs but, for signing the consent form, they wanted to that the consent of the CHT Regional Council regarding the plan should be obtained first. We approached the latter office for this purpose, but it was without a result. However, authorized representatives of some of the VCFs signed the consent form during the survey of the site.

We approached the authorities of several tea estates adjacent to Lawachara National Park, Satchari National Park and Rema-Kalenga Wildlife Sanctuary (Duncan Brothers Bangladesh Ltd., Ispahani Tea Ltd., National Tea Company, Rema Tea Company), in writing, with follow up telephone calls, to cooperate in assessing the potentials for those tea estates as OECMs but they were not immediately interested. They advised to discuss the issue with the Chairman of the National Tea Board but, not being hopeful of positive outcome, we did not proceed further. However, the site level management of Phulbari Tea Estate (M. Ahmed Group) at Sreemangal, Moulvibazar cooperated with us in surveying the site to assess its potential as an OECM, without a written consent though.

Similarly, the institutional sites like Chittagong University, Shahjalal University of Science and Technology (SUST) at Sylhet; Forestry Science and Technology Institute (FSTI), Sylhet and Citrus Research Center of BARI at Jointapur, Sylhet; and the private lands like Sharifpur cane garden at Vatipara, Derai, Sunamganj and Nuhash Polli in Gazipur were surveyed based non-formal consent of the site-level staff/collaborators, pending formal consent of their governance authorities.

2.3. Information collection

After having consent of the authorities, the selected sites were visited, and necessary information was collected through direct observation and by interviewing the assigned representatives of the site authority using a data collection form. The data collection form was designed based on the data requirement for the full assessment of a candidate OECM site as per IUCN-WCPA criteria. It included the following:

a) **Boundary of the site:**
- How the boundary of the site is defined (with reference to natural, customary, surveyed, or administrative boundaries).
- Whether the boundary is mapped and whether the map is publicly available, and whether it is in a digital (GIS) format.
- Whether the boundary is physically demarcated in the field.
- Whether there are any conflicts over the boundary that impact the site's important biodiversity values

b) **Size and configuration:**
- Size of the site (acre/ha/km^2).
- How the site's size and configuration relate to the conservation of its important biodiversity values.
- Whether the site is important because it connects other sites with important biodiversity values.
- Whether the site is part of a network of sites that, together, support important biodiversity values.

c) **Biodiversity values:**
- Compilation of all available information that demonstrates that the site supports important biodiversity values such as credible reports from reliable sources, including relevant traditional knowledge, and expert opinion from relevant experts.

d) **Governance and Management:**
- Governance type (governance by government, shared governance, private governance, or governance by indigenous peoples and local communities)
- Name and contact details of the representative(s) of the governing authority.
- Name and contact details of any Indigenous peoples or local communities who claim ownership or rights in the site.
- Name and contact details of any other rights-holders or stakeholders who are involved in the process (government agencies, private sector or civil society organizations)
- Long-term objectives for the site, as determined by the governing authority

- Whether and how the long-term objectives for the site are linked to the conservation of the site's important biodiversity values
- Management activities, especially those that impact the biodiversity values and ecosystem services of the site

e) **Pressures and Threats:**

- Current pressures (internal, external) on the biodiversity values and ecosystem services of the site
- How and to what extent the governance and management of the site can mitigate the pressures
- Anticipated future threats that may affect the important biodiversity values and ecosystem services of the site.

f) **Long-term basis for governance and management:**

- legal, official, customary, or other recognized basis for the institutions/organizations involved in the governance and management of the site that contributes to making the governance and management arrangements permanent
- Legal, official, customary or other recognized status of the site that contributes to the site's long-term status

g) **Equitable Governance and Management:**

- How and to what extent governance and management of the site recognize and respect the rights of indigenous peoples, local communities and other stakeholder groups (where applicable).
- How and to what extent governance and management of the site enable the participation of indigenous peoples, local communities and other stakeholder groups (where applicable).
- How and to what extent do the governance and management of the site encourages equitable sharing of costs and benefits of conservation of the site's biodiversity values.
- Recent or ongoing cases of abuse of individual or collective human rights involving the governing authority or other stakeholders, where these cases are connected to use, governance or management of the site

The survey form also included some additional information such as the conservation history of the site, whether the site adequately represents biodiversity and other ecological characteristics of the ecosystem, past and present state (forest health, biodiversity) of the site, disaggregation of total area of the site by land use category, and description of ecosystem services (provisioning, regulatory, supporting, cultural) of the site. Two supplementary tools (forms) were used for collection of information regarding threatened species of flora and fauna per Bangladesh Red lists (IUCN 2023, IUCN 2015). For identification of the plant and animal species, when needed, relevant publications with photographs (Feeroz et al., n.d.; Hasan, et al., 2014; Feeroz, et al., 2016; Rashid et al., 2017; Khan, 2018) and images available in internet sources were used as guides.

Aside from the primary data collected through the rapid survey, extensive literature survey was done to utilize biodiversity information of the sites generated by others through more detailed surveys. However, such secondary information was available for a limited number of the selected sites.

OECM concept sharing and site selection meeting with the VCF Network leaders of Khagrachari Hill District

Identification of location of potential VCF on map by concerned VCF representative in the OECM concept sharing and site selection meeting at Khagrachari

Presentation on participatory wildlife identification tool at the OECM concept sharing and planning meeting at Khagrachari

OECM concept sharing meeting with the Vante (Buddhist monk) of Taraban Bhabona Kendra, Panchari, Khagrachari

OECM field survey in Phulbari Tea Estate, Sreemangal, Moulvibazar

OECM Research team visiting Sharifpur Cane Garden, Sunamganj with local community members

OECM Research team at Pittachhara forest, Khagrachari with its owner Mr. Mahfuz Russel

OECM Research Assistant Biplob Chakma visiting Dhonmoni Karbari Para VCF with community members

OECM Research Assistant Biplob Chakma collecting information from local community members at Donurdhor Karbari Para through FGD

OECM Research Assistant Biplob Chakma visiting Nirbagozo Chara VCF with local guide community

OECM concept sharing and site selection meeting with the VCF Network leaders of Bandarban Hill District

OECM research team collecting information from the executive community members of Suknachari Para VCF, Rowangchari, Bandarban

OECM Research Assistant Biplob Chakma collecting information from local community members at Hlaching Mro Para, Bandarban, through KII

OECM research team collecting information from the executive community members of Kapru Para VCF, Lama, Bandarban

OECM concept sharing and site selection meeting with the VCF Network leaders of Rangamati Hill District

Training of OECM Assessors at Bana Bhaban, Dhaka, 29-Apr-2024

2.4. Assessment of the potential OECM sites

The OECM research team of Arannayk Foundation conducted the first screening of the 60 potential sites it had surveyed, based on the criteria defined by IUCN WCPA, and selected 48 sites for further assessment by the technical experts endorsed by the NTAC as 'Assessors'. Subsequently, trained Assessors assessed those 48 candidate sites following the IUCN-WCPA methodology and criteria (Jonas et al. 2023) based on the site profile reports prepared by Arannayk Foundation research team, with telephone interview of the site representatives for validation and additional information. For the assessment purpose, the profiles of the candidate sites were presented in the template prescribed by IUCN-WPCA (Jonas et al. 2023).

The IUCN-WPCA methodology of screening and assessing potential/candidate OECM sites involves a 3-step procedure as follows:

Step 1: Screening of proposed OECM (2 criteria) – a site that meets the screening criteria is a ***potential OECM***

Step 2: Consent for full assessment – a potential OECM where governing authority, indigenous peoples and local communities, and (as appropriate) other right-holders have given consent to carry out full assessment is a ***candidate OECM***

Step 3: Full assessment (6 criteria) – a candidate OECM that meets all criteria is ***confirmed as an OECM***. Sites that do not meet all criteria remain as candidate OECMs pending further information or changes to meet the criteria

Steps 1 and 2 can be carried out in any order, or combined, and Step 2 should be completed before step 3 is implemented.

STEP 1: SCREENING: IDENTIFYING A POTENTIAL OECM

Information required:

Ste Name: In English; in national or local language; temporary site name or site code (if final name unavailable)

Site location: Country; Sub-national administrative division(s); Other description of location (e.g., name of a river, mountain, area)

Site designation (if applicable): National or local designation of the site in national or local language, and in English; Regional or International designation e.g., Key Biodiversity Area, Ramsar site, etc.

Organizations/groups or individuals carrying out the screening process: Name, address and contact details

Date of the screening:

Main biodiversity value(s): (a) Rare, threatened or endangered species and ecosystems (b) Natural ecosystems that are under-represented in protected area networks (c) High level of ecological integrity or intactness (d) Significant populations/extent of endemic or range-restricted species or ecosystems (e) Important species aggregations, such as spawning, breeding or feeding areas (f) Importance for ecological connectivity, as part of a network of sites in a larger area).

Step 1 Screening:

TESTS	QUESTIONS	RESPONSE	JUSTIFICATION
CRITERION 1: The site is not a protected area (PA)	Is the site OUTSIDE any recognized PA?	[ ] Yes [ ] No	Briefly summarize the information that supports the response given

TESTS	QUESTIONS	RESPONSE	JUSTIFICATION
CRITERION 2: There is a reasonable likelihood that the site supports important biodiversity values	Does available information suggest that the site supports **at least one** of the following important biodiversity values? a) Rare, threatened or endangered species and ecosystems b) Natural ecosystems that are under-represented in protected area networks c) High level of ecological integrity or intactness d) Significant populations/extent of endemic or range-restricted species or ecosystems e) Important species aggregations, such as spawning, breeding or feeding areas f) Importance for ecological connectivity, as part of a network of sites in a larger area	[ ] Yes [ ] No	List the biodiversity values likely to be present, and briefly summarize the information that supports the response

Next steps:

- If the response to both criteria is 'YES', the site is a potential OECM. The next step is to seek consent to carry out a full assessment (step 2), if this has not already been secured.
- If the response to either of the criteria is 'NO', the site is NOT a potential OECM. The assessment does not proceed further.

STEP 2: CONSENT FOR FULL ASSESSMENT

Information required:

- Contact details for organizations/groups or individuals carrying out the full assessment
- Mandate or role of the organization/group or individual carrying out the full assessment
- Governance or management of the site: Name and contact details of the governing authority (or authorities).
- Identify the representative of the governing authority for the site (the authority may be government, private entity, Indigenous peoples, local communities, or a combination of these; the governing authority should have a recognized mandate or right to make decisions on the overall management and use of the site.
- Name and contact details of any Indigenous peoples or local communities who claim ownership or rights in the site.
- Name and contact details of any other rights-holders or stakeholders who are involved in the process (government agencies, private sector or civil society organizations)

Next steps: A potential OECM that has met the screening criteria (step 1) and for which the governing authority(ies) and other rights-holders have given their consent (if other rights-holders' consent is needed) for a full assessment to be carried out is referred to as a 'candidate OECM'. The candidate OECM should now be subject to a full assessment of the site against the OECM criteria (step 3)

STEP 3: THE FULL ASSESSMENT

Information required:

3.1. The Site and its Biodiversity Values

Boundary of the site:

- Describe how the boundary of the site is defined (for example, with reference to natural, customary, surveyed, or administrative boundaries).
- Describe whether the boundary is mapped and whether the map is publicly available, and whether it is in a digital (GIS) format.
- Describe whether the boundary is physically demarcated in the field.
- Describe whether there are any conflicts over the boundary that impact the site's important biodiversity values

Size and configuration:

- Note the size of the site, if known (e.g., land and sea area in km^2).
- Describe how the site's size and configuration relate to the conservation of its important biodiversity values.
- Describe whether the site is important because it connects other sites with important biodiversity values.
- Describe whether the site is part of a network of sites that, together, support important biodiversity values.

Confirmation of biodiversity values:

- Compile all available information that demonstrates that the site supports important biodiversity values such as:
- Credible reports from reliable sources, including relevant traditional knowledge
- Expert opinion from relevant experts

3.2. Governance and Management, and Effectiveness in In-situ Conservation

Governance and Management:

- Describe the long-term objectives for the site, as determined by the governing authority (for example: maintenance of water supply; sustainable production/ extraction of wild products; practice and preservation of spiritual values).
- Describe whether/how the long-term objectives for the site are linked to the conservation of the site's important biodiversity values.
- Describe the management activities (for example, protection, harvest controls, restoration), especially those that impact the biodiversity values and ecosystem services of the site.

Pressures and Threats:

- List any current pressures on the biodiversity values and ecosystem services of the site. These pressures may originate inside the site (e.g., illegal logging) or outside the site (e.g., pollution).
- Describe how and to what extent the governance and management of the site can mitigate the pressures on biodiversity and ecosystem values.
- List any anticipated future threats that may affect the important biodiversity values and ecosystem services of the site.

Long-term basis for governance and management:

- Describe any legal, official, customary, or other recognized basis for the institutions/organizations involved in the governance and management of the site that contributes to making the governance and management arrangements permanent.

- Describe any legal, official, customary or other recognized status of the site (for example, forest reserve, military zone, customary land, Particularly Sensitive Sea Area, archaeological heritage site) that contributes to the site's long-term status

3.3. Equitable Governance and Management

- Describe how and to what extent governance and management of the site recognize and respect the rights of indigenous peoples, local communities and other stakeholder groups (where applicable).
- Describe how and to what extent governance and management of the site enable the participation of indigenous peoples, local communities and other stakeholder groups (where applicable).
- Describe how and to what extent governance and management of the site encourage the equitable sharing of costs and benefits of conservation of the site's biodiversity values.
- List any recent or ongoing cases of abuse of individual or collective human rights involving the governing authority or other stakeholders (as identified in step 2), where these cases are connected to use, governance or management of the site.

STEP 3 ASSESSMENT

TESTS	QUESTIONS	RESPONSE	JUSTIFICATION
CRITERION 3: The site is a geographically defined area	Does the site have clear boundaries?	[ ] Yes [ ] Uncertain/ Partial [ ] No	Briefly summarize the information that supports the response given
CRITERION 4: The site is confirmed to support important biodiversity values	Does information confirm that the site supports at least one of the following important biodiversity values? a) Rare, threatened or endangered species and ecosystems b) Natural ecosystems that are under-represented in protected area networks c) High level of ecological integrity or intactness d) Significant population/extent of endemic or range-restricted species or ecosystems e) Important species aggregations, such as spawning, breeding or feeding areas f) Importance for ecological connectivity as part of a network of sites in a larger area	[ ] Yes [ ] Uncertain/ Partial [ ] No	List the biodiversity values confirmed to be present and briefly summarize the information that supports the response.

TESTS	QUESTIONS	RESPONSE	JUSTIFICATION
CRITERION 5: Institutions or mechanisms exist to govern and manage the site	Is there one or more institution(s) or mechanism(s) that govern(s) and manage(s) the site?	[ ] Yes [ ] Uncertain/ Partial [ ] No	Briefly summarize the information that supports the response given
CRITERION 6: Governance and management of the site achieve or are expected to achieve the in-situ conservation of important biodiversity values	Do the governance and management of the site prevent and mitigate threats, and conserve the site's important biodiversity values, or are they expected to do so?	[ ] Yes [ ] Uncertain/ Partial [ ] No	Briefly summarize the information that supports the response given
CRITERION 7: In situ conservation of important biodiversity values is expected to be for the long term	Is there a reasonable likelihood that the important biodiversity values for which the site is identified will be conserved in situ in the long-term?	[ ] Yes [ ] Uncertain/ Partial [ ] No	Briefly summarize the information that supports the response given
CRITERION 8: Governance and management arrangements address equity considerations	Do the governance and management arrangements include efforts to address the three aspects of equity (recognition, procedure, distribution), where applicable?	[ ] Yes [ ] Uncertain/ Partial [ ] No	Briefly summarize the information that supports the response given

ASSESSMENT SUMMARY AND FINAL RESULTS

Criteria	**Response** (tick one for each criteria)		
	YES	**UNCERTAIN/ PARTIAL**	**NO**
Screening assessment			
Criterion 1: The site is not a protected area (PA)		N/A	
Criterion 2: There is a reasonable likelihood that the site supports important biodiversity values		N/A	
Full assessment			
Criterion 3: The site is a geographically defined area			
Criterion 4: The site is confirmed to support important biodiversity values			
Criterion 5: Institutions or mechanisms exist to govern and manage the site			

Criterion 6: Governance and management of the site achieve or are expected to achieve the *in situ* conservation of important biodiversity values			
Criterion 7: *In situ* conservation of important biodiversity values is expected to be for the long term			
Criterion 8: Governance and management arrangements address equity considerations			

Decision Rules:

- A site with a '**yes**' response to every criterion is a **confirmed OECM**, subject to any stakeholder consent and approval by the governing authority.
- A site with a **combination of 'yes' and 'uncertain/partial'** responses**, or all 'uncertain/partial**' responses, **remains a candidate OECM until** further information or other changes allow it to be confirmed as an OECM.
- A site with **one or more** '**no**' responses is **not currently an OECM**, **but** might be reassessed in the future if a change at the site means that all criteria are now met

2.5. Verification of the OECM sites confirmed by technical experts

The AF research team submitted the site profiles and Assessors' assessment reports on the sites endorsed by the Assessors as 'confirmed' OECMs to the members of the Verification Team formed by the NTAC for verification. The verification process was hindered by the countrywide political unrest during July-August 2024 for which convening meeting of the Verification Team and organizing site visits for them was not possible until mid-September 2024. As the situation improved, the Verification Team held its first meeting on 14 September 2024 and decided to evaluate five sites in Khagrachari and Bandarban hill districts as the first batch about which two of the team members (Plant Taxonomist Dr. Khairul Alam and Wildlife Biologist Prof. Dr. Kamrul Hasan) had prior work experience. The sites were: Pittachhara private forest in Matiranga Upazila and Kamalchari Mukh VCF in Khagrachari Sadar Upazila of Khagrachari district and Bijoy Para VCF, Tulachari Para VCF and Aungjai Para VCF in Rowangchari Upazila of Bandarban district. The AF OECM research team proposed to include Shuknachari VCF to this list as it was adjacent to the three above-mentioned sites in Rowangchari, Bandarban and it was also included in the same earlier studies conducted by Dr. Khairul Alam (Alam, 2021) and a team of wildlife biologists from Jahangirnagar University including Prof. Dr. Kamrul Hasan (Feeroz et a., 2022). The verification team planned to visit those sites during 27-30 September 2024, but it could not be materialized due to further deterioration of law-and-order situation in CHT from the last week of September 2024. Under this circumstance, the Verification Team evaluated those six sites based on its team members prior experience on those sites. The verification of the other 'confirmed' candidate sites remains pending.

3. DESCRIPTION OF THE CANDIDATE SITES ASSESSED

Brief description of the 48 candidate sites that have been assessed by the trained and designated assessors are presented below.

3.1. Kamalchari Mukh Village Common Forest, Khagrachari

Kamalchari Mukh Village Common Forest (VCF) is located in Bhuachari Mouza, Kamalchari Union, Khagrachari Sadar Upazila, Khagrachari District, at approximately 23.096336°N, 92.031736°E. Spanning approximately 127.8 ha, the site represents a tropical hill forest ecosystem. Established in 1947 by the then Mouza Headman, Mr. Chandra Kanto Chakma, the forest has been traditionally conserved to ensure the availability of water and non-timber forest products for local use. Legally owned by the Government of Bangladesh as unclassed state forest (USF) land, the VCF is governed by the community-led Kamalchari Mukh VCF Management Committee through customary rules, based on the provisions (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900 (Govt. of Bangladesh, 1900).

The VCF harbors more than a hundred plant species including 55 tree species as recorded by Nath (2012) and Chowdhury, et al. (2018). The trees include some red-listed species (IUCN, 2023) such as the vulnerable (VU) *Artocarpus lacucha* (Dewa) and near-threatened (NT) *Lithocarpus acuminatus* (Kalo batna), *Pterygota alata* (Buddha narikel) and *Chukrasia tabularis* (Chikrassi). Notable other tree species include *Schima wallichii* (Kanak), *Aglaia cucullata* (Amur), *Syzygium cumini* (Jam), *Lannea coromandelica* (Bhadi), *Microcos paniculata (*Achar gola) and *Ficus racemosa* (Joggo dumur). Overall, *Melocanna baccifera* (Muli bansh) is the most extensive species.

Faunal diversity includes endangered (EN) Barking Deer (*Muntiacus muntjak*), vulnerable (VU) Rhesus Macaque (*Macaca mulatta*) and Kalij Pheasant (*Lophura leucomelanos*), and numerous bird, reptile, and amphibian species.

The forest provides multiple ecosystem services, including food, fuel, bamboo, water, and medicinal plants, as well as regulating services like soil fertility and carbon sequestration. The management committee of the VCF enforces regulations against illegal logging, hunting, fire setting, and pesticide use, with local monitoring and scheduled bamboo harvesting. Regular patrolling, bamboo harvesting every three years, and strict governance ensure sustainable use. The community is committed to conserving the forest for long-term ecological integrity and community well-being.

3.2. Pittachhara Private Forest, Matiranga, Khagrachari

Pittachhara Private Forest is a 9.31 ha privately-owned forest located at East Khedachara village in Khedachara Mouza, Belchari Union, Matiranga Upazila, Khagrachari District, at 23.098343°N, 91.871891°E. Established in 2016 by Mr. Russel and his friends under the "Pittachhara Forest and Biodiversity Conservation Initiative," its purpose is to restore and conserve the region's semi-evergreen tropical hill forest, once widely cleared for monoculture plantations and agriculture. The forest is well-demarcated and managed privately, independent of formal state involvement.

The area harbors rich biodiversity representative of the Indo-Burma hotspot. Flora includes key native tree species of Bangladesh hill forest zone such as *Dipterocarpus turbinatus* (Teli garjan), *Artocarpus chama* (Chapalish), *Terminalia bellirica* (Bohera) and different species of *Ficus* genera, and near-threatened (NT) species like *Pterygota alata* and *Swintonia floribunda* (Civit). The forest supports about 150 bird species, at least 12 mammal species and 20+ herpetofauna, and diverse amphibians and reptiles.

Notable fauna includes the critically endangered (CR) Elongated Tortoise (*Indotestudo elongata*), endangered (EN) Bengal Slow Loris (*Nycticebus bengalensis*) and Pig-tailed Macaque (*Macaca leonina*), and vulnerable (VU) Burmese Python (*Python bivittatus*).

Management activities include natural regeneration, enrichment planting, biodiversity monitoring, and extensive community engagement to curb hunting. The initiative has also inspired research and educational visits. Mr. Russel plans to expand the forest area, promote conservation among locals, and explore sustainable financing through eco-tourism and legal reforms to safeguard private forests. Under his stewardship, Pittachhara has become a model for effective private forest restoration and community-based biodiversity conservation in the Chittagong Hill Tracts.

3.3. Bijoy Para VCF, Rowangchari, Bandarban

Bijoy Para VCF is located in Bekhyong Mouza, Alikhong Union, Rowangchari Upazila, Bandarban District, at 22.197239°N, 92.331358°E, covering approximately 16.75 ha. Established in 1965 by Mr. Bijoy Chandra (indigenous community leader) to protect natural forest for sustainable community use, the site represents a tropical hill forest ecosystem rich in biodiversity. Legally government-owned USF land, it is managed by a local (indigenous) community-based organization, named "Bijoy Para Poribesh O Grameen Bon Songrokkhon Somity", operating under customary rights from the Chittagong Hill Tracts Regulation, 1900. The management committee enforces written bylaws for sustainable resource management.

As recorded by Alam (2021) and Feeroz et al. (2022), Bijoy Para VCF hosts 134 plant and 203 faunal species. Red-listed flora include vulnerable (VU) *Artocarpus lacucha, Alangium chinense* (Marleza gach), *Euonymus attenuatus* (Kala goina), *Leea acuminata* (Cham-kola gach), *Macropanax dispermus* (Reng gach), *Mitragyna diversifolia* (Rangkat-Type 1), *M. parvifolia* (Rangkat-Type 2), *Schizostachyum dullooa* (Dolu bansh) bamboo, *Calamus latifolius* (Budum bet), *Daemonorops jenkinsiana* (Golla bet), and near-threatened (NT) *Swintonia floribunda*, *Baccaurea ramiflora* (Lotkon), *Dillenia pentagyna* (Chalta), *Ficus auriculata* (Boro dumur) and *Holigarna caustica* (Barela).

Fauna includes the critically endangered (CR) Asiatic Black Bear (*Ursus thibetanus*), endangered (EN) *Macaca leonina*, Capped Langur (*Trachypithecus pileatus*) and *Muntiacus muntjak*, and vulnerable (VU) *Macaca mulatta* and *Lophura leucomelanos*. There are also several Near-threatened (NT) species such as Jungle Cat (*Felis chaus*), Leopard Cat (*Prionailurus bengalensis*), Large Indian Civet (*Viverra zibetha*), Common Tree Shrew (*Tupaia glis*), Tawny Cat Snake (*Boiga ochracea*), Painted Bull Frog (*Kaloula pulchra*) and White-browed Scimitar Babbler (*Pomatorhinus schisticeps*).

The VCF supplies local communities with forest products like timber, bamboo, wild fruits, medicinal herbs, and water, along with ecosystem services such as climate regulation and soil fertility. The management committee strictly regulates harvesting and prohibits hunting, supported by written plans and regular patrols. Bamboo is harvested sustainably in three-year rotations to fund community and conservation activities. The VCF has been effectively maintained for decades with minimal internal threats, though occasional unauthorized harvesting and hunting by outsiders occur. Recent improvements in monitoring and enforcement aim to ensure long-term sustainability.

3.4. Tulachari Para VCF, Rowangchari, Bandarban

Tulachari Para VCF is a 9.46 ha community-conserved forest area located in Rowangchari Mouza, Rowangchari Sadar Union, Rowangchari Upazila, Bandarban District, at approximately 22.189858°N, 92.345203°E. Established in 1965 by the local village leader to sustainably supply bamboo, wood, and stream water for the community's subsistence, it represents a tropical hill ecosystem with rich biodiversity. The site, legally classified as USF land, is managed by the local community under customary rights through the "Tulachari Para Poribesh O Grameen Bon Songrokkhon Samity," led by the traditional village head (Karbari). This Samity comprises all 54 families of Tulachari village and is governed by a seven-member executive committee with formal bylaws regulating resource use.

The densely covered tropical semi-evergreen forest, dominated by *Melocanna baccifera* bamboo, hosts 134 plant species (Alam 2021) including several red-listed species such as vulnerable (VU) *Alangium chinense*, *Artocarpus lacucha, Euonymus attenuatus, Leea acuminata, Macropanax dispermus*, *Mitragyna diversifolia, M. parvifolia*, *Schizostachyum dullooa*, *Calamus latifolius* and *Daemonorops jenkinsiana*, and near-threatened (NT) *Baccaurea ramiflora*, *Dillenia pentagyna, Ficus auriculata, Holigarna caustica* and *Swintonia floribunda.*

Fauna includes 150 bird species, 12 mammals, 21 reptiles and 13 amphibians (Feeroz 2022), including several red-listed species such as the critically endangered (CR) *Ursus thibetanus*, vulnerable (VU) *Lophura leucomelanos*, and near-threatened (NT) *Felis chaus*, *Tupaia glis*, *Kaloula pulchra*, *Boiga ochracea* and *Pomatorhinus schisticeps*.

Management aims to conserve biodiversity and ecosystem services such as water regulation, air quality, and carbon sequestration while providing sustainable raw materials. Regulations prohibit unauthorized tree and bamboo cutting, hunting, jhum cultivation, and bamboo shoot harvesting. The committee meets quarterly to enforce rules, allowing limited raw material collection by a few families annually, backed by fines and traditional penalties for violations. Despite minor external threats from neighboring villages, strengthened monitoring has ensured effective long-term conservation and ecosystem service protection.

3.5. Aungjai Para VCF, Rowangchari, Bandarban

Aungjai Para Village Common Forest (VCF) is located in Rowangchari Mouza, Rowangchari Sadar Union, Rowangchari Upazila, Bandarban District, at approximately 22.187733°N, 92.381906°E, covering about 32.11 ha. The area is demarcated naturally by streams and canals and digitally mapped by Arannayk Foundation. Established around 100 years ago by local forefathers primarily to ensure year-round water availability in streams, it is managed by the local community under customary rights led by a 7-member executive committee of the "Aungjai Para Poribesh O Grameen Ban Songrokkhon Samity." The site is government-owned as unclassed state forest land but locally governed via community bylaws aligned with the Chittagong Hill Tracts Regulation, 1900.

The VCF represents a tropical hill ecosystem with rich biodiversity. Dominated by *Melocanna baccifera* bamboo, the forest hosts 134 plant species: 90 trees, 19 shrubs, 17 woody climbers, and 48 herbs (Alam 2021). Red-listed flora includes the Vulnerable *Alangium chinense, Artocarpus lacucha, Euonymus attenuatus, Leea acuminata, Macropanax dispermus*, *Mitragyna diversifolia, M. parvifolia*, *Schizostachyum dullooa, Calamus latifolius, Daemonorops jenkinsiana*, and Near Threatened (NT) species like *Baccaurea ramiflora*, *Dillenia pentagyna*, *Ficus auriculata, Holigarna caustica* and *Swintonia floribunda*.

The forest harbors 200 faunal species: 150 birds, 16 mammals, 21 reptiles, and 13 amphibians (Feeroz et al. 2022). Red-listed fauna includes critically endangered (CR) *Ursus thibetanus*, endangered (EN) *Muntiacus muntjak*, vulnerable (VU) *Macaca mulatta* and *Lophura leucomelanos*, and the Near Threatened (NT) *Felis chaus* and *Kaloula pulchra*. Wild animals frequently migrate to this site from the surrounding degraded forests for food, shelter, and breeding.

The forest provides crucial ecosystem services such as water supply, bamboo for housing, wild fruits, medicinal plants, nutrient cycling, carbon sequestration, and ecotourism opportunities. Management activities focus on sustainable resource use, including regulated bamboo harvesting on a three-year rotation and strict prohibitions on hunting and unauthorized tree cutting, enforced by fines. The committee meets bi-monthly for monitoring and planning. Management effectiveness is strong, with minimal internal threats and active community enforcement. The community is committed to long-term conservation and sustainable use of the site's biodiversity and ecosystem services.

3.6. Shuknachari Para VCF, Rowangchari, Bandarban

Shuknachari Para VCF is a 12.55 ha community conserved forest located at 22.200608°N, 92.376600°E in Rowangchari Mouza, Rowangchari Sadar Union, Rowangchari Upazila, Bandarban District. Established in 1994 as a Para Ban (community reserve) by the local community under customary rights, this USF land is managed by the Shuknachari Grameen Ban Songrokkhon Samity – a seven-member committee – with written by-laws regulating sustainable resource use.

The site represents a tropical hill forest ecosystem and supports rich biodiversity without formal national or international conservation status. It hosts 134 plant species (Alam 2021), including 90 trees, 19 shrubs, 17 woody climbers and 48 herbs. The vegetation is dominated by *Melocanna baccifera* bamboo, and includes many useful herbs and shrubs valued by indigenous communities for food, medicine, and materials. Red-listed flora includes vulnerable (VU) *Alangium chinense, Artocarpus lacucha, Euonymus attenuatus, Leea acuminata, Macropanax dispermus*, *Mitragyna diversifolia, M. parvifolia*, *Schizostachyum dullooa, Calamus latifolius, Daemonorops jenkinsiana*, and near-threatened (NT) *Baccaurea ramiflora*, *Dillenia pentagyna, Ficus auriculata, Holigarna caustica* and *Swintonia floribunda.* The site also hosts a clustering, feather-leaved palm species – *Wallichia oblongifolia*, which is native to the CHT region of Bangladesh and the adjacent areas in India (Mizoram) and Myanmar.

Fauna includes 150 bird species, 20 mammals, 21 reptiles, and 13 amphibians (Feeroz 2022). The mammals include the endangered (EN) *Macaca leonina*, *Trachypithecus pileatus* and *Muntiacus muntjak*. The critically endangered (CR) *Ursus thibetanus* is occasionally sighted by the locals. The birds include vulnerable (VU) *Lophura leucomelanos* and near-threatened (NT) *Pomatorhinus schisticeps*.

The VCF is well-maintained, free from significant threats, and serves important ecological functions including habitat provision, carbon sequestration, and supporting ecosystem services vital to the local community's livelihoods and biodiversity conservation. Management focuses on sustainable access to bamboo, timber, and water for local use while prohibiting unauthorized tree cutting, hunting, and poaching. The committee enforces rules through fines and traditional punishments, meets regularly for monitoring, and harvests bamboo on a three-year rotation to fund community activities.

3.7. Itchari Mouza Bon, Khagrachari

Itchari Mouza Bon (VCF) is located at 23.096336°N, 92.031736°E in Itchari Mouza, Kamalchari Union, Khagrachari Sadar Upazila, Khagrachari District. Covering approximately 42.51 ha, this community-conserved tropical hill forest (USF land) has been protected by local communities since 1970. Initiated by the then Headman, its purpose was to ensure sustainable access to timber, bamboo, non-timber forest products, and perennial water supply for local irrigation needs. It is managed by the Itchari Mouza Forest Conservation Committee, composed of 11 elected members, guided by the Chittagong Hill Tracts Regulation, 1900 and community rules. Arannayk Foundation and local NGO BIRAM strengthened the committee's capacity between 2009–2012, establishing boundary demarcation and sustainable management. Subsequent support from UNDP's SID-CHT project (2018–2019) further improved the governance.

The VCF hosts rich biodiversity, with at least 118 plant species and 113 faunal species (Jashimuddin 2010; Bhattacharjee et al. 2020; UNDP 2021). Nearly half the area is covered by *Melocanna baccifera* bamboo. Red-listed plant species include vulnerable (VU) *Mitragyna parvifolia* (Dakroom) and *Artocarpus lacucha*, and the near-threatened (NT) *Pterygota alata*. Other trees include *Tectona grandis* (Teak), *Gmelina arborea* (Gamar), *Terminalia bellirica*, *Phyllanthus emblica* (Amloki), and *Syzygium cumini*.

Fauna includes critically endangered (CR) Phayre's Leaf Monkey (*Trachypithecus phayrei*) and *Indotestudo elongata*, vulnerable (VU) *Lophura leucomelanos*, and near-threatened (NT) *Felis chaus* and *Prionailurus bengalensis*. The VCF is a vital refuge for wildlife from nearby degraded forests.

The community enforces conservation regulations, monitors activities, and sustainably harvests bamboo in 3-year cycles. Through collective action, effective governance, and strong local commitment, the Itchari VCF has restored degraded areas and enhanced biodiversity, showing strong potential for long-term ecological sustainability.

3.8. Betchari Christian Para Village Common Forest, Khagrachari

Betchari Christian Para Village Common Forest (VCF) is located at 23.084112°N, 92.040285°E in Bhoyachari Mouza, Kamalchari Union, Khagrachari Sadar Upazila, Khagrachari District. The total area of the VCF is approximately 48.56 ha. Established in 1955 by the local indigenous community, the VCF has been managed under customary practices, now formalized through the Betchari Christian Para VCF Committee, consisting of a 7-member executive body and a general body of all community members. The SID-CHT project, implemented by UNDP in collaboration with Khagrachari Hill District Council and a local NGO, helped strengthen governance and management of the VCF during 2018-2019.

The site harbors rich biodiversity of flora and fauna. There are 177 plant species including 53 trees, 21 shrubs, 3 bamboos, 70 herbs, 29 climbers, and one epiphyte (UNDP 2021). The trees include vulnerable (VU) *Brownlowia elata* (Moos), *Baccaurea ramiflora* and *Artocarpus lacucha*. The other important (major) tree species include *Schima wallichii*, *Artocarpus chama*, *Albizia procera*, and *Gmelina arborea*.

Fauna totals 130 species: 39 mammals, 55 birds, and 17 reptiles (UNDP 2021), including critically endangered (CR) *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, vulnerable (VU) Great Hornbill (*Buceros bicornis*) and *Python bivittatus*, and near-threatened (NT) *Felis chaus*. The forest provides breeding grounds and seasonal refuge for wildlife from surrounding degraded areas.

Management prohibits unauthorized harvesting, hunting, jhum cultivation, and pesticide use. Bamboo is harvested on a 3-year cycle, and proceeds support conservation and community development. Strong local commitment, traditional regulations, and effective community monitoring have made the VCF a resilient, biodiverse habitat with high sustainability potential.

3.9. Goyaichari Akhbari Para Village Common Forest, Guimara, Khagrachari

Goyaichari Akhbari Para Village Common Forest (VCF) is located in Goaichari Mouza, Sinduk Chari Union, Guimara Upazila, Khagrachari District, at 22.880416ºN, 91.977818ºE. It spans approximately 202.34 ha area. Established by the local Marma and Chakma communities in 1982-83, the VCF was initiated to conserve biodiversity for sustainable use of forest resources and maintain streamflow to support agriculture. The forest (legally USF land) is managed by a locally formed VCF Management Committee based on customary rights, supported by the Chittagong Hill Tracts Regulation, 1900. The committee includes a general body with one representative from each household and a nine-member executive body.

The VCF hosts rich tropical semi-evergreen hill forest vegetation. Notably, it includes red-listed tree species like vulnerable (VU) *Dipterocarpus gracilis* and *Artocarpus lacucha*, and near-threatened (NT) *Lithocarpus acuminatus*, *Baccaurea ramiflora,* and *Swintonia floribunda*. Other important species include *Dipterocarpus turbinatus*, *Terminalia arjuna* (Arjun), *Phyllanthus emblica*, *Michelia champaca*, *Terminalia bellirica*, and several *Ficus* species. The flora also includes several bamboo species, namely *Melocanna baccifera*, *Bambusa tulda* (Mitinga bansh)*, B. balcooa* (Borak bansh), *B. polymorpha* (Pharua bansh) and numerous shrubs, vines, and herbs.

Fauna includes the critically endangered (CR) Asian Elephant (*Elephas maximus*) and *Ursus thibetanus*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, vulnerable (VU) *Lophura leucomelanos* and *Python bivittatus*, and many other mammals, reptiles, and birds. The site also serves as a seasonal refuge and breeding ground for displaced wildlife.

Management activities include patrolling, entry regulation, bans on tree felling, wildlife hunting, jhum cultivation, pesticide use, and unsupervised harvesting. Strengthened by community commitment and past project support, the VCF has significantly reduced previous disturbances such as illegal logging and recreational impacts. It now serves as a resilient ecosystem providing water, food, and ecological services to adjacent communities, and demonstrates potential for long-term ecological sustainability.

3.10. Tindukchari Para Bon, Guimara, Khagrachari

Tindukchari Para Village Common Forest (VCF), located at 22.893960°N, 91.975622°E in 223 Tinduk Chori Mouza, Sindukchari Union, Guimara Upazila of Khagrachari District, covers approximately 81 ha of tropical hill forest. Established in 1903 by the local mouza Headman, its purpose is to ensure sustainable access to timber, bamboo, and non-timber forest products for local communities.

The VCF (legally USF land) is managed through customary rights by the Tindukchari VCF Conservation Committee, composed of 11 community representatives. Management was strengthened in 2017 under the USAID-funded CHT Watershed Co-Management Activity, which improved governance, boundary demarcation, and alternative livelihoods for forest-dependent households. The forest supports 62 nearby families, all actively involved in its protection.

The site harbors rich biodiversity with native flora such as *Gmelina arborea*, *Dipterocarpus turbinatus*, *Syzygium cumini*, and several bamboo species. Red-listed plant species include the vulnerable (VU) *Anisoptera scaphula* (Boilam) and the near-threatened *Lithocarpus acuminatus*.

Fauna includes the critically endangered (CR) *Elephas maximus*, *Ursus thibetanus*, Clouded Leopard (*Neofelis nebulosa*), Chinese Pangolin (*Manis pentadactyla*), and *Indotestudo elongata*, along with various reptiles, birds, and small mammals.

Key management practices include bans on tree felling, hunting, jhum cultivation, pesticide use, and unauthorized collection of forest products. Entry is regulated, and forest monitoring is conducted through community patrolling. The VCF serves as a vital refuge for wildlife from surrounding degraded areas and provides multiple ecosystem services such as water regulation, food, and carbon sequestration. Its century-long community stewardship has proven highly effective, demonstrating strong sustainability potential and ongoing commitment to conservation.

3.11. Banchara Para Bon, Dighinala, Khagrachari

Banchara Para Bon, a 135.63 ha VCF, is located in Dighinala Mouza, Dighinala Sadar Union, Dighinala Upazila, Khagrachari District, at approximately 23.315559°N, 92.087327°E. Established in 1980 by the local community for sustained water supply and non-timber forest product use, its management was later strengthened in 2018–2019 through the CHT-WCA project implemented by UNDP with the Hill District Council and a local NGO. The VCF is managed by the community-based Banchara Para Bon Management Committee, structured with a general body (one member per household) and a 9-member executive body elected every three years.

Ecologically, the site represents a tropical hill ecosystem with rich biodiversity. Dominant flora includes *Melocanna baccifera* bamboo and a variety of tree, shrub, herb, vine, and epiphyte species. Major tree species include *Dipterocarpus turbinatus* and *Syzygium cumini*. Red-listed plant species include endangered (EN) *Uvaria cordata* (Bagh ranga) shrub, vulnerable (VU) *Artocarpus lacucha* tree and *Dendrobium fimbriatum* epiphyte, and near-threatened (NT) *Ficus auriculata*, *Baccaurea motleyana* and *Lithocarpus acuminatus* trees and *Aerides multiflora* epiphyte.

Fauna includes critically endangered (CR) *Ursus thibetanus* and *Manis pentadactyla*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, and vulnerable (VU) *Python bivittatus* and *Lophura leucomelanos*. The VCF serves as a seasonal refuge for wildlife from degraded nearby forests.

Management activities emphasize biodiversity conservation and sustainable resource use. Prohibited actions include unauthorized tree/bamboo cutting, hunting, jhum cultivation, and pesticide use in streams. Bamboo is harvested on a three-year rotation cycle, and violations incur traditional penalties. The committee and community members patrol the site regularly, especially during bamboo harvest seasons. The management system has been effective and sustainable over decades, significantly preserving biodiversity and ecosystem services. Former issues such as illegal resource collection and disturbance by recreational visitors have reduced due to improved governance and awareness.

3.12. Shriti Bikash Karbari Para Village Common Forest, Dighinala, Khagrachari

Shriti Bikash Karbari Para VCF lies at approximately 23.366191°N, 92.053124°E in Dighinala Mouza, Dighinala Sadar Union, Dighinala Upazila, Khagrachari District. It spans 36.44 ha of tropical hill forest, bordered by Gangaram Reserved Forest to the east and Donordhor Karbari Para VCF to the south. The site was established in 1970 by the local Headman to ensure water availability for agriculture and sustainable use of forest products. The forest is managed by a community-based committee based on the provisions of the Chittagong Hill Tracts Regulation, 1900. The committee includes 13 executive members and a general body comprising the whole community of 107 households. In 2018–19, the USAID-funded CHT-WCA project, implemented by UNDP, Hill District Council, and a local NGO, supported boundary demarcation, mapping, and capacity building.

The VCF is rich in biodiversity, with around 40% area covered by bamboo (mainly *Melocanna baccifera*). Tree species include near threatened (NT) *Baccaurea ramiflora* and *Ficus auriculata*, while *Dipterocarpus turbinatus*, *Aphanamixis polystachya* (Pitraj), *Artocarpus chama*, and *Syzygium cumini* are the major species. Understory species include medicinal herbs and wild vegetables.

The forest supports diverse fauna, including the critically endangered (CR) *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, *Macaca leonina* and *Trachypithecus pileatus*, and vulnerable (VU) *Python bivittatus*, King Cobra (*Ophiophagus hannah*) and *Lophura leucomelanos*.

Management activities include banning unauthorized tree/bamboo cutting, hunting, burning, *jhum* cultivation, pesticide use, and unsanctioned harvesting. Traditional rules and fines are enforced. The forest is patrolled regularly, especially during the bamboo harvesting season, which follows a three-year rotation to ensure sustainability. Revenue from bamboo sales supports forest and community development. Over the last two decades, the VCF has been effectively managed, maintaining its natural condition and serving as a refuge for wildlife from surrounding degraded forests. The community remains committed to its long-term conservation.

3.13. Donurdhor Karbari Para Bon, Dighinala, Khagrachari

Donurdhor Karbari Para Bon (VCF) is located at 23.361951°N, 92.055146°E in Dighinala Mouza, Dighinala Sadar Union, Dighinala Upazila, Khagrachari District, near the Gangaram Reserve Forest. It spans approximately 48.58 ha and represents a well-preserved tropical hill ecosystem. Established in 1947-48 by the then Headman of the mouza, its primary purpose has been to conserve forest resources and ensure year-round stream water and non-timber forest products for the community. The site gained enhanced support through the USAID-funded CHT-WCA project (2018-2019), which aided in mapping, boundary demarcation, and strengthening management. Legally an USF land, the VCF is managed the Donurdhor Karbari Para Bon Songrokkhon Committee, a 21-member elected body, under customary rights supported by the Chittagong Hill Tracts Regulation, 1900. The committee oversees conservation efforts, sustainable harvesting, and enforcement of traditional rules.

The site harbors rich biodiversity. The vegetation (flora) is dominated by *Melocanna baccifera* bamboo with three other Bamboo species including the vulnerable (VU) *Schizostachyum dullooa* and diverse tree species including the vulnerable (VU) *Anisoptera scaphula*, and the near-threatened (NT) *Baccaurea ramiflora* and *Swintonia floribunda*. The major tree species include *Terminalia bellirica*, *Aphanamixis polystachya*, *Gmelina arborea*, *Schima wallichii* and *Albizia chinensis* (Chakua koroi).

Fauna includes a wide range of mammals, reptiles, amphibians and birds including the critically endangered (CR) *Manis pentadactyla* and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, *Trachypithecus pileatus*, and vulnerable (VU) *Python bivittatus* and *Lophura leucomelanos*.

Key management activities include prohibiting tree/bamboo cutting, hunting, fire-setting, jhum cultivation, and pesticide use. Bamboo harvesting follows a three-year rotation, with revenues supporting conservation and community needs. The committee enforces rules through patrolling and traditional sanctions. Since 2018, effective community-based monitoring has curbed illegal activities, demonstrating successful community-led conservation.

3.14. Dane Dhanpata Mouza Bon, Dighinala, Khagrachari

Dane Dhanpata Mouza Bon (VCF) is located near Jogesh Chandra Para village at 23.413557°N, 92.019730°E in Dane Dhan Pata Mouza, Babuchara Union, Dighinala Upazila, Khagrachari District. Spanning approximately 60.7 ha, the site represents a tropical hill forest ecosystem. It was first brought under community-based management in 1965 by the then Mouza Headman, aiming to protect forest resources and ensure perennial stream flow. Governance of the VCF is rooted in customary laws under the Chittagong Hill Tracts Regulation, 1900, implemented by the Dane Dhan Pata Mouza Bon Songrokkhon Samity, a nine-member elected community body.

The site boasts rich biodiversity, including tropical semi-evergreen flora such as *Dipterocarpus turbinatus*, *Syzygium cumini*, and *Lagerstroemia speciosa* (Jarul), along with threatened species like the Vulnerable (VU) *D. gracilis* (Sil garjan) and *Lophopetalum wightianum* (Raktan) trees and *Dendrobium fimbriatum* orchid. Near-threatened (NT) species *Baccaurea ramiflora* tree and *Aerides multiflora* orchid. *Melocanna baccifera* bamboo covers about 10% of the area.

Fauna includes critically endangered (CR) Indian Pangolin (*Manis crassicaudata*) and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, and vulnerable (VU) *Python bivittatus* and *Lophura leucomelanos*.

Management activities include rotational bamboo harvesting, habitat protection, and restrictions on tree cutting, hunting, jhum cultivation, and pesticide use. Community patrols are conducted, especially during bamboo harvesting season. During 2018-2019, the SID-CHT project further enhanced management through boundary demarcation, committee capacity building, and livelihood support. The VCF provides vital ecosystem services and serves as a biodiversity refuge amid surrounding landscape degradation. Effective community stewardship has maintained the forest's ecological integrity, ensuring its continued conservation and sustainability.

3.15. Modhyo Dhanpata Mouza Bon, Dighinala, Khagrachari

Modhyo Dhanpata Mouza Bon (VCF) is located in Middle Dhonpata Mouza, Babu Chora Union, Dighinala Upazila, Khagrachari District, at approximately 23.441479°N, 92.023877°E. Covering about 266.4 ha, it is bounded by several canals and represents a tropical hill ecosystem. Established in 1965 by the local headman, the forest is managed by the Modhyo Dhonpata Mouza Bon Songrokkhon Samity, a community association of nine elected members, operating under customary rights and local governance rules. Although legally government-owned (USF land), the local community manages the site to conserve forest resources for water supply and sustainable non-timber forest products, under the provisions of the Chittagong Hill Tracts Regulation, 1900.

The forest contains significant biodiversity, including 40% coverage of *Melocanna baccifera* bamboo and diverse native trees, shrubs, herbs, and climbers. Along with the major tree species *Albizia procera* (Sada koroi), *Gmelina arborea*, *Dipterocarpus turbinatus* and *Artocarpus chama*, the forest hosts the vulnerable (VU) *Artocarpus lacucha* and *Lophopetalum wightianum*, and the near-threatened (NT) *Baccaurea ramiflora*.

Fauna includes the critically endangered (CR) *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, vulnerable (VU) *Macacca mullata*, *Python bivittatus* and *Lophura leucomelanos*, and the near-threated (NT) *Prionailurus bengalensis*, as well as numerous other species of mammals, reptiles, and birds. The site serves as an important habitat and breeding ground, especially as surrounding forests have degraded.

Management activities focus on conserving the forest for ecosystem services including bamboo and wild vegetable supply, fuel wood, medicinal plants, and perennial water flow. The management committee prohibits unauthorized tree cutting, hunting, fire setting, shifting cultivation, bamboo shoot harvesting, and pesticide use in streams. They organize patrols quarterly, or more frequently during bamboo harvesting, and practice sustainable bamboo harvesting on three-year rotations. Strengthened by a UNDP-supported project, the committee has effectively preserved the forest’s ecological integrity and remains committed to its long-term conservation.

3.16. Jarulchari Bagaichari Dojor Para Bon, Dighinala, Khagrachari

Jarulchari Baghaichari Dojor Para Bon (VCF), located near Notun Chandra Karbari Para village in Jarulchori Mouza, Babuchora Union, Dighinala Upazila, Khagrachari District at 23.405903°N, 92.033903°E, covers approximately 97 ha area. Established in 1966 by the local Mouza Headman, it is managed by the Jarulchari Baghaichari Dojor Para Bon Songrokkhon Committee – a community-based group, based on customary rights (on USF lands) provided by the Chittagong Hill Tracts Regulation, 1900.

The forest represents a tropical hill ecosystem rich in biodiversity, including significant native flora such as *Melocanna baccifera* bamboo (covering 25-30% of the area), red-listed tree species like the vulnerable (VU) *Dipterocarpus gracilis* and *Lophopetalum wightianum*, and near-threatened (NT) *Baccaurea ramiflora*, alongside a wide variety of shrubs and herbs.

Fauna includes the critically endangered (CR) *Neofelis nebulosa* and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak* and vulnerable (VU) *Macacca mullata*, *Python bivittatus* and *Lophura leucomelanos*, as well as numerous other mammals, reptiles, and birds. The site functions as a critical habitat and migration refuge for wildlife displaced by nearby forest degradation.

Management focuses on conserving ecosystem services vital to local livelihoods, such as water supply, bamboo and non-timber forest products, medicinal herbs, and soil and water regulation. Prohibited activities include unauthorized tree and bamboo cutting, hunting, fire-setting, shifting cultivation, bamboo shoot harvesting, and pesticide use. The committee enforces these rules through monitoring, patrolling, and traditional sanctions. Management effectiveness has been strong, maintaining the site's ecological integrity and biodiversity as a critical refuge amid regional habitat loss. The community remains committed to its long-term conservation.

3.17. Pablakhali Mouza Bon, Dighinala, Khagrachari

Pablakhali Mouza Bon (VCF) is located in Pablakhali Mouza, Kobakhali Union, Dighinala Upazila, Khagrachari District at approximately 23.291110°N, 92.090734°E. Covering approximately 214.98 ha, it lies within a tropical hill ecosystem, bordered by streams and nearby villages. Established in 1946–47 by the then Mouza Headman, the forest was conserved to ensure sustainable access to forest resources like timber, bamboo, fuelwood, and wild vegetables, as well as to maintain the perennial flow of water for community use. Legally owned by the government as USF and, it is managed locally by a 17-member Pablakhali Mouza Forest Management Committee, following customary rules under the Chittagong Hill Tracts Regulation, 1900.

The site harbors high biodiversity, with about 40% covered by *Melocanna baccifera* bamboo and the rest by a diverse array of native trees, shrubs, herbs, and climbers including several red-listed species such as the Vulnerable (VU) *Artocarpus lacucha*, *Lophopetalum wightianum*, *Castanopsis castanicarpa* (Lamba kanta batna), *Lithocarpus polystachyus* (Kanta batna), *Horsfieldia amygdalina* (Holdu Barela), *Scaphium scaphigerum* (Sampan), and *Schleichera oleosa* (Kusum), and the near-threated (NT) *Pterygota alata* and *Swintonia floribunda*.

Fauna includes the critically endangered (CR) *Neofelis nebulosa*, *Indotestudo elongata*, endangered (EN) *Macaca leonina* and *Muntiacus muntjak*, and the vulnerable (VU) *Macaca mulatta*, *Python bivittatus*, and *Lophura leucomelanos*, alongside numerous other bird, mammal, and reptile species. The site also attracts wildlife from surrounding degraded forests, offering refuge and breeding grounds.

Management activities include forest patrolling, regulation of resource extraction (e.g., rotational bamboo harvesting), prohibition of destructive practices like hunting and jhum cultivation, and enforcement of community-approved rules. The CHT-WCA project (2018-19) supported capacity-building, mapping, and livelihood diversification. As a result, management effectiveness has significantly improved, enabling sustained biodiversity conservation and provision of vital ecosystem services.

3.18. Shahamoni Santi Vila Notun Mog Para Bon, Panchari, Khagrachari

Shaha Moni Shanti Villa Notun Mog Para Bon (VCF) is located at 23.398366°N, 91.913960°E in Chengi Mouza, Chengi Union, Panchari Upazila, Khagrachari District. Encompassing approximately 96.76 ha, this VCF was established in 2001–2002 by the then Mouza Headman to ensure perennial water supply and sustainable use of forest products. The site is managed by the local community through the Shaha Moni Shanti Villa Mog Para VCF Management Committee, which operates under customary rights provided by the Chittagong Hill Tracts Regulation, 1900, and community-formulated regulations. The committee collaborates with government institutions and development partners.

This forest supports significant biodiversity, with 89 recorded plant species and 126 animal species (UNDP, 2021). Major plant species include *Artocarpus chama*, *Terminalia chebula* (Haritaki), *Terminalia bellirica* and *Syzigium cumini* trees and three bamboo species – *Bambusa bambos* (Kanta bansh), *Bambusa tulda* and *B. polymorpha*. Red-listed flora includes vulnerable (VU) *Schleichera oleosa* and near-threatened (NT) *Ficus auriculata* trees. Several ecologically important shrubs and herbs are present, many of which provide food and medicinal resources to locals.

Among fauna, several threatened species are present such as the critically endangered (CR) *Manis pentadactyla*, endangered (EN) *Muntiacus muntjak*, vulnerable (VU) *Macaca mulatta* and *Python bivittatus*, and near-threatened (NT) *Prionailurus bengalensis*. The site also supports breeding of birds like Red Junglefowl (*Gallus gallus*) and Lineated Barbet (*Psilopogon lineatus*). Many wildlife species migrate here from degraded nearby forests, making the VCF vital for species aggregation and conservation connectivity.

Management activities include strict prohibitions against tree felling, hunting, fire-setting, jhum cultivation, and pesticide use. These are enforced through traditional rules and community patrols. With support from the CHT-WCA project (2018-19), the management committee enhanced capacity, mapped boundaries, and initiated livelihood support. Over the past two decades, this community-led conservation has successfully preserved forest integrity and ecosystem services such as water provision, soil health, and carbon storage.

3.19. Nirbogazo Chara Village Common Forest, Laxmichari, Khagrachari

Nirbogazo Chara Village Common Forest (VCF), locally known as Nirbogazo Chara Reserve, is situated at 22.824083°N and 91.943656°E in Laxmichari Mouza, Laxmichari Upazila, Khagrachari District. Its total area is approximately 81 ha. It was established as a community reserve in 1947 by local leaders to ensure water supply and sustainable use of non-timber forest products. In 2018–2019, the USAID-funded project (CHT-WCA), implemented by UNDP, supported the community in strengthening management, demarcating boundaries, and promoting alternative livelihoods.

Though legally owned by the government (USF land), the forest is managed by the Nirbogazo Chara VCF Management Committee under customary laws under the provisions of the Chittagong Hill Tracts Regulation, 1900. This committee includes a general body with one representative per household and an 11-member executive body, reformed every three years through elections.

Flora of the forest includes dense *Melocanna baccifera* bamboo and common tree species of the hill forests of Bangladesh such as *Dipterocarpus turbinatus*, *Artocarpus chama*, *Mangifera sylvatica* (Uriam), including red-listed species like vulnerable (VU) *Anisoptera scaphula* and *Bouea oppositifolia* (Mailaam) and near-threatened (NT) *Swintonia floribunda*.

Fauna includes endangered (EN) *Muntiacus muntjak*, vulnerable (VU) *Macaca mulatta*, and near-threatened (NT) Bengal Monitor (*Varanus bengalensis*) alongside numerous other birds, mammals, and reptiles. It also serves as a seasonal refuge for wildlife from nearby degraded areas.

Management activities prohibit tree felling, hunting, fire setting, jhum cultivation, and pesticide use. Resource extraction is regulated, with bamboo harvested every three years. Forest patrolling ensures rule enforcement. The management has been effective in sustaining biodiversity and ecosystem services like water regulation, carbon sequestration, and soil fertility, making it a critical habitat amidst growing regional deforestation.

3.20. Maishchari Mouza Bon, Mohalchari, Khagrachari

Maishchari Mouza Bon (VCF) is located near Sati Para village in Maishchari Mouza, Mohalchari Sadar Union, Mohalchari Upazila, Khagrachari District, at approximately 23.004948°N, 91.978419°E. Covering about 40.46 ha, this site represents a tropical hill forest ecosystem and supports rich native biodiversity. It was first brought under community management in 2004 by the Mouza Headman to ensure sustainable access to ecosystem services such as bamboo, wild vegetables, and stream water. During 2018-2019, the USAID-funded CHT-WCA project (implemented by UNDP) helped strengthen management through capacity-building, boundary demarcation, and alternative livelihood support.

The site is legally state-owned land (USF) but managed by the local Maishchari Mouza Forest Management Committee based on customary right provided by the Chittagong Hill Tracts Regulation, 1900. The committee consists of 13 members and enforces community-agreed conservation rules.

The VCF harbors significant biodiversity, including 96 plant species and 108 animal species (UNDP, 2021). The plants include some red-listed tree species such as the vulnerable (VU) *Schleichera oleosa* and *Artocarpus lacucha*, and the near-threatened *Swintonia floribunda*. Other tree species include *Phyllanthus emblica*, *Dipterocarpus turbinatus*, *Terminalia bellirica*, etc. *Melocanna baccifera* bamboo dominates 30% of the area.

Fauna includes 43 mammals, 37 birds, 12 reptiles, 6 fish, and 61 insects. There are several red-listed species such as the critically endangered (CR) *Ursus thibetanus* and *Indotestudo elongata*, and the endangered (EN) *Muntiacus muntjak*. Birds like *Gallus gallus* and Red-breasted Parakeet (*Psittacula alexandri*) are common. Streams support fish, crustaceans, and mollusks that are important for local diets.

Management involves community patrols, biannual meetings, and regulated bamboo harvesting. Illegal resource extraction, hunting, and jhum cultivation are prohibited and penalized. Despite economic pressures, community stewardship has effectively preserved biodiversity and ecological functions. Continued community commitment and past project support have helped maintain and improve the forest's condition, ensuring long-term conservation.

3.21. Ultachari Bihar Para Bon, Mohalchari, Khagrachari

Ultachari Bihar Para Bon, also known as Ultachari Village Common Forest (VCF), is located beside Ultachari Bihar Para village in Keyangghat Mouza, Kayangghat Union, Mohalchari Upazila, Khagrachari District, at approximately 23.022309°N, 92.055403°E. Covering around 80.93 ha, the site represents a tropical hill forest ecosystem. Established in 1965 by the local Headman to ensure sustainable access to water and forest products, the forest has since been managed by a community-formed committee. With support from the USAID-funded CHT-WCA project (around 2018), governance and management capacity of the committee have been strengthened, along with boundary demarcation of the forest and alternative livelihood support to the community. Legally classified as USF land, the site is managed by the local community under customary laws based on the provision (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900. A 13-member executive body oversees management.

The forest is rich in biodiversity, with tropical semi-evergreen vegetation including the near-threated tree species *Baccaurea ramiflora* and *Swintonia floribunda*. Major species include *Dipterocarpus turbinatus*, *Artocarpus chama*, *Syzygium cumini*, and two bamboo species – *Melocanna baccifera*, *Bambusa tulda*.

Fauna is also diverse, including three critically endangered (CR) *Trachypithecus phayrei*, *Manis pentadactyla*, and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, and vulnerable (VU) *Macacca mullata* and *Python bivittatus*.

Management activities focus on conservation, resource protection, and community benefit. Forest patrols are conducted at least quarterly, with stricter enforcement during bamboo harvest seasons. Unauthorized access and resource extraction are prohibited. The site provides vital ecosystem services – water, food, fuel, and cultural value – and serves as a refuge for wildlife from degraded surrounding forests. Its long-term effective community-based management has preserved its ecological integrity, ensuring sustainable conservation into the future.

3.22. Korollyachari Sarnath Bonobihar Para Bon, Mohalchari, Khagrachari

Korollyachari Sarnath Bonobihar Para Bon (VCF) is situated near Sarnath Bon Bihar in Kayang Ghat Mouza, Kayang Ghat Union, Mohalchari Upazila, Khagrachari district, at approximately 23.002808°N, 92.047517°E. The site spans 24.28 ha, comprising 23.06 ha of natural forest and 1.21 ha of horticultural plantation. Established in 1967 by the then Mouza Headman, the forest was conserved to ensure stream water supply and sustainable use of non-timber forest products. In 2018–2019, the UNDP-implemented CHT-WCA project helped strengthen community management through boundary demarcation, committee reformation, and livelihood support.

Legally an unclassed state forest (USF) land governed by the Deputy Commissioner and Hill District Council, the VCF is managed by the community under customary rights under the provision (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900. The 17-member Korollyachari VCF Management Committee follows customary rules and community decisions to manage the site.

The site supports a rich tropical hill forest ecosystem, with *Melocanna baccifera* bamboo covering 30% of the area. Key tree species include *Dipterocarpus turbinatus*, *Artocarpus chama*, *Aphanamixis polystachya*, *Legerstroemia speciosa*, *Terminalia bellirica*, *Mangifera sylvatica* and *Alstonia scholaris* (Chatim). Red-listed tree species include vulnerable (VU) *Lophopetalum wightianum*, and near-threatened (NT) *Swintonia floribunda* and *Baccaurea ramiflora*. The understorey hosts diverse shrubs, herbs, climbers, and epiphytes.

Fauna includes endangered (EN) *Trachypithecus pileatus* vulnerable (VU) *Macacca mullata*, *Python bivittatus*, *Lophura leucomelanos*, and other mammals, birds, and reptiles. The forest also serves as a refuge and breeding ground for wildlife from surrounding degraded areas.

Management activities include regular patrols, restriction on unauthorized access and resource collection, and prohibition of commercial harvesting. Management effectiveness is reflected in the preservation of biodiversity and ecosystem services, including water supply, carbon sequestration, and soil health. Despite minor degradation, community commitment and external support have ensured the forest's continued conservation and resilience.

3.23. Ramdhon Para Ban, Alikadam, Bandarban

Ramdhon Para Ban (VCF) is located in Tainfa Mouza, Alikadam Sadar Union, Alikadam Upazila, Bandarban District at approximately 21.694408°N, 92.354014°E. Covering 32.20 ha, it represents a tropical hill forest ecosystem. Established in 1973 under customary governance by the village Karbari, it was later strengthened through the USAID-funded CHT Watershed Co-management Activity (2018–2020), resulting in a formal community-based governance system under written bylaws. The forest is managed by the 11-member Ramdhon Para Ban Songrokkhon Committee, supported by a general body of community members. Although legally government-owned USF land, the site is effectively governed and managed by the community based on the customary rights provided by the Chittagong Hill Tracts Regulation, 1900.

The forest hosts significant biodiversity. Flora includes red-listed tree species, namely the vulnerable (VU) *Dipterocarpus gracilis*, *Lophopetalum wighianum*, *Artocarpus lacucha* and *Syzygium syzygioides* (Khudi jam), and the near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata*. Other tree species include *Syzygium cumini*, *Phyllanthus emblica*, *Terminalia chebula* and the most dominant *D. turbinatus*. There are three species of bamboo – *Melocanna baccifera*, *Bambusa tulda* and *B. vulgaris*.

Key fauna of the forest includes the critically endangered (CR) *Elephas maximus* and *Manis pentadactyla*, and the endangered (EN) *Trachypithecus pileatus* and *Muntiacus muntjak*. It also supports numerous provisioning and regulating ecosystem services vital to the local community, including bamboo, wild vegetables, fuelwood, medicinal plants, and water.

A written management plan guides sustainable use and conservation, prohibiting jhum cultivation, hunting, and pesticide use, while allowing limited bamboo harvests for funding. Active forest patrolling and community compliance have improved conditions, reversing earlier degradation. Currently, management effectiveness is estimated at around 70%, with further strengthening of community engagement needed for long-term sustainability.

3.24. Hlachong Aung Para Ban, Alikadam, Bandarban

Hlachong Aung Para Ban (VCF) is located in Toain Mouza, Noapara Union, Alikadam Upazila, Bandarban District, at 21.637575°N, 92.329467°E. Covering 34.59 ha, it is a well-preserved tropical hill forest bordered by natural features and demarcated by boundary pillars. Established in 2000 by the local Mouza Headman, the VCF is collectively stewarded by 64 Marma households of Hlachong Karbari Para, based on customary rights. The site received significant management support in 2018-2019 under the USAID-funded CHT-WCA project, implemented by UNDP in collaboration with the Hill District Council and a local NGO.

Although legally government-owned unclassed state forest, the VCF is managed by a nine-member Hlachong Aung Para Bon Songrokkhon Committee, formed by the community under the legal provision of the Chittagong Hill Tracts Regulation, 1900. The committee, led by an elected President, operates under a written management plan that prohibits jhum cultivation and hunting, allows limited sustainable bamboo harvesting, and imposes fines on illicit resource extractors. Quarterly meetings and active community monitoring ensure implementation of conservation measures.

The forest hosts over 40 plant species including several threatened and near-threatened species such as the vulnerable (VU) *Dipterocarpus gracilis* and *Artocarpus lacucha*, and near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata*. Major species include *Dipterocarpus turbinatus*, *Ficus benghalensis* (Bot), *Vitex peduncularis* (Goda), *Bursera serrata* (Gutgutia), *Albizia chinensis*, and wild banana (*Musa ornata*). It also contains three bamboo species, including the vulnerable (VU) *Schizostachyum dullooa*.

Fauna of the site includes the critically endangered (CR) *Ursus thibetanus* and *Indotestudo elongata*, endangered (EN) *Trachypithecus pileatus* and *Muntiacus muntjak*, and the vulnerable (VU) *Buceros bicornis*. The VCF provides critical refuge for wildlife displaced from nearby degraded forests.

Beyond biodiversity, the VCF supports community livelihoods by supplying timber, bamboo, food insects, wild honey, and clean water, and plays roles in cultural rituals, soil fertility, and climate regulation. While conservation is generally effective, external tree theft remains a challenge. Continued external support is seen as essential for long-term sustainability.

3.25. Bodujhiri Para Ban, Lama, Bandarban

Bodujhiri Para Ban, a 23.59 ha VCF, is located in Gozalia Mouza, Gozalia Union, Lama Upazila, Bandarban District, at 21.857225°N, 92.139281°E. Its boundary is clearly marked by concrete pillars and natural streams. Established in 2013 by the village Karbari, Mr. Songjon Tripura, the VCF was created to sustain local biodiversity, streamflow, and other essential ecosystem services. The forest is managed by the Tripura community, consisting of 22 households, under a structured management committee – Bodujhiri Para Bon Songrokkhon Committee – with both general and executive bodies, headed by an elected President.

During 2018–2019, the UNDP-led CHT-WCA project supported the VCF with digital mapping, boundary delineation, and livelihood initiatives. The community has a written management plan that prohibits unauthorized resource extraction, hunting, jhum cultivation, and harvesting without permission. Regular patrolling and monthly meetings ensure compliance with fines or traditional sanctions for violators.

The forest hosts at least 50 plant species, including several red-listed species such as the vulnerable *Dipterocarpus gracilis*, *Syzygium syzygioides* and *Mitragyna parvifolia* and *Careya arborea* (Kumbhi), and the near-threatned (NT) *Ficus auriculata*. Bamboo species *Bambusa tulda* and *B. vulgaris* (Baijja bansh) are also present.

Fauna of the forest includes threatened species like the critically endangered (CR) *Manis pentadactyla* and *Indotestudo elongata*, endangered (EN) *Nycticebus bengalensis*, and vulnerable (VU) *Python bivittatus*, as well as common species like Wild Boar (*Sus scrofa*), *Gallus gallus* and Hill Myna (*Gracula religiosa*).

The VCF serves as a critical refuge for wildlife migrating from nearby degraded habitats and provides key provisioning, regulating, and supporting ecosystem services. Due to improved governance, resource violations have significantly declined, and the forest is effectively conserved with strong community stewardship.

3.26. Gazon Para Ban, Lama, Bandarban

Gazon Para Ban is a 19.68 ha VCF located in Duluzhiri Mouza, Saroi Union, Lama Upazila, Bandarban District, at 21.871647°N, 92.196214°E. It is surrounded by hills to the east and south and streams to the north and west. It consists entirely of natural forest and supports diverse native flora and fauna characteristic of the southern hill ecosystem of Bangladesh. Established in 1971 by the village head, Mr. Gazon Karbari, the VCF has been conserved by the community ever since. The USAID-funded CHT-WCA project (2018-19) helped strengthen management capacity and formalize boundary mapping.

Though a government-owned USF land, the VCF is managed by a community committee formed under customary rights, suppported by the Chittagong Hill Tracts Regulation, 1900. The Gazon Para VCF Committee has 11 members, including a President, General Secretary, Treasurer, and general members, and follows the directives (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900 alongside locally approved regulations.

The forest hosts at least 70 plant species, including threatened species like the vulnerable (VU) *Dipterocarpus gracilis* and *Syzygium syzygioides* and the near-threatened (NT) *Ficus auriculata* and *Lithocarpus acuminatus*. Major tree species include *Dipterocarpus turbinatus*, *Gmelina arborea*, *Syzygium cumini* and *Ficus hispida* (Kak dumur), along with bamboo species *Melocanna baccifera* and *Bambusa tulda*.

Fauna includes the critically endangered (CR) *Manis pentadactyla* and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, and vulnerable (VU) *Macacca mullata*, *Lophura leucomelanos*, *Python bivittatus*, as well as common species like *Sus scrofa* and *Gallus gallus*.

The VCF provides vital ecosystem services including timber, bamboo, honey, and fish provisioning, as well as streamflow regulation, climate moderation, and soil nutrient cycling. Management activities strictly prohibit unauthorized cutting, hunting, and jhum cultivation, with penalties for violations. Regular patrolling and community monitoring ensure protection. The community's effective management has preserved the forest's biodiversity and maintained year-round water in the adjacent canal. Though occasional illegal extraction occurs, enhanced monitoring continues. The committee is committed to ongoing conservation and seeks support from government and NGOs to secure its future.

3.27. Painkhyang Para Ban, Naikyongchari, Bandarban

Painkhyang Para Ban (VCF) is located near Kukichara Marma Para in Douchari Mouza, Douchari Union, Naikyongchari Upazila, Bandarban District, at 21.445686°N, 92.313700°E. The forest covers

100.84 ha, and has well-defined boundaries marked by pillars and mapped digitally by the SID-CHT project. Established in 1988 by local indigenous communities led by the village head (Karbari), the VCF was created to meet community needs for timber, bamboo, non-timber forest products, and stream water. About 250 families from Marma and Tripura communities across five villages depend on the forest. The USAID-funded CHT-WCA project (2018-19) helped strengthen the management committee and improve governance.

Though legally government-owned USF land, the VCF is effectively managed by the Paikhyang Para Ban Songrokkhon Committee, a community association operating under customary rights, supported by the Chittagong Hill Tracts Regulation, 1900. The 11-member committee, led by a President, enforces community-approved rules regulating use and conservation.

The forest hosts around 50 plant species, including the threatened (Vulnerable) tree species *Dipterocarpus gracilis* and *Syzygium syzygioides*, and near-threatened (NT) *Ficus auriculata*. Major tree species include *Albizia procera*, *Dipterocarpus turbinatus* and *Legerstroemia speciosa*, alongside three bamboo species.

Fauna includes the critically endangered (CR) *Ursus thibetanus*, *Elephas maximus* and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak*, vulnerable (VU) *Macacca mullata*, *Python bivittatus* and *Buceros bicornis*, and many other common mammals, reptiles, birds, and amphibians of the region. The forest serves as habitat, breeding ground, and migratory stopover for diverse wildlife.

The VCF supplies timber, fuelwood, bamboo, wild fruits, honey, and fish, while also providing water regulation, climate moderation, soil fertility, and carbon sequestration. Management prohibits unauthorized tree felling, hunting, and shifting cultivation, enforcing penalties for violations. Regular community patrolling and monthly committee meetings maintain forest health. Despite occasional threats from external timber extraction, the management committee, supported by the village head and local authorities, effectively mitigates risks. The community remains committed to conserving the forest and its biodiversity sustainably into the future.

3.28. Yang Nik Mro Para Ban, Naikyongchari, Bandarban

Yang Nik Mro Para Ban is a 94.76 ha VCF located in 276 Torgu Mouza, Douchari Union, Naikyongchari Upazila, Bandarban District, at 21.473756°N, 92.327489°E. With 70% natural forest, the site is part of the tropical hill ecosystem and holds significant biodiversity. Established in 2000 by the village head, Mr. Yang Nik Karbari, the VCF aims to ensure sustainable water supply for agriculture and non-timber forest product use by the local community. The SID-CHT project (2018–19) helped strengthen its governance and provided alternative livelihoods to forest-dependent families, increasing community involvement in forest management.

The forest is managed collectively by 12 households through the Yang Nik Para VCF Committee. This committee follows the Chittagong Hill Tracts Regulation, 1900 alongside community-adopted regulations, with a nine-member executive body elected every three years.

The forest harbors at least 100 plant species, including several red-listed species such as the vulnerable (VU) *Dipterocarpus gracilis*, *Artocarpus lacucha* and *Syzygium syzygioides* trees and *Schizostachyum dullooa* bamboo, and the near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata* trees. The major tree species are *Bombax ceiba* (Shimul), *Albizia lebbeck* (Kalo koroi) and *Protium serratum* (Gutguttya) trees, alongside two bamboo species – *Melocanna baccifera* and *Bambusa tulda*.

Fauna of the forest includes the critically endangered (CR) *Ursus thibetanus* and *Manis pentadactyla*, endangered (EN) *Nycticebus bengalensis*, and vulnerable (VU) *Macacca mullata*, *Lophura leucomelanos* and *Buceros bicornis*. The forest serves as a crucial habitat and seasonal refuge for wildlife migrating from degraded nearby areas.

The VCF provides essential ecosystem services, including fuelwood, medicinal herbs, bamboo shoots, water purification, carbon sequestration, and soil nutrient cycling, along with cultural and scenic values. Management strictly prohibits unauthorized tree cutting, hunting, and shifting cultivation, imposing fines or traditional penalties for violations. Regular patrolling is conducted, especially during bamboo harvesting, which follows a sustainable three-year rotational system. Though occasional theft by outsiders occurs, strengthened monitoring has minimized such threats. The committee remains committed to the long-term conservation and sustainable management of the forest and its biodiversity.

3.29. Pung Rao Mro Para Ban, Naikyongchari, Bandarban

Pung Rao Mro Para Ban, a 30.86 ha VCF, is located in 276 Torgu Mouza, Douchari Union, Naikyongchari Upazila, Bandarban District, at 21.484947°N, 92.314886°E. The site features dense natural vegetation typical of the tropical hill forest ecosystem. Established in 1990 by village head Mr. Pung Rao Mro, the forest was conserved to secure community access to stream water and non-timber forest products for the community. The USAID-funded CHT-WCA project (2018-19) supported the community with mapping, boundary demarcation, and capacity building to enhance governance.

Legally owned by the Government of Bangladesh as USF land, the site is managed by the local community under customary rights according to the Chittagong Hill Tracts Regulation, 1990. The community formed the “Pung Rao Para Ban Samity,” a nine-member executive committee responsible for forest management.

The forest hosts around 30 tree species, including several red-listed tree species such as the vulnerable (VU) *Dipterocarpus gracilis*, *Artocarpus lacucha*, *Syzygium syzygioides* and *Diospyros malabarica* (Gab), and the near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata*. The major species are *Bombax ceiba*, *Albizia lebbeck* and *Protium serratum*, alongside two bamboo species – *Melocanna baccifera* and *Bambusa tulda*.

Fauna includes the critically endangered (CR) Hoolock gibbon (*Hoolock hoolock*), *Ursus thibetanus* and *Manis pentadactyla*, endangered (EN) *Nycticebus bengalensis*, and vulnerable (VU) *Macacca mullata* and *Buceros bicornis*. The site acts as a refuge for wildlife displaced by deforestation in surrounding areas.

Provisioning services include timber, bamboo, fuelwood, and medicinal plants; regulating services involve water flow and soil fertility. Management prohibits unauthorized tree cutting, hunting, and shifting cultivation, enforced by fines or traditional sanctions. Bamboo harvesting follows a sustainable three-year rotation, with proceeds funding forest management and community projects. The committee reports no current threats and is committed to preserving the forest’s biodiversity and ecosystem functions indefinitely.

3.30. Mongjoy Para Ban, Naikyongchari, Bandarban

Mongjoy Para Ban, an 81.97 ha VCF, is situated in Raju Mouza, Gumdum Union, Naikyongchari Upazila, Khagrachari District, at 21.307250°N, 92.187783°E. About 80% area of the VCF is covered with natural tropical hill forest. It has clearly marked boundaries with pillars and a digital map prepared under the SID-CHT project. Established in 2017 through a collaborative effort of villagers, the Mouza Headman, and the Karbari, the VCF aims to safeguard natural resources and water for community welfare. The entire village collectively owns the forest based on customary rights under the Chittagong Hill Tracts Regulation, 1900. The Mongjoy Para Ban Management Committee, elected by the community, governs the site with written by-laws and consults community members on management decisions.

The forest harbors approximately 150 plant species, including some red-listed species such as the vulnerable (VU) *Dipterocarpus gracilis*, *Lophopetalum wightianum*, *Artocarpus lacucha* and *Syzygium syzygioides*. The major tree species are *Albizia procera*, *Syzygium cumini*, *Ficus benghalensis*, *F.*

hispida, *F. racemosa* and *Bombax ceiba*. There are four bamboo species – *Melocanna baccifera*, *Bambusa vulgaris*, *B. tulda*, and the vulnerable (VU) *Schizostachyum dullooa*.

Fauna includes endangered (EN) *Nycticebus bengalensis* and *Muntiacus muntjak*, and vulnerable (VU) *Macacca mullata*, *Lophura leucomelanos*, and *Python bivittatus*. Occasionally, the critically endangered (CR) *Elephas maximus* and *Ursus thibetanus*, and vulnerable (VU) *Buceros bicornis* are also sighted. The site supports species migration from nearby forests and acts as refuge for range-restricted species like porcupines.

The VCF provides vital ecosystem services including timber, firewood, wild fruits, medicinal herbs, honey, fish, water flow regulation, climate moderation, and soil fertility. Management prohibits unauthorized tree/bamboo cutting and hunting, maintains fire lines, and follows a written plan. The committee meets quarterly to review and plan activities, with community oversight during annual general meetings. Management effectiveness is estimated at 80%, though biodiversity monitoring is not yet regular. Occasional illicit harvesting by outsiders remains a challenge.

3.31. Paglachara Para VCF, Rowangchari, Bandarban

Paglachara Para Village Common Forest (VCF) is located in Rowangchari Mouza, Rowangchari Union, Rowangchari Upazila, Bandarban District at 22.152307°N, 92.315941°E, covering an area of 15.44 ha. Established in the early 1960s by people displaced by the Kaptai dam project, it has been managed by the community under the leadership of the Karbari (village chief) and, more recently, by a formal 7-member executive committee of the “Paglachara Poribesh O Grameen Ban Songrokkhon Samity.” Though the land is government-owned USF land, the community manages it based on customary rights under the Chittagong Hill Tracts Regulation, 1900. Boundary demarcation and management capacity were enhanced with support from the CHT-WCA project (around 2018) and the COMPASS CHT-FLR project (2018–2023) – both funded by USAID.

The VCF contains a well-preserved tropical mixed evergreen forest with around 60 native tree and shrub species, including the critically endangered (CR) *Hydnocarpus kurzii* (Chalmugra), endangered *Canarium resiniferum* (Dhup) and vulnerable *Scaphium scaphigerum* trees. The major tree species are *Haldina cordifolia* (Haldu), *Artocarpus chama*, *Terminalia bellirica*, *Dipterocarpus turbinatus*, *Anogeisus lanceolata* (Phuljhumuri), *Bombax ceiba* and *Erythrina variegata* (Mandar). There are four bamboo species, namely *Melocanna baccifera*, *Bambusa tulda*, Ora (*Dendrocalamus longispathus*) and the vulnerable (VU) *Schizostachyum dullooa*.

Fauna of the forest includes at least 40 species, including the endangered (EN) *Nycticebus bengalensis* and *Muntiacus muntjak*. Locals also claimed possibility of the critically endangered (CR) *Ursus thibetanus*. It serves as a refuge and breeding ground for various mammals and migratory birds.

The VCF supports vital ecosystem services such as stream water, timber, food, medicinal plants, and spiritual values, while contributing to carbon sequestration and biodiversity conservation. Management activities include bi-monthly meetings, regular monitoring, and enforcement of rules against illegal extraction and hunting. With strong community ownership, effective rules, and sustained vigilance, Paglachara VCF has remained ecologically intact and is expected to remain a long-term conservation success.

3.32. Talukder Para VCF, Rowangchari, Bandarban

Talukder Para Village Common Forest (VCF) is situated in Rowangchari Mouza, Rowangchari Sadar Union, Rowangchari Upazila, Bandarban District, at approximately 22.152307°N, 92.315941°E. Covering 20.24 ha, it is bounded by Mong Kyamer Jhiri (stream), Painongro hill, and adjacent lands. Established in 1928 by community leader Mungbruhri Marma to ensure sustainable access to water, timber, and bamboo, it is governed under customary rights within the framework of the Chittagong Hill Tracts Regulation, 1900. Legally owned by the government, it is managed by the Talukder Paraban Songrokkhon Committee, a 7-member executive body with written bylaws.

The forest is rich in biodiversity, supporting around 100 species of trees and shrubs, including the critically endangered (CR) *Hydnocarpus kurzii* tree; vulnerable (VU) *Artocarpus lacucha*, *Lophopetalum wightianum* and *Syzygium syzygioides* trees and *Schizostachyum dullooa* bamboo; and near-threatened (NT) *Baccaurea ramiflora*, *Swintonia floribunda*, *Dillenia pentagyna* and *Ficus auriculata* trees. *Melocanna baccifera* bamboo covers most of the area of the VCF. There are also *Bambusa tulda* and *Dendrocalamus longispathus* (Ora bansh) bamboos.

Fauna includes the critically endangered (CR) *Manis pentadactyla* and *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, and vulnerable (VU) *Macacca mullata*, *Buceros bicornis* and *Python bivittatus*. The forest also supports various other species of mammals, reptiles and birds.

Management activities include regular monitoring, community meetings, enforcement of harvesting bans, and fire prevention. External support from donor-funded projects (CHT-WCA, COMPASS CHT-FLR) helped strengthen governance and capacity between 2018–2023. Conservation effectiveness is high, with no major threats except occasional fire risks from nearby shifting cultivation. The community's proactive engagement and the VCF's long-standing protection ensure its resilience, though formal registration and a long-term plan are suggested for future sustainability.

3.33. Na Vangga VCF, Barkal, Rangamati

Na Vangga Village Common Forest (VCF), located in Begenachori Mouza, Barkal Sadar Union, Barkal Upazila, Rangamati District (22.785728°N, 92.327481°E), covers approximately 104.86 ha. Established in 1990 by Gandhi Kumar Karbari, the VCF was created to ensure access to forest resources and ecosystem services, particularly water, for the local community. Legally government-owned USF land, the VCF is managed by the Na Vangga VCF Committee, composed of nine community-elected members with a written set of by-laws. The committee receives official recognition and allocation from the Hill District Council.

The VCF supports a diverse tropical hill ecosystem with around 100 plant species and 113 species of wild animals. The vegetation is dominated by *Melocanna baccifera* bamboo, along with two other bamboo species – *Bambusa tulda* and *B. polymorpha*. The forest contains several red-listed tree species such as the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Syzygium syzygioides* and *Artocarpus lacucha*, and near-threatened (NT) *Ficus auriculata*. The major tree species include *Dipterocarpus turbinatus*, *Gmelina arborea, Albizia odoratissima* (Tentua koroi), *Albizia chinensis*, *Albizia procera, Artocarpus chama*, *Haldina cordifolia* and *Syzygium cumini*.

Fauna of the forest includes the critically endangered (CR) *Ursus thibetanus*, *Manis pentadactyla* and Sambar Deer (*Rusa unicolor*), endangered (EN) *Muntiacus muntjak*, and vulnerable (VU) *Lophura leucomelanos* and *Prionailurus bengalensis*.

Management activities include regular monitoring, quarterly meetings, and strict enforcement of bans on unauthorized resource extraction and hunting, with penalties for violations. The VCF provides critical provisioning, supporting, and regulating ecosystem services and serves as a refuge for wild animals from surrounding degraded areas. Its effective community-based governance has ensured the forest's protection and sustainability over decades, with no current significant threats identified by the management committee.

3.34. Begena Chori VCF, Barkal, Rangamati

Begena Chori Village Common Forest (VCF) is located in Begenachori Mouza, Barkal Sadar Union, Barkal Upazila, Rangamati District, at 22.776300°N, 92.337150°E. Covering an area of 33.32 ha, this site demarcated by natural features and boundary pillars, represents the tropical hill forest ecosystem. It was established in 1963 by Headman Nilmoni under the Chittagong Hill Tracts Regulation, 1900, to ensure sustainable access to water and non-timber forest products for the local community. Since inception, it has been managed by the local community of Beganachori Para village, headed by the

Karbari (chief) of the village with support from the Mouza Headman, and later strengthened by the CHT-WCA project (2018–19). An 11-member executive committee manages the forest under customary rules and a written management plan. Management activities include regulated extraction of bamboo and trees, prohibition of poaching, and periodic harvesting of mature bamboo for village development. Monitoring is conducted regularly, and all activities aim at long-term sustainability.

The VCF hosts 161 plant species and 126 animal species (UNDP 2021). The flora includes several red-listed tree species, namely the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable *Dipterocarpus gracilis*, *Artocarpus lacucha* and *Syzygium syzygioides*, and near-hreatened *Ficus auriculata*. There are four bamboo species – *Melocanna baccifera* (major), *Bambusa tulda*, *B. polymorpha*, and the vulnerable (VU) *Schizostachyum dullooa*.

Fauna includes the critically endangered (CR) *Manis pentadactyla*, endangered (EN) *Nycticebus bengalensis* and Blue-throated Lizard (*Ptyctolaemus gularis*), vulnerable (VU) *Python bivittatus* and near-threatened (NT) *Prionailurus bengalensis*.

The forest provides essential provisioning (bamboo, water, wild foods), regulating (climate, pollution control), and supporting (soil fertility, carbon sequestration) ecosystem services. With no significant threats identified, the community maintains effective conservation practices and is confident in the forest's continued sustainability.

3.35. Digholchari Hazachara Para VCF, Belaichari, Rangamati

Digholchari Hazachara Para Village Common Forest (VCF) is located in Belaichari Mouza, Belaichari Sadar Union, Belaichari Upazila, Rangamati District, at 22.491564°N, 92.373139°E. The 8.59 ha forest is bounded by natural features including a stream, hills, and a waterfall. Established in 2001 by the village Karbari, Mr. Pottyaram Chakma, the VCF aims to conserve forest resources to ensure sustainable access to water and raw materials for housing and daily use. Legally owned by the government (USG land), the forest is managed by an 11-member committee of the local community (30 households), named 'Digholchari Hazachara Para VCF Committee'. Management decisions are made by community consensus, based on written bylaws and a formal management plan developed with the support of the USAID-funded CHT-WCA project (2018–2019), implemented by UNDP and local partners.

The site hosts a rich diversity of flora, with about 60% forested by native trees and 40% by bamboo species like *Melocanna baccifera*, *Bambusa tulda* and *B. polymorpha*. Red-listed tree species include the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Artocarpus lacucha* and *Syzygium syzygioides*, and near-threatened (NT) *Ficus auriculata*.

Fauna of the forest includes the critically endangered (CR) *Ursus thibetanus*, *Manis pentadactyla* and *Indotestudo elongata*, and endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, along with a variety of other birds, reptiles, amphibians, and aquatic species.

Management activities focus on biodiversity conservation, with restrictions on tree felling, bamboo harvesting, and hunting, all enforced by community monitoring. Sustainable bamboo harvesting supports community development. The site is currently free of significant threats, and the community is confident in the long-term sustainability of its conservation efforts with continued support from government and NGOs.

3.36. Sapchari Para VCF, Belaichari, Rangamati

Sapchari Para Village Common Forest (VCF) is situated in Kengrachari Mouza, Kengrachari Union, Belaichari Upazila, Rangamati District, at 22.561725°N, 92.3459786°E. Covering an area of 47.53 ha, the site lies adjacent to Sapchari Para village and is demarcated by boundary pillars and digitally mapped. The site represents a tropical hill forest ecosystem and was established in 1980 by the village community, led by the Karbari, to sustainably conserve natural resources. It has since been managed by the Sapchari Para Bon Songrokkhon Committee, comprising 16 members elected from the 69 local households, under customary rights and in accordance with provision (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900.

The forest supports rich biodiversity. Flora includes 165 species – 52 trees, 22 shrubs, 60 herbs, and 31 climbers (UNDP 2021) with several red-listed species such as the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Dipterocarpus gracilis*, and near-threated (NT) *Swintonia floribunda* and *Ficus auriculata*. Major tree species include *Gmelina arborea*, *Albizia procera*, *Dipterocarpus turbinatus*, *Ficus hispida*, *F. racemosa* (Joggo dumur), *Protium serratum*, *Syzygium cumini* and *Phyllanthus emblica*. Bamboo species like *Melocanna baccifera*, *Bambusa tulda*, *B. bambos* and *B. polymorpha* are abundant.

Fauna includes 184 species: 34 mammals, 95 birds, 30 reptiles, 10 fish, 9 amphibians, and 77 insects (UNDP 2021), including the critically endangered (CR) *Manis crassicaudata*, endangered *Trachypithecus pileatus* and *Muntiacus muntjak*, and vulnerable (VU) *Macacca mullata*, *Python bivittatus* and *Buceros bicornis*.

The management committee enforces strict regulations prohibiting unauthorized tree felling, bamboo harvesting, and wildlife hunting. Violations incur fines. A written management plan guides sustainable use and biodiversity conservation, contributing to ecosystem services such as water provision, wild food, soil fertility, and carbon sequestration. With active community engagement and support from projects like CHT-WCA, the VCF is effectively managed and free from internal or external threats, ensuring long-term sustainability of conservation outcomes.

3.37. Taraban Bhabona Kendra, Panchari, Khagrachari

Taraban Bhabona Kendra, a Buddhist meditation center, is located at 23.382337°N, 91.912904°E in Chengi Mouza, Chengi Union, Panchari Upazila, Khagrachari District. Covering 80.97 ha, about 80% of the site comprises natural forest, with the remainder used for buildings, open spaces, mango orchards, and an Agar (*Aquilaria malaccensis*) plantation. Established in 1997 by Headman Nilmoni Chakma, the site originally covered 202.43 ha, but about 121.46 ha were lost to local encroachment over time. The remaining area is now well conserved and functions as a tropical hill ecosystem with rich biodiversity. The site is managed by a 22-member committee led by President Usha Kanti Chakma and is spiritually under Rajban Bihara, Rangamati. It is respected by locals for its religious significance, which helps in preserving its ecological integrity. The Principal, Adi Kalyan Bhikkhu, and the monks ensure that the forest remains intact to maintain a peaceful environment for meditation.

Floral diversity includes red-listed species such as vulnerable (VU) *Scaphium scaphigerum* and near-threatened (NT) *Pterygota alata*, *Swintonia floribunda* and Hargoja (*Dillenia pentagyna*) along with typical hill forest tree species like *Dipterocarpus turbinatus*, *Artocarpus chama*, *Michelia champaca*, *Syzygium cumini*, *Dillenia indica* (Chalta), *Aphanamixis polystachya*, *Alstonia scholaris*, *Bombax ceiba*, *Lagerstroemia speciosa*, *Ficus benghalensis*, *Terminalia bellirica*, *Terminalia arjuna*, *Phyllanthus emblica*, *Sterculia villosa* (Udal, Fashya udal), *Schima wallichii*, *Haldina cordifolia* and *Ficus racemosa*. Bamboo species like *Melocanna baccifera* and *Bambusa tulda* are also present.

The site hosts a range of fauna including the critically endangered (CR) *Manis pentadactyla*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, and the vulnerable (VU) *Python bivittatus*. Numerous bird species including migratory visitors and breeders such as hornbills and black kites have been observed.

Management actions include boundary demarcation, limited income-generating plantations, and forest patrols. While occasional hunting persists, it is discouraged and has declined. Overall, the forest is effectively protected, largely due to community respect for its spiritual value, ensuring long-term biodiversity conservation and sustainability.

3.38. Bame Oijyangchari Para VCF, Barkal, Rangamati

Bame Oijyangchari Para Village Common Forest (VCF) is located in Vhusanchara Mouza, Vhusanchara Union, Barkal Upazila, Rangamati District, at 22.790256°N, 92.353767°E. Encompassing 95.33 ha, the site is part of a tropical hill forest ecosystem and is surrounded by hills, with clearly demarcated boundaries marked by pillars and digitally mapped under the CHT-WCA project. Established in 1958 by Karbari Doyadhon Karbari, the VCF was created to provide a sustainable source of bamboo and timber for the local community. The site is legally government-owned USF land but managed under customary rights by the 69-household local community. Management is led by an 11-member committee, named Bame Oijyangchari Para VCF Committee, with bylaws and a written management plan ensuring participatory governance and sustainable use.

The VCF is rich in biodiversity. Around 80% is dominated by *Melocanna baccifera* bamboo with other bamboo species – *Bambusa polymorpha* and *B. tulda*. Over 100 species of trees, shrubs, herbs, and climbers are present, including red-listed species such as the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Dipterocarpus gracilis*, *Artocarpus lacucha* and *Syzygium syzygioides*, and near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata*.

Fauna includes threatened species like the critically endangered (CR) *Manis pentadactyla* and *Rusa unicolor*, endangered (EN) *Trachypithecus pileatus* and *Nycticebus bengalensis*, and the vulnerable (VU) *Python bivittatus*, along with many species of birds, reptiles and insects.

The committee enforces strict rules against unauthorized extraction and wildlife hunting, ensuring effective conservation. Forest resources are distributed equitably among community members. There are currently no major threats, and the community's commitment and structured governance contribute to the site's ecological sustainability and long-term biodiversity conservation.

3.39. Bonjogichara Mouza Bon, Jurachari, Rangamati

Bonjogichara Mouza Bon (VCF) is located in Bonjogichara Mouza, Bonjogichara Union, Jurachari Upazila, Rangamati District, at 22.652717°N, 92.324997°E. Covering 48.08 ha, it is demarcated by natural streams and boundary lines of nearby villages. Established in 1965 by Headman Purno Mohon Chakma, the VCF was created to ensure sustainable access to non-timber forest products and water for local communities. It represents a well-conserved tropical hill forest ecosystem. Legally a USF land, the VCF is customarily managed by 422 households from Bonjogichara Mouza. It is governed by a 13-member management committee, led by the Mouza Headman, under written bylaws. With support from the CHT-WCA project (2018–2019), community capacity was strengthened through mapping, boundary demarcation, and institutional reform.

The site holds high biodiversity value, with a 2021 UNDP survey recording 112 plant species and 152 animal species (UNDP 2021). About two-thirds of the forest is covered by *Melocanna baccifera* bamboo. Major tree species include *Ficus hispida*, *Terminalia bellirica*, *Phyllanthus emblica*, *Protium serratum* and *Syzygium cumini*. Other tree species inlcude *Artocarpus chama*, *Terminalia chebula*, *Lagerstroemia speciosa*, *Diperocarpus turbinatus*, *Gmelina arborea*, Sorbaik Gulo (*Ficus semicordata*), *Mangifera sylvatica*, *Vitex peduncularis*, and *Garuga pinnata* (Shil bhadi). There are also several threatened species like the vulnerable (VU) *Artocarpus lacucha* and *Syzygium syzygioides* trees and *Schizostachyum dullooa* bamboo, and near-threatened (NT) *Baccaurea ramiflora* and *Ficus auriculata* trees.

Fauna includes the critically endangered (CR) *Indotestudo elongata* and *Manis crassicaudata*, endangered (EN) *Muntiacus muntjak*, and vulnerable (VU) *Lophura leucomelanos* and *Python bivittatus*, along with numerous birds and other mammals and birds, reptiles.

The management committee enforces strict regulations on extraction and hunting, with fines for violations. A written management plan guides sustainable harvesting, such as the regulated sale of bamboo. Despite occasional illegal activities, monitoring has improved. With strong community commitment, the VCF continues to provide critical ecosystem services and maintains high prospects for long-term ecological sustainability.

3.40. Bame Panchari Para Bon, Jurachari, Rangamati

Bame Panchari Para Bon (VCF) is located in Ereichaori Mouza, Bonjogichara Union, Jurachari Upazila, Rangamati District, at 22.695953°N, 92.383614°E. Covering 90.36 ha, the site is bounded by Andhar Manik Mouza to the north, a private hill to the east, and Bame Panchari stream to the south and west. Established in 1960 under the leadership of Headman Doya Mohon Chakma, the forest was officially recognized as a VCF in 2014. The CHT-WCA project supported boundary mapping and governance strengthening in 2018–2019. Legally a USF land, the VCF is customarily managed by 210 households of Ereichaori Mouza under the Chittagong Hill Tracts Regulation, 1900. An 11-member management committee, led by the Mouza Headman, makes decisions based on community consensus.

About 60% of the site is dominated by *Melocanna baccifera* bamboo, with the remaining area covered in diverse native trees, shrubs, herbs, climbers, and epiphytes. Key tree species include *Albizia procera*, *A. odoratissima, Lagerstroemia speciosa*, *Protium serratum* and *Mangifera sylvatica*, along with the threatened (Vulnerable) *Syzygium syzygioides* and near-threatened (NT) *Swintonia floribunda* and *Ficus auriculata*.

Fauna includes the endangered (EN) *Muntiacus muntjak* and *Nycticebus bengalensis*, and vulnerable (VU) *Macacca mullata*, *Lophura leucomelanos* and *Python bivittatus*, among others.

The committee enforces a strict no-hunting and controlled-harvest policy. Bamboo is harvested every three years, with revenue supporting community welfare. Frequent monitoring, adherence to a community-developed management plan, and strong leadership ensure effective conservation. The forest is currently well-preserved, with high prospects for long-term ecological sustainability.

3.41. Vhangamura Jadi Tug VCF, Kaptai, Rangamati

Vhangamura Jadi Tug Village Common Forest (VCF) is situated in Vaijjatoli Mouza, Kaptai Sadar Union, Kaptai Upazila, Rangamati District, at 22.441561°N, 92.281853°E. The 36.0 ha forest has well-defined boundary, clearly marked by pillars and streams, and a digital map prepared under the SID-CHT project during 2018-2019. The VCF represents a humid tropical hill forest ecosystem with rich biodiversity and is well conserved.

Established in 2004 by the mouza Headman to ensure sustainable forest resource use for local livelihoods, protection efforts intensified from 2011. Though legally owned by the government as USF land, customary ownership and management of the forest lie with the Vhangamura Jadi Tug village community under the provisions (Rule 41A) of the Chittagong Hill Tracts Regulation, 1900. An 11-member community committee, led by the village Karbari and headed by a President, manages the site based on consensus.

About half the forest is dominated by bamboo species – *Melocanna baccifera*, *Bambusa tulda* and the vulnerable (VU) *Schizostachyum dullooa* – with the rest densely vegetated by over 200 species of trees, shrubs, and herbs including the threatened (Vulnerable) tree species *Horsfieldia amygdalina*, *Syzygium syzygioides* and *Scaphium scaphigerum*. Major tree species include *Albizia procera*, *Albizia lebbeck*, *Gmelina arborea*, *Vitex peduncularis*, *Protium serratum, Ficus benghalensis* and *Lagerstroemia speciosa*.

Fauna includes the critically endangered (CR) *Ursus thibetanus* and *Manis crassicaudata*, endangered (EN) *Muntiacus muntjak*, *Nycticebus bengalensis* and *Trachypithecus pileatus*, and vulnerable (VU) *Python bivittatus* and *Lophura leucomelanos*.

The VCF provides vital ecosystem services including timber and bamboo for housing, wild fruits and vegetables for food, drinking water, climate regulation, streamflow maintenance, disease prevention, and soil fertility. Management involves selective bamboo harvesting every three years, strict prohibition of unauthorized tree cutting and poaching wild animals, and regular monitoring guided by a community-developed management plan. Revenues support local social welfare. The forest is well preserved with no significant threats, reflecting strong community commitment and promising long-term sustainability of its biodiversity and ecosystem functions.

3.42. Badalchari Badichara VCF, Langadu, Rangamati

Badalchari Badichara Village Common Forest (VCF) is located in Nolua Mouza, Bogachattor Union, Langadu Upazila, Rangamati District, at 22.940697°N, 92.289581°E. The 191.15 ha VCF is bordered by Doluchari mouza to the north, Nogudor mouza to the east, Nolua Chara stream to the south, and Badichara stream to the west. Its boundaries are clearly marked by pillars and streams, and a digital map was created under the CHT-WCA project in 2018-2019. The VCF represents a humid tropical hill forest ecosystem rich in biodiversity.

Established in 1990 by the village Karbari to secure water, timber, bamboo and other forest products for community use, the site has been managed by a village committee under the Karbari's leadership. The community now manages the VCF through a 15-member executive committee of the "Badalchari Badichara Grameen Bon O Poribesh Sangrokkhon Samity," which includes a President, Vice-President, General Secretary, Treasurer, Auditor, and members. The land is legally government-owned (USF) but customarily managed by the village under the Chittagong Hill Tracts Regulation, 1900.

A UNDP survey recorded 169 plant species (44 trees, 41 shrubs, 56 herbs, 26 climbers and 2 epiphytes) and 159 species of wild animals (5 mammals, 29 reptiles, 4 crustaceans, 2 mollusks, 13 fishes, 11 amphibians, and 95 birds) from this VCF (UNDP 2021). The flora is dominated by several bamboo species (*Melocanna baccifera*, *Bambusa bambos*, *B. tul*da, *B. polymorpha, Dendrocalamus longispathus*) covering 80-90% of the area. Major tree species include *Dipterocarpus turbinatus*, *Gmelina arborea*, *Albizia procera*, *Phyllanthus emblica*, and *Vitex peduncularis*. Several threatened tree species are present, such as the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Artocarpus lacucha* and *Syzygium syzygioides*, and near-threatened *Baccaurea ramiflora* and *Ficus auriculata*.

Fauna includes the critically endangered (CR) *Elephas maximus*, Gaur (*Bos gaurus*) and *Manis crassicaudata*, endangered (EN) *Muntiacus muntjak*, *Trachypithecus pileatus* and *Nycticebus bengalensis*, and the vulnerable (VU) *Lophura leucomelanos*.

The VCF provides essential ecosystem services including timber and bamboo for housing, wild fruits, vegetables, edible insects, drinking water, streamflow regulation, soil conservation, climate regulation, water purification, and carbon sequestration. Management involves sustainable bamboo harvesting every seven years, fire line establishment to prevent wildfire, monitoring of resource use, and plans to install a gravitational water supply system. Proceeds support local religious and educational institutions. The committee effectively protects the site, and it is well preserved.

3.43. Ranjit Para VCF, Langadu, Rangamati

Ranjit Para Village Common Forest (VCF) is located in Petanya Machra Mouza, Bogachattor Union, Langadu Upazila, Rangamati District, at 22.950519°N, 92.283108°E. The site covers about 72.85 ha and is bordered by Tijubap Chora stream to the north, Badachori VCF to the east, Myarichor Mouza to the south, and a road to the west. Boundaries are clearly marked with concrete pillars and digitally mapped under the SID-CHT project in 2018-19. The VCF represents a humid tropical hill forest ecosystem important for biodiversity and acts as a watershed area for Kaptai Lake. It was established in 1990-91 and strengthened under the leadership of Mr. Thowai and Chakma Circle Chief Raja Devashis Roy in 2005, with additional capacity building support from the UNDP-implemented CHT-WCA project.

Though legally government-owned as USF land, it is customarily managed by 70 indigenous families of Ranjit Para village under rights provided by the Chittagong Hill Tracts Regulation, 1900. A 21-member management committee, headed by a President and including various executive posts, oversees sustainable management following written by-laws.

The VCF's flora is dominated by *Melocanna baccifera* and *Bambusa tulda* bamboos, alongside important tree species including *Gmelina arborea*, *Legerstroemia speciosa*, *Dipterocarpus turbinatus*, *Albizia procera*, *Vitex peduncularis*, and *Mangifera sylvatica*. Several threatened or near-threatened species occur, including the critically endangered (CR) *Hydnocarpus kurzii*, vulnerable (VU) *Dipterocarpus gracilis*, *Syzygium syzygioides* and *Lophopetalum wightianum*, and near-threated (NT) *Swintonia floribunda* and *Ficus auriculata*.

Fauna is diverse, including the critically endangered (CR) *Elephas maximus*, endangered (EN) *Trachypithecus pileatus*, *Muntiacus muntjak*, vulnerable (VU) *Macacca mullata*, *Python bivittatus*, *Lophura leucomelanos*, and near-threatened (NT) *Felis chaus*, *Prionailurus bengalensis* and *Varanus bengalensis*.

The VCF provides essential ecosystem services such as bamboo for housing, wild foods, medicinal herbs, and water, along with supporting nutrient cycling, carbon sequestration, and streamflow regulation. Management activities focus on sustainable bamboo harvesting, habitat conservation, hunting prohibition, and forest monitoring to prevent unauthorized access. Seedling planting is planned to restore bamboo gaps. The committee effectively protects the site and manages resources sustainably, though restoration of species diversity is recommended to enhance ecological outcomes.

3.44. Doshbengye Chara VCF, Langadu, Rangamati

Doshbengye Chara Village Common Forest (VCF) is located in Challyatoli Mouza, Vasanyadam Union, Langadu Upazila, Rangamati District, at 22.919136°N, 92.293208°E. The 127.31 ha forest is bordered by Nolua Chara, Gorachori, Thalamma Mouza, and Jetagodinya Chara villages. The site, digitally mapped in 2018–19 by the CHT-WCA project, represents a humid tropical hill forest ecosystem rich in biodiversity.

Established in 2011 by the local indigenous community with facilitation from Mr. Binoy Prshad Karbari, the VCF's management was further strengthened by the UNDP-implemented CHT-WCA project during 2018–2019. Legally owned by the Government of Bangladesh, the land is customarily managed by 75 families of Doshbengye Chara village under the Chittagong Hill Tracts Regulation, 1900. A community-elected 11-member committee, headed by a President and including various executive posts, governs the forest following a written management plan.

Around 40% of the VCF is covered by *Bambusa tulda* and *B. polymorpha* bamboos, while the rest hosts over 100 native plant species, including major trees like *Albizia procera*, *Gmelina arborea*, *Vitex peduncularis*, *Garuga pinnata* and *Mangifera sylvatica*, and the near-threatened (NT) *Lithocarpus acuminatus*, *Swintonia floribunda*, and *Ficus auriculata*.

The forest supports rich fauna including the critically endangered (CR) *Manis crassicaudata*, endangered (EN) *Muntiacus muntjak* and *Trachypithecus pileatus*, and vulnerable (VU) *Macacca mullata* and *Lophura leucomelanos*. Occasional sightings of the critically endangered (CR) *Elephas maximus* and *Bos gaurus* were also reported by the locals. The area is prone to human-elephant conflict due to surrounding habitat loss (The Country Today, 2023).

The VCF provides timber, bamboo, food, and clean water, and supports streamflow, carbon sequestration, and climate regulation. While there are no major current threats, conservation efforts focus on regulating resource use and prohibiting hunting and unauthorized tree felling. The committee conducts periodic monitoring but sees a need for stronger measures to conserve water resources.

3.45. Basonto Pangkhua Para Bon, Rangamati

Basonto Pangkhua Para Bon (VCF) is situated in Basanto Mouza, Balukhali Union, Rangamati Sadar Upazila, Rangamati District, at 22.639514°N, 92.322014°E. The 46.51 ha VCF is naturally bounded by streams on three sides and the Basonto Pangkhua Para village on the east. Digitally mapped during the CHT-WCA project in 2018-2019, the forest represents a humid tropical hill ecosystem rich in biodiversity.

Established in 1950 by the village's Karbari (chief) to secure water and forest resources for the community, the VCF has since been managed by a community-formed committee. Its governance was further strengthened during 2018–2019 with support from the UNDP-implemented CHT-WCA project. Although legally owned by the government as USF land, it is customarily managed by 30 indigenous families under the Chittagong Hill Tracts Regulation, 1900. An 11-member management committee, headed by a President, oversees the VCF under a set of written bylaws.

About 40% of the forest area is natural forest and the remaining 60% is mostly shrubby vegetation. A 2021 UNDP study recorded 130 plant species, including fruit-yielding and culturally significant species (UNDP 2021). Notable tree species include the threatened (Vulnerable) *Artocarpus lacucha* and near-threatened (NT) *Lithocarpus acuminatus* and *Ficus auriculata*. The other major species include *Legerstroemia speciosa*, *Gmelina arborea*, *Neolamarckia cadamba* (Kadam), *Lannea coromandelica* and *Mangifera sylvatica*.

The site hosts 155 animal species including 88 birds and 25 mammals. Threatened fauna includes the critically endangered (CR) *Indotestudo elongata*, endangered (EN) *Muntiacus muntjak* and *Nycticebus bengalensis*, and vulnerable (VU) *Python bivittatus* and *Lophura leucomelanos*.

Management aims to ensure sustainable access to forest resources and aquatic biodiversity. Logging and hunting are prohibited without permission, and violators are fined. Restoration efforts have improved conditions, with no current internal or external threats to its conservation.

3.46. Doluchari VCF, Rangamati

Doluchari Village Common Forest (VCF), also known as Doluchari Public Reserve, is located in Baradam Mouza, Mogban Union, Rangamati Sadar Upazila, Rangamati District, centered around 22.552386°N, 92.135942°E. Spanning 68.70 ha of hilly terrain (50–150 m elevation), the VCF is surrounded by four indigenous villages and intersected by streams such as Kukujjyachari chara and Doluchari chara, which eventually flow into Kaptai Lake. It was established and protected by the local community to preserve biodiversity and sustain natural resources.

The VCF, leagally a government-owned USF land, is governed by a 21-member community management committee under customary rights per the Chittagong Hill Tracts Regulation, 1900. The community enforces strict by-laws that prohibit timber extraction, large-scale harvesting of forest products, jhum cultivation, and wildlife hunting.

Doluchari VCF hosts 113 plant species, including 39 trees, 19 shrubs, 25 herbs, 16 climbers and 4 epiphytes. The plants include the endangered (EN) shrub *Uvaria cordata* and vulnerable (VU) *Ficus fistulosa*, *Ficus variegata* (Red stem fig) and *Syzygium balsameum* (Buti Jam) trees; *Saprosma ternatum* (Kafrul Gachh) shrub, *Schizostachyum dullooa* bamboo, and *Dendrobium fimbriatum* orchid. There are also several near-threatened (NT) plant species namely *Ficus auriculata*, *Lithocarpus acuminatus* and *Swintonia floribunda* trees, *Tarenna campaniflora* (Haru Lodi) shrub and *Aerides multiflora* epiphyte (Feeroz et al., 2016).

Fauna includes 38 mammals, 61 reptiles, 33 amphibians, and 187 birds. Red-listed species inlcude the critically endangered (CR) *Manis pentadactyla*, *Ursus thibetanus*, and *Indotestudo elongata*, endangered (EN) Assamese Macaque (*Macaca assamensis*), *Macaca leonina*, Fishing Cat (*Prionailurus viverrinus*), *Muntiacus muntjak*, and Spotted Flying Lizard (*Draco maculatus*), vulnerable (VU) Hog Badger (*Arctonyx collaris*), Binturong (*Arctictis binturong*), Asian Leaf Turtle (*Cyclemys dentata*), Malayan Box Turtle (*Cuora ambonensis*), *Ophiophagus hannah*, Grey Peacock-Pheasant (*Polyplectron bicalcaratum*) and *Lophura leucomelanos*. Additionally, 9 endangered and 20 vulnerable butterfly species further enrich this biodiversity hotspot (Feeroz et al., 2016).

Management is effective, with regular patrolling and enforcement of regulations. Although occasional hunting and external threats like forest fires exist, the community remains committed to permanent conservation. The forest provides vital ecosystem services, including water for irrigation, bamboo and medicinal plants, carbon sequestration, and cultural value to the local indigenous community.

3.47. Chittagong University Campus, Hathazari, Chittagong

The Chittagong University Campus (CUC), located in Jangal Paschim Patty Mouza, Fatehpur Union, Hathazari Upazila, Chittagong District, between 22.45833°N - 22.48333°N latitude and 91.77500°E - 91.79583°E longitude, spans around 850 ha of hilly and plain terrain. Established in 1966, it serves academic and research purposes and is managed by the university's administrative structure, led by the Vice-Chancellor under the governance of the Senate and Syndicate.

Approximately 72% of the campus consists of hillocks (15–90 m high), with the remaining area comprising valleys, plains, streams, crop fields, and lakes. Despite past degradation, ongoing plantations and natural regeneration have restored much of the original semi-evergreen forest, supporting rich biodiversity.

Chittagong University Campus hosts 304 tree species belonging to 201 genera under 69 families (Hossain et al., 2016; Akhter et al., 2022), including a good number of red-listed species such as *Corypha taliera* (Tali Palm) – which is now extinct from the wild (EW); the critically endangered (CR) *Podocarpus neriifolius* (Banshpata); endangered (EN) *Gardenia resinifera* (Bon Kainnary, Dikmali); vulnerable (VU) *Bouea oppositifolia*, *Alstonia neriifolia* (Bon chatim) and *Anisoptera scaphula*; and near-threatened (NT) *Lithocarpus acuminatus.* In fact, most of the native and naturalized tree species of the hill forests of Bangladesh are conserved in the Chittagong University campus.

Fauna includes 27 mammals, 36 reptiles and 215 bird species. The mammals include endangered (EN) *Trachypithecus pileatus* and vulnerable (VU) *Prionailurus viverrinus* (Ahsan et al., 2015). The reptiles include vulnerable *Python bivittatus* and Monocellate Cobra (*Naja kaouthia*). The birds include vulnerable *Lophura leucomelanos* and the globally critically endangered Indian Griffon Vulture (*Gyps fulvus*). Other notable species include Blue-naped Pitta (*Pitta nipalensis*) and *Gallus gallus* (Ahsan and Chowdhury, 2008; Kabir et al., 2017).

Management is facilitated by various university departments and the Institute of Forestry and Environmental Science (IFESCU), which supports conservation through nurseries, environmental awareness, and wildlife rescue. Though some recent infrastructure developments have disturbed habitats, the site remains ecologically significant, delivering vital ecosystem services and acting as a semi-natural refuge for biodiversity in a semi-urban landscape.

3.48. Jahangirnagar University Campus, Savar, Dhaka

Jahangirnagar University Campus, located in Savar, Dhaka, Bangladesh (23.8667°N, 90.2667°E), spans 280 hectares and was established in 19970 and formally launched in January 1971. Positioned 32 km north of Dhaka city, the campus features diverse habitats including 24 ha of wetlands, woodlands, grasslands, and scrublands. Once part of the Madhupur Sal (*Shorea robusta*) forest, its original deciduous vegetation has largely been replaced by secondary growth and plantations. The campus is governed by the university administration headed by a Vice-Chancellor, appointed by the President of Bangladesh (the Chancellor), and supported by the Pro-Vice Chancellors, Treasurer, Syndicate, and Senate.

Due to the unique landscape comprising mosaics of undulating highlands, perennial lakes and seasonal wetlands is rich in floral and faunal diversity. Flora includes 917 vascular plant species from 574 genera and 145 families with red-listed species like *Corypha taliera*, which is now extinct from the wild (EW); endangered (EN) *Cycas pectinata* (Moni Raj), vulnerable (VU) *Artocarpus lacucha* and *Careya arborea*; and near-threatened (NT) *Ochna jabotapita* var. *pumila* (Bonmollika). The site has a particularly rich collection of wild fruit trees such as *Artocarpus chama*, *A. lacucha*, *Ficus benghalensis*, *F. benjamina* (Jiri pakur), *F. hispida*, *F. racemosa, F. religiosa* and *Dillenia indica* providing food and habitat support to birds and mammals. Other major tree species include *Shorea robusta*, *Dipterocarpus turbinatus*, *Hopea odorata*, *Bombax ceiba*, *Albizia procera*, *A. lebbeck*, *Barringtonia acutangula* (Hijal), *Crateva nurvala* (Borun), *Cassia fistula* (Sonalu), *Saraca asoca* (Ashok), *Butea monosperma* (Palash), *Lagerstroemia speciosa* (Jarul), etc. Waterbodies harbor aesthetic aquatic plants like *Nymphaea nouchali* (Nil Shapla), *N. pubescens* (Sada Shapla) and *N. rubra* (Lal Shapla) (Khan et al. 2021).

The site is rich in avifauna with 195 bird species, including the vulnerable (VU) Greater Spotted Eagle (*Clanga clanga*), near-threatened (NT) Grey-headed Fish-eagle (*Ichthyophaga ichthyaetus*) and globally near-threatened Red-breasted Parakeet (*Psittacula alexandri*). Notable mammals include endangered (EN) *Prionailurus viverrinus* and near-threatened (NT) *Felis chaus*, Large Indian Civet (*Viverra zibetha*) and Small Indian Civet (*Viverricula indica*). Reptiles include Common Krait (*Bungarus caeruleus*), Rat snake (*Coelognathus radiatus*), Common wolf snake (*Lycodon aulicus*), and near-threatened (NT) *Varanus bengalensis*. Several rodents and five bat species, including Indian Flying Fox (*Pteropus giganteus*), are also recorded (Mahany et al., 2009; Akter et al., 2013, Mahonta et al., 2016, Sharmin et al., 2018).

Management activities include strict regulation of human activities, protection of wetlands, and demarcation of settlement-free ecological zones. Facilities like a wildlife rescue center, butterfly park, botanical garden, and butterfly and bird fairs promote conservation awareness and education. Despite pressures from infrastructure development, the site maintains significant ecological integrity. The campus is a well-managed, semi-natural landscape within a semi-urban setting, serving as a model for in-situ and ex-situ biodiversity conservation.

4. ASSESSMENT RESULTS

Out of the 48 candidate sites assessed, the Assessors appraised 36 sites as ‘Confirmed’ OECMs (Table-1) as those sites fulfilled all IUCN-WPCA criteria for OECM. The verification team endorsed six of the confirmed OECM sites (#1-6 in Table-1), while verification of the remaining (30) Assessor-confirmed sites remained pending.

The remaining 12 sites (9 VCFs in Rangamati district and 3 institutional lands) also fulfilled all criteria for OECM but remained as ‘Candidate’ sites (Table-2) as there were no written consents from the site authorities to enlist and report those sites as OECMs by the Government.

Table-1. List of confirmed OECM sites

Sl. #	Site Name	Union	Upazila	District	Size (ha)	Assessor
1	Kamalchari Mukh VCF*	Kamalchari	Khagrachari Sadar	Khagrachari	127.80	Mehedi Hasan Khan[1]
2	Pittachhara Private Forest*	Belchari	Matiranga	Khagrachari	9.31	Mehedi Hasan Khan[1]
3	Bijoy Para VCF *	Alikhyong	Rowangchari	Bandarban	16.75	Kazi Zenifar Azmiri[2]
4	Tulachari Para VCF*	Rowangchari	Rowangchari	Bandarban	9.46	Kazi Zenifar Azmiri[2]
5	Aungjai Para VCF*	Rowangchari	Rowangchari	Bandarban	32.11	Kazi Zenifar Azmiri[2]
6	Suknachari Para VCF*	Alekhong	Rowangchari	Bandarban	12.56	Kazi Zenifar Azmiri[2]
7	Itchari Mouza Bon	Kamalchari	Khagrachari Sadar	Khagrachari	42.51	Mehedi Hasan Khan[1]
8	Betchari Christian Para VCF	Kamalchari	Khagrachari Sadar	Khagrachari	48.56	Mehedi Hasan Khan[1]
9	Goyaichari Akhbari Para VCF	Sinduk Chori	Guimara	Khagrachari	202.34	Mehedi Hasan Khan[1]
10	Tindukchari Para VCF	Sinduk Chori	Guimara	Dighinala	81.00	Mehedi Hasan Khan[1]
11	Banchara Para Bon	Dighinala	Dighinala	Khagrachari	135.63	Md. Sharifuzzaman[3]
12	Shriti Bikash Karbari Para VCF	Dighinala	Dighinala	Khagrachari	36.44	Md. Sharifuzzaman[3]
13	Donurdhor Karbari Para Bon	Dighinala	Dighinala	Khagrachari	48.58	Md. Sharifuzzaman[3]
14	Dane Dhanpata VCF	Babuchara	Dighinala	Khagrachari	60.70	Md. Sharifuzzaman[3]
15	Modhyo Dhanpata Mouza Forest	Babu Chora	Dighinala	Khagrachari	266.4	Md. Sharifuzzaman[3]
16	Jarulchari Baghaichari Dojor Para Bon	Babu Chora	Dighinala	Khagrachari	97.00	Dr. S.M. Rubaiot Abdullah[4]
17	Pablakhali Mouza Forest	Kobakhali	Dighinala	Khagrachari	214.98	Dr. S.M. Rubaiot Abdullah[4]
18	Shaha Moni Shanti Villa Mog Para VCF	Chengi	Panchari	Khagrachari	96.76	Md. Sharifuzzaman[3]
19	Nirbogazo Chara Village Common Forest	Laxmichari	Laxmichari	Khagrachari	81.00	Md. Sharifuzzaman[3]
20	Maishchari Mouza Bon	Mohalchari	Mohalchari	Khagrachari	40.46	Dr. S.M. Rubaiot Abdullah[4]
21	Ultachari Bihar Para Bon	Kayangghat	Mohalchari	Khagrachari	80.93	Dr. S.M. Rubaiot Abdullah[4]
22	Korollyachari Sarnath Bonobihar Para Bon	Kayangghat	Mohalchari	Khagrachari	24.28	Dr. S.M. Rubaiot Abdullah[4]
23	Ramdhon Para Ban	Alikadam Sadar	Alikadam	Bandarban	32.20	Md. Kamrul Islam[5]
24	Hlachong Aung Para Ban	Noapara	Alikadam	Bandarban	34.59	Md. Kamrul Islam[5]

*Verified by Verification Team
[1] Assistant Project Director, SUFAL Project, BFD
[2] Senior Program Assistant, IUCN, Bangladesh
[3] Wildlife and Biodiversity Conservation Officer, Management Planning Unit, BFD, Agargaon, Dhaka
[4] Associate Professor, Forestry & Wood Technology Discipline, Khulna University, Khulna
[5] Research Officer, Bangladesh Forest Research Institute, Chattogram

Sl. #	Site Name	Union	Upazila	District	Size (ha)	Assessor
25	Bodujhiri Para Ban	Gozalia	Lama	Bandarban	23.59	Md. Kamrul Islam[5]
26	Gazon Para Ban	Saroi	Lama	Bandarban	19.68	Md. Kamrul Islam[5]
27	Painkhyang Para Ban	Douchori	Naikyongchari	Bandarban	100.84	Md. Kamrul Islam[5]
28	Yang Ring Mro Para Ban	Douchori	Naikyongchari	Bandarban	94.76	Md. Kamrul Islam[5]
29	Pung Rao Mro Para Ban	Douchori	Naikyongchari	Bandarban	30.86	Md. Kamrul Islam[5]
30	Mongjoy Para Ban	Gumdum	Naikyongchari	Bandarban	80.97	Md. Kamrul Islam[5]
31	Paglachora Para VCF	Rowangchari	Rowangchari	Bandarban	15.44	Kazi Zenifar Azmiri[2]
32	Talukder Para VCF	Rowangchari	Rowangchari	Bandarban	20.24	Kazi Zenifar Azmiri[2]
33	Na Vangga VCF	Barkal Sadar	Barkal	Rangamati	104.86	Ms. Dipannita Bhattacharya[6]
34	Begena Chori VCF	Barkal Sadar	Barkal	Rangamati	33.32	Ms. Dipannita Bhattacharya[6]
35	Digholchari Hazachara Para VCF	Belaichari Sadar	Belaichari	Rangamati	8.59	Anup Dutta[7]
36	Sapchari Para VCF	Kengrachari	Belaichari	Rangamati	47.53	Anup Dutta[7]

Table-2. List of Candidate OECM retaining ‘Candidate’ Status

Sl. #	Site Name	Union	Upazila	District	Size (ha)	
1	Taraban Bhabana Kendra	Changi	Panchari	Khagrachari	80.97	Dr. S.M. Rubaiot Abdullah[4]
2	Bame Oijyangchari Para VCF	Bhusanchara	Barkal	Rangamati	95.33	Ms. Dipannita Bhattacharya[6]
3	Bonjogichara Mouza Bon	Bonjogichara	Jurachari	Rangamati	48.08	Anup Dutta[7]
4	Bame Panchari Para Bon	Bonjogichara	Jurachari	Rangamati	90.36	Anup Dutta[7]
5	Vhangamura Jadi Tug VCF	Kaptai Sadar	Kaptai	Rangamati	36.00	Ms. Dipannita Bhattacharya[6]
6	Badalchari Badichara VCF	Bogachattor	Langadu	Rangamati	191.15	Md. Kamrul Islam[5]
7	Ranjit Para VCF	Bogachattor	Langadu	Rangamati	72.85	Md. Kamrul Islam[5]
8	Doshbengye Chara VCF	Vasanyadam	Langadu	Rangamati	127.31	Md. Kamrul Islam[5]
9	Basanto Pangko Para Bon	Balukhali	Rangamati Sadar	Rangamati	46.51	Anup Dutta[7]
10	Doluchari VCF	Mogban	Rangamati Sadar	Rangamati	68.70	Anup Dutta[7]
11	Chittagong University Campus	Fatehpur	Hathazari	Chittagong	850.20	Ms. Dipannita Bhattacharya[6]
12	Jahanginagar University Campus	Savar Pourasava	Savar	Dhaka	280.00	Md. Kamrul Islam[5]

[6] Wildlife and Biodiversity Conservation Officer, Wildlife Management & Nature Conservation Division, BFD, Chattogram
[7] Assistant Professor, Forestry & Environmental Science, Shahjalal Science and Technology University (SUST), Sylhet

4. DISCUSSION

Potential of VCFs for OECM recognition

The study reveals that most of the VCFs in CHT have the potential to be recognized as OECMs. Because they are rich biodiversity, harbor many species of flora and fauna that are in threatened state in Bangladesh, and still retain the natural ecosystem of the region (tropical evergreen and semi-evergreen forest) which is now highly degraded elsewhere. Local (indigenous) communities have been managing the VCFs in a sustainable manner for decades to generations and concerned authorities and stakeholders such as the Hill District Councils, CHT Regional Council, Tribal Circle Chiefs, MoCHTA and MoEFCC recognize the de facto communal ownership of the VCFs as their customary rights. Moreover, in the recent years, institutional and management capacities of majority of the VCF communities have been strengthened by the CHT-WCA project and some by Arannayk Foundation.

Land right of indigenous communities over the VCFs

Indigenous communities in CHT maintain de facto rights over Village Common Forests (VCFs) based on Rule 41A of the Chittagong Hill Tracts Regulation, 1900. According to this Rule, the Headman is responsible for the conservation of the resources of his mauza. For this purpose any headmen may: (a) prohibit the removal of bamboos, timber and other forest produce by residents of his mauza other than for their domestic purpose or by non-residents of his mauza for any purposes, and (b) exclude any area or areas in his mauza from the jhuming area with a view to keeping such area or areas as a mauza reserve of bamboos, timber and other forest produce (GoB, 1900). Based on this legal provision, traditional authorities (Circle Chiefs, Headmen) informally regulate VCFs under customary land management (Roy, 2000). While not governed by the Forest Act, 1927, VCFs align with national policy promoting community-based forest management (Ministry of Environment and Forest, 1994).

The Hill District Council Acts of 1989 (as amended in 1998) have entrusted the three Hill District Councils (HDCs) in CHT with the management of natural resources in USF lands. However, while these laws devolve authority over USFs from the central government to the HDCs, this is not yet fully operational due to overlapping jurisdictions with the District Administration and Forest Department. While not explicitly mentioned in the laws, the HDCs support management of the VCFs by the local indigenous communities through customary governance and local development programs (Roy, 2000). The absence of formal legal title, overlapping jurisdiction, and weak enforcement expose VCFs to encroachment and legal uncertainty. Despite these limitations, VCFs are increasingly acknowledged in conservation discourse as Other Effective area-based Conservation Measures (OECMs) (IUCN & UNDP, 2015). Securing legal recognition remains critical for sustaining indigenous stewardship and biodiversity conservation.

Potential of tea estates and other biodiversity-rich private lands for OECM recognition

The survey of private forests and institutional lands was limited in this study, but there are considerable number of such sites with good biodiversity such as the Korean EPZ in Chittagong and Khyangs (Buddhist religious institutions) in CHT. In Sylhet region, there are private forests, which are conserved by absentee landlords. The tea gardens adjoining National Parks, Wildlife Sanctuaries and other natural forests in Sylhet, Habiganj and Moulvibazar districts also have great potential to qualify as OECMs. These opportunities should be explored. Many of those tea estates have significant areas under natural forest cover (tropical evergreen forest) with rich floral and faunal diversity. Moreover, movement of wild animals takes place between those tea estates and the adjacent natural forests. Aside from that, the tea plantations characteristically harbor certain species of ground/bush dwelling birds. The tea gardens can even be treated as unique agricultural system like the Saffron Heritage System in Kashmir, India (UNDP and NBA, 2022). However, owners/management of the tea estates appeared to be reluctant to cooperate toward this end. As we approached General Managers of some of those tea estates (Duncan Brothers Bangladesh Ltd., Ispahani Tea Ltd., National Tea Company, Rema Tea Company), they advised that they could cooperate only if the National Tea Board agrees to it.

Need for MoEFCC engagement in mobilizing stakeholder participation

The above cases call for initiative from the MoEFCC to facilitate cooperation of the public and private-sector organizations/institutions holding or governing lands with significant biodiversity values, including the influencers such as the Ministry of Chittagong Hill Tracts Affairs (MoCHTA), CHT Regional Council, Hill District Councils, National Tea Board and academic and religious institutions in the national initiative on OECM. In this regard, it is mentionable that the nine VCFs of Rangamati district that remained as 'Candidate' sites due to lack of written consent from the site authorities (Table-2) is due to the fact that the representatives of those sites wanted to have endorsement of Chairman, CHT Regional Council for issuing such written consent although they wished to have their VCFs recognized by the Government as OECMs and conferred verbal consent for surveying the sites. The lack of written consent for the other three 'candidate' sites (Buddhist religious institution Taraban Bhabona Kendra at Panchari, Khagrachari, Chittagong University campus and Jahangirnagar University campus) was due to similar reasons.

Legal basis for the government to recognize and report OECMs

Unlike protected areas (PAs), a formal declaration by the government through gazette notification is not necessary for OECM sites owned and managed by indigenous people and local communities, private sector organizations and individuals. However, as a Party to the Convention on Biological Diversity (CBD), the government is internationally obliged to promote area-based conservation beyond reserved forests (CBD, 2022). Target 3 of the Kunming-Montreal Global Biodiversity Framework encourages reporting of such areas as OECMs. The 'National Biodiversity Strategy and Action Plan' also supports inclusive conservation (Ministry of Environment, Forest and Climate Change, 2016). While UNEP-WCMC reporting is voluntary, doing so aligns Bangladesh with global conservation targets and acknowledges indigenous and local stewardship (IUCN & UNDP, 2015). Formal recognition mechanisms are needed to enable consistent documentation of these areas.

The legal basis for declaring suitable USF lands in CHT, such as the VCFs, as OECMs has been a matter of debate and discussion among the stakeholders. In this regard, literature reveals that the Chittagong Hill Tracts Regulation, 1900 (Rule 41A) authorizes the Mauza Headmen to conserve the natural resources of his mauza, control jhum cultivation and establish mauza reserves of bamboos, timber and other forest produce (Government of Bangladesh, 1900) and the Hill District Council Acts of 1989 (as amended in 1998) has entrusted the three Hill District Councils (HDCs) with the management of natural resources, including USFs.

Need for full assessment of potential OECM sites documented but not assessed

Twelve potential OECM sites surveyed by the Arannayk Foundation research team were not put to assessment due to lack of time and resources. These sites include three VCFs from Khagrachari and two VCFs from Bandarban district for which the site authorities gave written consent for including the sites as OECMs. The other sites include one VCF in Rangamati, a private cane (rattan) garden owned by a community group in Sunamganj, a tea garden in Moulvibazar, a private resort in Gazipur (Nuhash Polli) and three government institutional lands (FSTI Campus, SUST Campus, Citrus Research Center) in Sylhet. The NTAC may take steps to assess those sites based on the documentation made by Arannayk Foundation.

5. CONCLUSION AND RECOMMENDATIONS

The study underscores that Bangladesh has numerous biodiversity-rich sites with the potential to be recognized as OECMs. The VCFs in CHT, in particular, possess strong potential for OECM recognition. Institutionalizing the identification and assessment of OECMs will support Bangladesh's biodiversity targets and international conservation commitments. For time and other resource constraints, the study, however, covered only a limited number of potential sites. Therefore, identification and assessment of potential OECMs should continue as a long-term program.

With the establishment of the NTAC, the foundation for the institutionalization of the needed long-term program has been laid out. Now, with the help of the NTAC, BFD needs to play a proactive role in developing a national strategy and plan of action on OECMs. For identification of prospective sites, information about the initiative may be disseminated widely through mass media (newspaper and television, etc.) and website of the Department, inviting proposals from interested stakeholders for assessment and enlisting their prospective sites. Ways to incentivize the owners of the OECMs need to be identified and institutionalized in order to make the stakeholders interested in conserving the biodiversity values of their sites.

MoEFCC should lead multi-stakeholder engagement involving MoCHTA, CHT institutions, Forest Department, National Tea Board and other relevant organizations to build consensus and collaboration.

Immediate activities should include:

a) Developing a national strategy and guidelines for identification and reporting of OECMs, aligned with the IUCN-WCPA and UNEP-WCMC guidelines

b) Endorsing the six verified sites to the National Focal Person (Secretary, MoEFCC) for necessary action, including data submission to WD-OECM

c) Verification of the remaining sites that have been confirmed as OECMs by the assessors

d) Organizing a joint meeting or separate meetings with CHT institutions (Regional Council, Hill District Councils) and the Administrations of Chittagong University and Jahangirnagar University, to facilitate signing of the consent forms by the authorized representatives of the candidate OECM sites under their jurisdiction that have fulfilled all other criteria for OECM.

e) Organizing full assessment of the remaining documented sites that have not been assessed by designated assessors.

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Sustainable Market Linkage on Alternative Income Generating Activity (AIGA) for Livelihood Sustainability of Dependent Communities to reduce their Reliance on Forest Ecosystems

by

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1. Introduction

Bangladesh is a small but densely populated developing country in the tropical region (Ullah et al., 2020). The total area of forest land in Bangladesh is about 2.6 million hectares (BBS, 2021; BFD, 2016a). For protection of Bangladeshi forest ecosystems the 'Forest Policy 2016' proposed some mitigation and adaptation policies and practices, where distinct focus issues were on natural forests (Sal forest, Hill forest and Mangroves), forest communities, AIGAs, and market value chains. To comply with the policies and practices Bangladesh Forest Department (BFD) has adopted several natural forests protection initiatives through implementing several development projects. Sustainable Forests and Livelihoods (SUFAL) Project under Bangladesh Forest Department (BFD) initiated several natural forests protection initiatives. One most potential initiative is increasing access to alternative income generating activities (AIGAs). Since, the sustainable management of AIGAs is a challenging task when local communities depend heavily on natural resources for their livelihood, SUFAL project also try to design exit plan/strategy for keeping their AIGAs sustainable in the long-run. Accordingly, SUFAL project approved a research on the stated issues under SUFAL Innovation Grant (3rd call) on titled "Sustainable Market Linkage on Alternative Income Generating Activity (AIGA) for Livelihood Sustainability of Dependent Communities to Reduce their Reliance on Forest Ecosystems".

1.1. Problem statements

The total area of forest land in Bangladesh represents 17.5% of the total land area in the country (BFD, 2016b). The forest sub-sector contributes to 1.6 percent of GDP and 12 percent of agricultural GDP. Forests are critically important for the existence of human civilization. Nearly 2 billion people in the world live within a 10-km radius of forests, while approximately 1 billion live within a 1-km radius of forests (Newton et al., 2020) who depends on forests and their resources for livelihood and other necessities (FAO and UNEP, 2020). Forests are a source of food, fuel, fiber, and income (Agrawal et al., 2013; Angelsen et al., 2014), contributing directly to the livelihoods of millions of people, forests regulate climate, sequester carbon, and serve as a habitat (Hajjar et al., 2020; Houghton et al., 2015; Newton et al., 2016). Despite offering such benefits, natural forests are decreasing. During the 2015–2020 period, 10 million hectares of forests in the world were destroyed every year (FAO and UNEP, 2020) where humans are more responsible for forest loss (McGowan, 2016; Venter et al., 2016; Wang et al., 2019).

Despite having one of the lowest amounts of forests per capita (0.009 ha/person) (Henry et al., 2021), Bangladesh has lost 40% of its forests since 1930 and has seen a reduction of 106 square kilometers each year between 1990 and 2015 (Reddy et al., 2016; FAO, 2015). Most of the natural forests in Bangladesh are state-owned and managed by the Bangladesh Forest Department (BFD) is largely regulated by state-directed policies (BFD, 2016a, 2016c, 2017; DoE, 2016;GED, 2015; MoEF, 2012, 2017a, 2017b, 2020a, 2020b). To protect natural forests BFD has implemented the USAID funded 'Nishorgo Support Project' (NSP) during 1999–2009 (Fox et al., 2007), Integrated Protected Area Co-management (IPAC) project during 2009–2012 (BFD, 2018), Climate Resilient Ecosystems and Livelihoods (CREL) Project (2013–2017), followed by implementing a World Bank funded Sustainable Forests & Livelihoods (SUFAL) project during 2019-2023 (BFD, 2016a). Through the projects, BFD has adopted several natural forests protection initiatives on institutional development, information systems, research, training, improving protected areas and wildlife management through collaborative forest management (CFM), restoration of degraded forests, plantations, coastal green belt and field infrastructure, increasing access to alternative income generating activities (AIGAs), forest extension services & trees outside forests (TOF), etc. (BFD, 2016a). Accordingly, a visible progress has been made during the 7th five-year plan period which is reflected in the growth performance of the sector.

Kamrul Islam et al. (2019) found that alternative income generation activities (AIGAs) support to local people and enhance peoples' access to livelihood capital which reduces dependency of forest dependent communities (FDC) on forest resources for their living. Also, developing the capacity of local communities reduces forest dependence and ensures effective participation in the management process. But sustainable management of common pool resources is a challenging task when local communities depend heavily on natural resources for their subsistence. Ullah et al. (2020) identified that poor people are heavily dependent on forests for fuelwood, agriculture, and land. This over-dependency has translated into the proximate drivers of deforestation. The study also found that poor people are more likely to engage in deforestation (Ullah et al., 2020; Angelsen et al., 2014; Nerfa et al., 2020; Specht et al., 2019). In addition to households linked to deforestation drivers having a low annual income (Ullah et al., 2020; Specht et al., 2009; Tani, 2017b; Timko et al., 2010), less education (Specht et al., 2019) and land property (Ullah et al., 2020; Yanai et al., 2020). Moreover, farmers and laborers were more likely to engage in deforestation. It also identified that the households with a comparatively low socioeconomic status are causing higher levels of deforestation. Therefore, to protect forest loss, ensuring significant livelihood sustainability of the FDCs through AIGAs is essential.

Livelihoods comprise the capabilities, assets (including both material and social resources) and activities for means of living (Chinta Srinivas, 2020). All such activities that involve means of finding food, water, shelter, and clothing for self and his dependents can be referred to as livelihoods. Livelihood outcomes are the achievements of livelihood strategies, such as more income (e.g., cash), increased well-being (e.g., non-material goods, like self-esteem, health status, access to services, sense of inclusion), reduced vulnerability (e.g., better resilience through increase in asset status), improved food security (e.g., increase in financial capital in order to buy food) and a more sustainable use of natural resources (e.g., appropriate property rights). For thus, if a forest dependent family can live their livelihood by an AIGA in a sustainable manner, then the household (HH) reduces their dependency on forest.

A sustainable AIGA mostly depends on sustainable marketing systems. In Bangladesh, FDC faces three outstanding sources of risks and uncertainties in marketing of AIGA-commodities (Bangladesh Forest Management Plan, 2016). The first risk of AIGA-commodity marketing came from smallness in quantity of the produces (or marketable surplus) from minimum productive assets that make them marginal in the market and have less control over the price or the potential buyers. Small volume of the products also does not attract large purchasers that sell their products at less price to the small or local trader. The second risk is price instability, which occurs not only due to the small amount of marketable surplus but also the nature of the produces as some products are perishable (i.e., crops) which have limited storage opportunities. And, the third risk is unorganized marketing channels. AIGA peoples often depend on traditional distribution channels because of the absence of an organized marketing system, as a result, price of the IGA commodity is volatile and they, sometimes, fail to sell their total marketable surplus. On the other hand, IGA people have limited access over the value chain of an IGA commodity that makes them more marginal and vulnerable. They need a strong linkage both in the backward for inputs and forward for sales. The 'Bangladesh Forest Management Plan (BFMP) 2016' as well as '8th Five-Year Plan' stated that although participants may express preference for a particular AIGA, a market analysis should be conducted to determine if there is a demand for that product, and to determine what type of profit can be expected. To address the above hindrance settings, firstly it is essential to clear the picture about the present marketing linkages, market demand, profitable income, and the needs for a sustainable marketing system of AIGA-commodities (obj-1).

Indeed, if there is no sustainability in terms of marketing systems, it is hard to achieve long-term profitable income for any AIGA. Even huge AIGAs start making a loss eventually. This lower profitable income is a big constraint to make FDC's livelihood sustainable. A livelihood can be classified as sustainable, when it is resilient in the face of external shocks and stresses, when it is not dependent upon external support, when it is able to maintain the long-term productivity of natural resources and when it does not undermine the livelihood options of others (Sneddon, 2000). For thus, in Bangladesh, if a forest dependent family can live their livelihood by an AIGA in a sustainable manner, then the household (HH) reduces their dependency on forest. Otherwise, they take switching decisions to forest & forest resources which again increase the forest loss. A possible option to address this problem is: firstly, determining the options for livelihood sustainability of AIGA people under the embedded marketing risks; and secondly, examining the effects of the combined changes of these risks in different market scenarios (obj-2).

When first establishing a new business venture of AIGA, there are numerous steps that FDC people can take to ensure that it is profitable. But realization that actions taken today can have long-term consequences, presents a new challenge to decision taking people in assessing the desirability of AIGA. To ensure more income from AIGA, FDC people need to adopt a wide range of rational risk management practices, effectively. The Forest Policy 2016 (draft) proposed some mitigation and adaptation policies and practices (section 5.4): for Bangladeshi forest ecosystems, natural forests (sal forest, hill forest and mangroves), plantations, forest communities, AIGAs, revolving savings and loan fund (RLF), smart farming, market value chains, capacity building, and forest protection (MoEF, 2020). Special consideration also focuses on exit strategy (section 5.4.18) in terms of project implementation. Considering the stated issues, it should identify what sustainability measures need to be included in the forest policy (obj-3).

Through this proposed research project, the sustainable policy measures will be focused on sustainable market linkage for AIGAs for sustainable livelihoods of FDCs. The proposed study will not formulate any policy on forest ecosystems, but identify measures for sustainable AIGAs, but will find out the exit plan for ongoing SUFAL project or next project activities to keep the AIGAs sustainable to reduce the FDC's reliance on forest ecosystems of Bangladesh.

1.2. Objectives of the study

The specific objectives are-

(i) To clear the picture about the sustainable marketing system of AIGAs;
(ii) To determining the level of livelihood sustainability of AIGA people;
(iii) To identify the sustainable measures of AIGAs.

1.3. Research questions

The specific questions are-

(i) What is the present structure of market of AIGAs?
(ii) What are the potential AIGAs under SUFAL Project?
(iii) What are the measures of AIGAs for livelihood sustainability options?

2. LITERATURE REVIEW

The reviewed literature covers a wide range of Alternative Income-Generating Activities (AIGAs) linked to forest ecosystems, emphasizing their roles in livelihood improvement, income generation, and environmental sustainability. Studies highlight that forest conservation efforts, such as forest co-management and agroforestry, have positively affected local livelihoods, especially in regions like the Chittagong Hill Tracts and Madhupur Sal Forest (Ahammad et al., 2023; Akter et al., 2022; Ray et al., 2023). However, challenges related to land tenure, governance, and biodiversity conservation remain significant.

Research on AIGAs like NTFP collection, poultry, duck, pigeon, cow, and goat rearing reveals their potential for supporting forest-dependent communities economically. For instance, poultry and duck farming are seen as profitable but face marketing, veterinary, and logistical constraints (Akhter et al., 2020; Zannat et al., 2018). Goat and cow rearing show promise for improving nutrition and income, especially for women and children, though concerns about animal health and market access persist (Bakhtiar & Hoddinott, 2023; Prank et al., 2023).

Despite the positive outcomes, several studies emphasize uneven benefit distribution, limited participation from marginalized groups, and the lack of institutional support and policy integration (Hossain et al., 2015; Ahmad et al., 2021). Additionally, while forest policies have evolved to acknowledge ecosystem services, they often lack concrete strategies to scale AIGAs effectively (Muhammed et al., 2008; Rahman & Giessen, 2018). Further, the empirical findings do not suggest consistent results, which makes it difficult to identify that whether the AIGA return more incomes, production is sustainable and how the FDC's prefer to participate in AIGA. Therefore, the present study is examining the above-mentioned issues.

3. METHODOLOGY

The study has been conceptualized with keeps an eye on a work-flow in five-steps called the research framework (Figure-1). The first step is literature review which includes review of literature, designing of study, study area finalization, and data source identification. Where the second step is about preparatory work. This step includes sample selection procedure and distribution, finalization of methodology, development of the field survey schedule, and submission of inception report. The most important is the third step which is about data collection & quality control. It includes preparation of study instruments, field-testing and finalization of study instruments, collection of data using all instruments, study management, and quality control. The fourth step is about data management, processing through analysis using statistical models. The final step is report preparation, validation and submission with incorporating the comments.

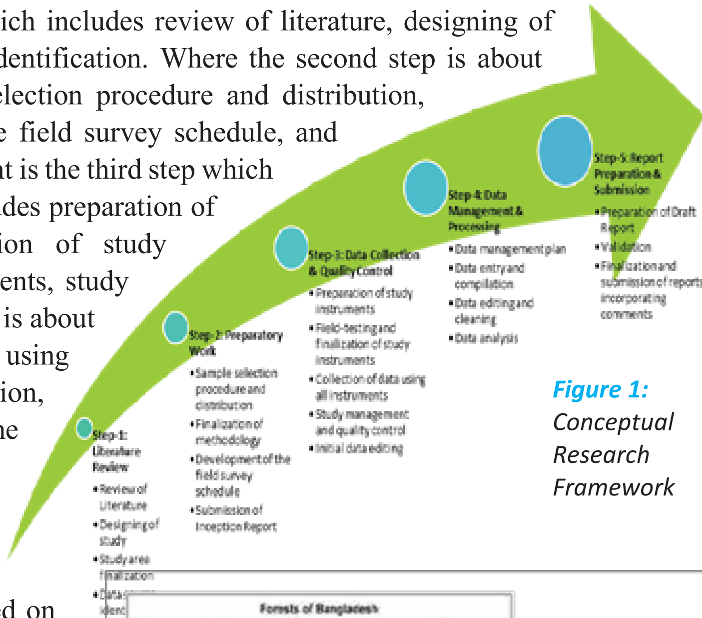

Figure 1: Conceptual Research Framework

3.1. Study area/research site

Despite being, a small country Bangladesh has an impressive variety of forest ecosystems. Based on topography and location, forests has been classified as hill forests, natural mangrove, mangrove/coastal plantation forest, plain land sal-forests, community/village forests and freshwater swamp forests covering 32 districts in the country. Three major types of forestland (Hill, Mangrove and Sal forest) are under the supervision of Bangladesh Forest Department (BFD). Based on the research questions, total eight (8) districts: Dhaka, Mymensingh, Tangail, Sylhet, Chattogram, Cox's Bazar, Bhola and Patuakhali, selected purposively for the study area, shown in Figure-2.

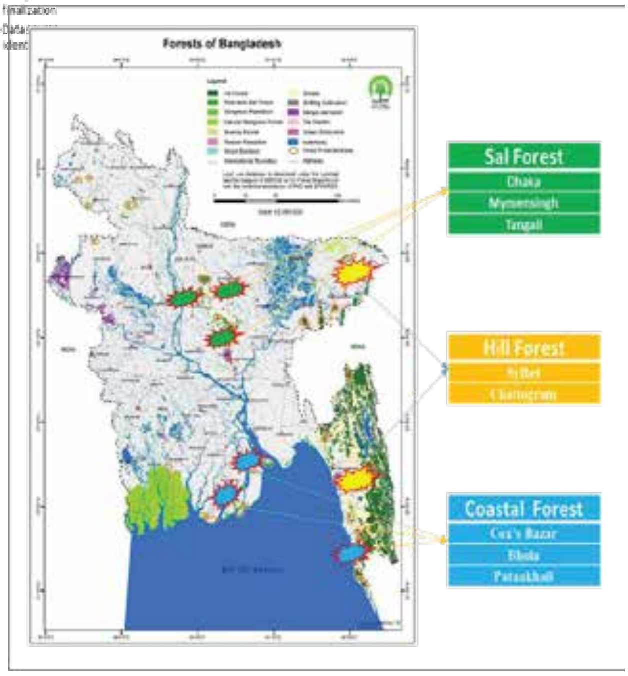

***Figure 2:** Research Location in Bangladesh map*

3.2. Research methods

Research methods Conceptualization of the study approach is set in a systematic and sequential manner. The steps to be taken are consultations, literature review, preparation of study instruments; data source identification, collection of primary data using all instruments and quality control, conducting key informant interview, focus group discussions, collection of secondary information, data entry and analysis, published in peer review journals, preparation of report and submission.

3.2.1. *Selection of sampling method, samples and study site*

Before sampling design for this research, at first we the research team preliminary visited study fields/areas. The visited peoples show their status, AIGAs, benefits, constraints, and possible solutions, which help the research team to design sampling, AIGA selection, and research methodology and survey approaches.

3.2.1.1. Selection of AIGAs

Preliminary field visit and review of SUFAL documents showed that the SUFAL project considered 4 broad categories of AIGAs, namely Production (crops, fisheries & livestock based AIGAs), Processing (cap making, handicraft, etc.), Trade (retailing, wholesaling, etc.) and Services (barbering, etc.). Among the four, this study designed with more emphasis on the production-based value chain and its market linkages because a significant portion of the forest dependent community had selected the production-based AIGAs. The study also identify the potential AIGAs under SUFAL Project.

3.2.1.2. Sample size

From the 8 districts the AIGA participating FDC people and other stakeholders were selected. Here, the study were used the purposive sampling techniques for collecting necessary information from samples. In the study location, the size of population was unknown; therefore, the formula developed by Daniel (1999) is applicable in determining the sample size.

The formula is

$$\mathrm{n} = \frac{z^2.\mathrm{p.q}}{e^2} x\ DE \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, n= the desired sample size; z= the standard normal deviate; p= target proportion; p=success; q= 1-p; DE= design effect; and e= the precision level.

Since, the size of AIGA people is not known to us, therefore, considering the z=1.96 at 95% level of confidence, probability at 50% (p=0.5 and q=1-p=0.05), DE set to 9% (so, DE=0.9) and e set to ± 4%, the sample size are estimated at AIGA people-490, Value chain/ market actors-800, FGD-40, KII-26, EO-2. The study includes both qualitative and quantitative surveys. The distribution of sample given in Table-2, below.

Table 1: Sample distribution in the selected districts as well as forest ecosystems

Forest Ecosystem	Selected District		Sample size	
			AIGA people*	Value chain/ market actors
Sal Forest	1	Dhaka	56	100
	2	Mymensingh	58	100
	3	Tangail	72	100
	Sub-total (Sal)		***186***	***300***
Hill Forest	4	Sylhet	82	100
	5	Chattogram	52	100
	Sub-total (Hill)		***134***	***200***
Coastal Forest	6	Cox's Bazar	71	100
	7	Bhola	23	100
	8	Patuakhali	76	100
	Sub-total (Coastal)		***170***	***300***
Total	**8**		**490**	**800**

* *Distribution based on the village covered by Probability Proportional to Size (PPS) sampling technique*

3.2.1.3. Drafting research questionnaire

After preliminary field visit, review of SUFAL documents, selection of AIGAs for the study and the validation meeting, the research team has been drafted five (5) category of questionnaires as the research tools. The questionnaire focuses on the research aims and objectives. The list of questionnaires and the parameters given in Table-4, below:

Table 2: List of draft questionnaires and the parameters

Sl	Research Tools	Respondents
1	Questionnaire for AIGA People	People in FDCs and their AIGAs
2	Questionnaire for Market Actor	Input & Output channel for AIGA
3	Questionnaire for FGD	Market intermediaries and value chain actors
4	Questionnaire for KII	Field experts
5	Questionnaire for EO	Academics & Practitioners

3.2.1.4. Methods validation workshop

The study approach and methodologies were finalized by a Methodology Validation Workshop, conducted on dated April 2, 2024 in the venue of Karobi Hall, Bana Bhaban, Agargaon, Dhaka with the chaired by Mr. Gobinda Roy, Project Director, SUFAL Project.

3.2.2. Parameters measurements/algorithm

In order to answer the research questions and to achieve the research objectives, mathematical programming and econometric techniques are employed in this study. As conceptualized the study, the research process flow keeps an eye on an algorithm in three-levels (Figure-2). Each level can be considered as an extension of the previous one with the increased complexity in objectives.

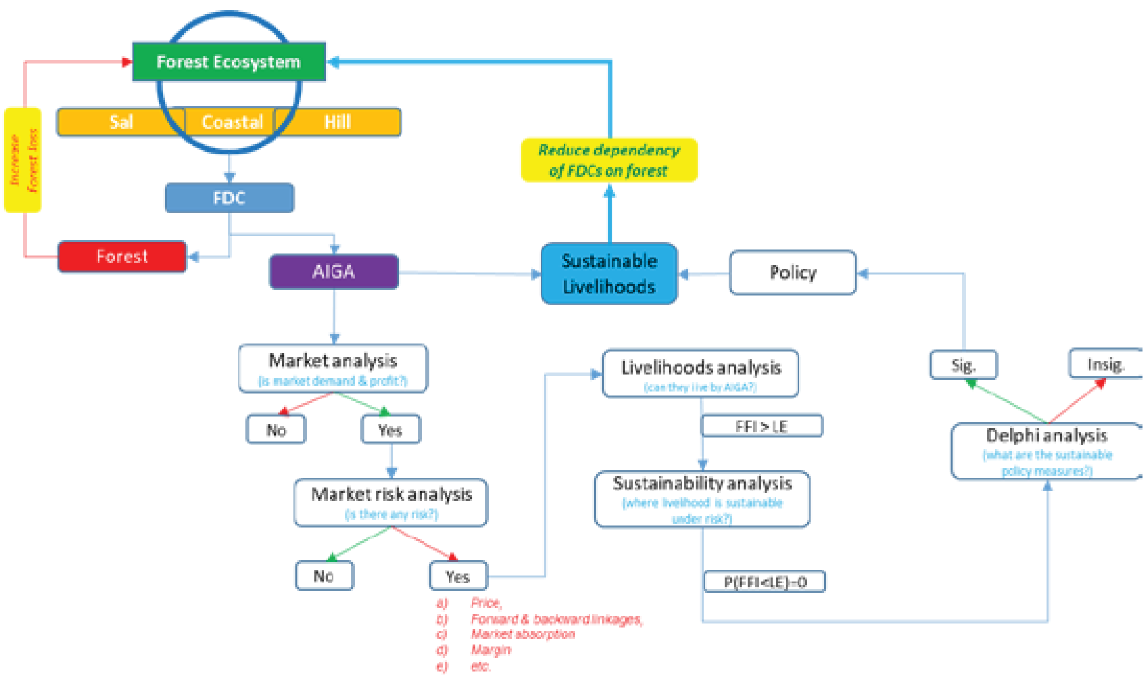

Figure 3: Conceptual Research process flow

First level of algorithm: identification of present market structure, embedded risks and the needs for sustainable marketing system for AIGAs. The first question of the study is about the sustainable marketing system, which analyzed in the first level of algorithm through identification of present market structure, embedded risks and the needs for sustainable marketing system for AIGAs.

Second level of algorithm: estimation of livelihood sustainability options of AIGAs. This level is two folds, at first identification of the potential AIGAs under SUFAL Project; where second fold is three level: one is the estimation of livelihood sustainability options of AIGAs by approaching an economic indicators namely AIGA income, second is the incorporation of risks, and third is the scenario analysis to see the consequences of an action under different sets of factors, and provided an accurate picture of the outcomes.

Third level of algorithm: determination of policy measures for sustainable AIGA. This level is three folds: one is the determination of the strength, weakness, opportunity and threats of the selected AIGAs that have been already initiated and implementing by SUFAL project in different landscapes by approaching SWOT analysis; in the second fold, causes of risks and potential possible measures in terms of sustainable AIGAs by applying factor analysis with HH level data of FDCs. In the third fold, the significant factors within the risks be sort-out using the fuzzy Delphi method by testing the expert group's opinions.

3.2.2.1. Analytical tools

All the modeling and mapping works will be conducted using the latest version of the R statistical software, Xlstate, RiskAMP and the available relevant packages.

Estimation of income from AIGAs

The study applies the profitability analysis techniques. Total cost (TC) includes all types of variable and fixed cost items involved in the production process. The total cost is estimated as follows:

$$TC_i = \sum_{j=1}^{n} P_{x_{ij}} x_{ij} + \mathrm{TFC_i}$$

where, $\sum_{i=1}^{n} P_{x_{ij}} x_{ij}$ = $\mathrm{TVC_i}$ = Total variable cost;x_{ij} = Quantity (kg/ha) of the jth variable;$P_{x_{ij}}$= Per unit price (Tk/kg) of the jth variable input;and$\mathrm{TFC_i}$ = Total fixed cost.

The gross returns (GR) calculated by multiplying the total output at the farm gate price.

$$GR_i = \sum_{i=1}^{n} p_i * y_i$$

where,y_i = Quantity of the main product; andP_i = Per unit price.

Farmers' profit is estimated in two ways: (a) gross margin (GM) and (b) net margin (NM). GM is estimated where variable cost is deducted from total return, and then NM is estimated by deducting fixed costs from gross margin. For this purpose, the following equation proposed by Dillon and Hardaker (1993) is used.

$$\mathrm{GM}_i = GR_i - TVC_i$$

$$\mathrm{NM}_i = GM_i - \mathrm{TFC_i}$$

Break-even points of AIGAs

One of the important indicators of success of the commercial farmer is the break-even point. Breakeven equations are calculated by arithmetic manipulation of the profit equation and solving for the item of interest. In breakeven point:

$$\mathrm{HI}_i - \mathrm{HE}_i = 0 \qquad \ldots\ldots\ldots\ldots..(2)$$

Where, HI_i is household income, and HE_i is household expenditures for a period of time.

Monte-Carlo simulation

Specifically, in Monte-Carlo simulation approach, the possible values of the input random variables are sampled (generated) in each experiment according to their distributions.

Let, random variables of $X = (X_1, X_2, X_3, \dots\dots\dots\dots.., X_n)$ $\dots\dots\dots\dots..(2)$

where, x = input variables

Then, the values of the output variable Y are calculated through the performance function (2) at the samples of input random variables.

$Y = g(X) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. \dots\dots\dots..(3)$

Therefore, with a number of experiments carried out in this manner, a set of samples of output variable Y are available for the statistical analysis, which estimates the characteristics of the output variable Y.

Here, the purpose of sampling on the input random variables $X = (X_1, X_2, X_3, \dots\dots.., X_n)$ is to generate samples that represent distributions of the input variable from their cumulative density functions (*cdf*), as below.

$cdf = F_{x_i}(x_i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \dots\dots. \dots..(4)$

where, i= 1, 2, 3, ………. n

The samples of the random variables then used as inputs to the simulation experiments. Two steps are involved for this purpose: Step 1 – generating random variables that are uniformly distributed between 0 and 1, and Step 2 –transforming the values of the uniform variable obtained from Step 1 to the values of random variables that follow the given distributions $F_{x_i}(x_i)$ (where i= 1, 2, 3, ………. n).

The importance of uniform numbers over the continuous range [0, 1] is that they can be transformed into real values that follow any distributions of interest. A random-generator produces a sequence of uniform numbers between 0 and 1.

Let, generated uniform variable, $z = (z_1, z_2, z_3, \dots\dots\dots\dots.., z_n)$

where, N is the number of samples. N= 1, 2, 3, ………. n

Then the task is to transform the samples of [0, 1] uniform variable into values of random variable X_i that follows a given distribution $F_{x_i}(x_i)$. The inverse transformation method may use for such a transformation as it is a simple and direct transformation. The transformation is demonstrated in below figure 3.

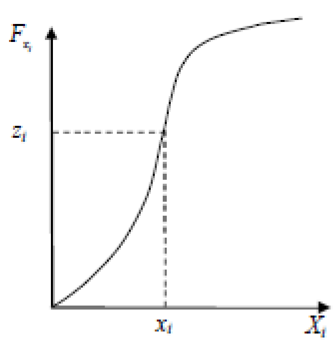

Figure 4: *The inverse transformation of Monte-Carlo simulation method*

By this method, the random variable is given by-

$$x_i = F_{x_i}^{-1}(z_i) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)$$

where,

$F_{x_i}^{-1}$ is the inverse of the *cdf* of the random variable X_i; and i= 1,2,3, …….., N

For example, if *X* is normally distributed with $N(\mu_x\ \sigma_x)$,

$$\text{since, } z = F_x(x) = \Phi\left(\frac{x-\mu_x}{\sigma_x}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. (6)$$

$$\text{then, } x = \mu_x + \sigma_x\ \Phi^{-1}(z) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \ldots \ldots \ldots \ldots \ldots .. (7)$$

Monte-Carlo simulation methods has been used on an economic indicators namely AIGA income (AI). This model also will be used to incorporation of risks in AIs.

Incorporation of risks in the income equations

The income level under risks was estimated in two stage analysis. At first, profit from AIGA was estimated in terms of net margin where, the income from AIGA was calculated by multiplying total quantity returns during a year by multiplying their market prices. The total produces may be sold, sometimes used for household consumption or used for further production. These non-market transactions were valued by multiplying market price. By deducted the variable cost and fixed cost the net income has been calculated. Here, 7 variables i.e. purchase of price of products, price of feed, labour wage, repairing cost by climate hazards, transportation cost by market distance, sale price, and mortality rate are stochastic. In this purpose, the following equation proposed for this study:

$$HI = \sum_{i:k=0}^{n} \left(NR_{iga} : \left\{ \begin{array}{c} \sum_{k=1} Return_{iga} : \left[\sum_{k=1} \tilde{Y}_i : (N_k - \widetilde{mr}_k) * \widetilde{ma}_k * \widetilde{cp}_k \right] \\ -\sum_{k=1} VC_{iga} : \left[\begin{array}{c} \sum_{k=1} \left(N_k * X_{k:feed} * \widetilde{fp}_k\right) \\ + \sum_{k=1} \left(N_k * \widetilde{X_{k:hhl}} * wr_k\right) \\ + \sum_{k=1} \left(N_k * \widetilde{X_{k:dis}} * tc_k\right) \\ + \sum_{k=1} \left(\widetilde{ch}_k * rc_k\right) \\ + \sum_{k=1} (OVC_k) \end{array} \right] \\ -\sum_{k=1} FC_{iga} : \left[\sum_{k=1} \left(N_k * X_k * p_k\right) \right] \end{array} \right\} \right) \ldots \ldots \ldots \ldots .. (2)$$

In that case, base case scenario of risks has been incorporated in stochastic income modeling using Monte-Carlo simulation (s) with 1000 iterations.

4. Result and Discussion

Sustainable Forests and Livelihoods (SUFAL) Project under Bangladesh Forest Department (BFD) initiated several natural forests protection initiatives, of which most potential is increasing access to alternative income generating activities (AIGAs). However, sustainable management of AIGAs is a challenging task when local communities depend heavily on natural resources for their livelihood. Thus, the study assumed that, if a forest dependent family can live their livelihood by an AIGA in a sustainable manner, then the household (HH) reduces their dependency on forest ecosystems. Otherwise, the HH takes a switching decision to other AIGAs or to forest, which again increases the forest loss.

4.1. Hypothesis

At first the study setting-up the assumptions by determining the level of dependency on forest ecosystems in Bangladesh. In this case, the study applied three socio-economic indicators, are: (i) household size, (ii) expenditure patterns of households, and (iii) their income diversifications.

4.1.1. Household size of HHs in FDCs

The household size in forest ecosystems like Sal, Hill, and Coastal areas typically varies due to differences in socio-economic, cultural, and environmental factors. Understanding household size in these ecosystems is essential as it directly impacts resource use, income distribution, and sustainability. HH Member in Forest Ecosystem results shows in Table 5. Result shows that the average HH size is 5.09 which is something higher than the national figures. Larger households often exert more pressure on forests for fuel-wood, fodder, and NTFPs. Smaller households may face labor shortages for livelihood activities, while larger ones benefit from shared labor but may require more resources. In ecosystems prone to climate risks (e.g., coastal areas), smaller households may struggle with resilience, while larger households may have a higher adaptive capacity but also greater resource demands. Table-9 also illustrated that most of HH in the forest ecosystems (25.71%) are with 5 members, while nationally 4 members family is more about 30.30% (Population and housing Census, 2023). Male and female is almost same i.e. 2.58 and 2.51, respectively.

Table 3: Household (HH) of FDCs and the size

(A) HH Size in		Male		Female		Total	
		Mean	StdDev	Mean	StdDev	Mean	StdDev
Forest Ecosystem	Coastal Forest	2.74	1.25	2.75	1.27	5.53	1.84
	Hill Forest	2.83	1.08	2.49	1.20	5.33	1.46
	Sall Forest	2.20	1.00	2.22	1.04	4.36	1.40
	Ecosystem Total (n=490)	**2.58**	1.16	**2.51**	1.20	**5.09**	1.70
National (BD)	National Total (Except city-corporation) SYB-BBS, 2023	1.99	-	2.08	-	4.07	-
	National Total (General) SYB-BBS, 2023	-	-	-	-	4.02	-
	National Total (General) HIES 2022	-	-	-	-	4.26	-
(B) Frequency of HH Member		**FDC (HH nos.)**		**National (HH nos. in %)**			
		n	**%**	**P&HC 2023**	**SYB 2023**	**HIES 2022**	
HH member in Forest Ecosystem	HH with 1 member	3	0.71	2.34	4.76	2.40	
	HH with 2 members	20	4.25	12.65	14.72	10.60	
	HH with 3 members	63	12.74	23.62 **b**	22.35 **b**	20.80 **b**	
	HH with 4 members	97	19.58 **b**	30.30 **a**	25.98 **a**	27.60 **a**	
	HH with 5 members	126	25.71 **a**	18.01 **c**	16.54 **c**	19.60 **c**	
	HH with 6 members	81	16.51 **c**	7.80	8.18	10.60	
	HH with 7 members	62	12.74	2.92	3.66	4.20	

(A) HH Size in	Male		Female		Total	
	Mean	StdDev	Mean	StdDev	Mean	StdDev
HH with 8 members	23	4.72	1.19		1.74	2.10
HH with 9 members	11	2.12	0.57		0.90	1.00
HH with 10 members	4	0.94	0.28		0.50	1.10
HH with 10+ members	0	0.00	0.32		0.66	
Total (n=490)	490	100	100		100	100

Source: Author's own calculation, 2024

a: Ranked one category of HH

b: Ranked two category of HH

c: Ranked three category of HH

4.1.2. Expenditure patterns of HHs in FDCs

The household expenditure patterns of forest-dependent communities in Bangladesh significantly affect their livelihood sustainability. Expenditure reflects how households allocate their resources toward necessities like food, education, healthcare, housing, and productive investments. Table 44 **shows the** HH expenditure. The most proportionate item is foods about 21.45% estimated at tk. 11916.6 which is similar to national figure (tk. 12318). The total expenditure was estimated at tk. 21867.2 which is lower than the national figure (26842) according to HEIS-2022. Based on field survey, it was also estimated that people cover tk. 2,430.9 from their own source, thus they need to purchase items by tk. 19436.32. Household expenditure patterns significantly influence the livelihood sustainability of forest-dependent communities in Bangladesh. High expenditure on basic needs and healthcare, coupled with low investment in education or productive assets, perpetuates reliance on forest resources and unsustainable practices. Addressing these issues through financial inclusion, improved healthcare, education initiatives, and livelihood diversification can help build resilience, reduce dependency on forests, and ensure long-term sustainability for these communities.

Table 4: Expenditure patterns of HHs in FDCs

Sl	Expenditure Items	Monthly Demand		and Supply in tk.				% share of total
		HH Expenditure		HEIS, 2022	Own source		Purchase	
1	Rice	4690.4	11916.6	12318	18.96%	889.3	3801.13	21.45%
2	Flour	377.9			-	-	377.93	1.73%
3	Potatoes/vegetables	1642.8			31.95%	524.9	1117.93	7.51%
4	Fresh fish/ dried fish	1353.9			7.04%	95.3	1258.61	6.19%
5	Chicken/Broiler/Duck/Pigeon	1145.5			31.30%	358.5	786.93	5.24%
6	Beef / Khasi meat	913.8			-	-	913.82	4.18%
7	Eggs	86.7			84.25%	73.1	13.66	0.40%
8	Milk	144.8			77.59%	112.4	32.45	0.66%
9	Pulses & spices	470.5			17.50%	82.3	388.16	2.15%
10	Oils & consumables	1090.2			-	-	1090.20	4.99%
11	Restaurants and Hotels (Tea / Coffee)	180.9		66	-	-	180.93	0.83%
12	Sweets/ Confectionery (Biscuit, Cake, Roti, Chanachur)	457.8		806	-	-	457.80	2.09%
13	Cost of Clothing and Footwear	1687.8		1779	-	-	1687.78	7.72%
14	Housing and house-repair expenses	945.7		3334	25.00%	236.4	709.30	4.32%

Sl	Expenditure Items	Monthly Demand and Supply in tk.						% share of total
		HH Expenditure		HEIS, 2022	Own source		Purchase	
15	Purchase and repair of furniture, TV, mobile phone,	467.7		1115	-	-	467.66	2.14%
16	Mobile phone recharge, MB charges	649.3	781.2	734	-	-	649.33	2.97%
17	DIS and internet connection cost	131.9			-	-	131.89	0.60%
18	Education expenses	1173.0		383	5.00%	58.7	1114.36	5.36%
19	Medical expenses	242.3		1906	-	-	242.29	1.11%
20	Family festival, Social/religious festivals, travel, transport	439.3		1533	-	-	439.34	2.01%
21	Loan installment	1640.4	3574.8	2866	-	-	1640.43	7.50%
22	Other expenses	1934.4			-	-	1934.38	8.85%
	HH's Total Expenditure (HE)	**21867.2** (81.47% of HEIS2022)		**26842**		**2,430.9** (11.12% of HH)	**19436.32** (88.88% of HH)	100%

Source: Author's own calculation, 2024

4.1.3. Income diversification of HHs in FDCs

HHs in FDCs earn income from different sources i.e. from AIGA and non-AIGA. Among the non-AIGA, the sources are 1. Crop production, 2. Small business, 3. Service/Job, 4. Remittance, 5. Wage laborer, and 6. Others. Total non-AIGA income estimated at tk. 112201.3 per year.

Table 5: HH income

Income source other than AIGA (Y)	% of n(=490)	Annual Income (tk.)
1. Crop production	13.92%	8710.9
2. Small business	5.72%	9806.4
3. Service/Job	11.22%	22468.7
4. Remittance	3.54%	10174.7
5. Wage laborer	20.75%	22464.9
6. others	37.60%	38575.8
Sub-Total (HI)	**-**	**112201.3**

Source: Author's own calculation, 2024

4.1.4. Null Hypothesis

Based on above table, the annual total expenditure was at estimated tk. 262406.4 of which HH's Daily need 20.53%, Weekly need 22.08%, Monthly need 40.01%, and Yearly need 17.38% of the total expenditures. On the other hands, HHs recover tk. 29170.6 from their own source and total non-AIGA income estimated at tk. 112201.3 per year. Thus, total support from HHs is tk. 141371.9 and remaining amount tk. 121034.5 which they may will earned by different forest dependent sources. The objective of this study is to identify that is the AIGAs are the sustainable options for forest dependent communities household for this remaining income source.

The above result tables noted-out that a forest dependent family should earn at least tk.121035 from their AIGA/s to live their livelihood in a sustainable manner. Then, the household (HH) reduces their dependency on forest ecosystems. Otherwise, the HH takes a switching decision to another AIGAs or to forest, which again increases the forest loss. Therefore, in the level of sustainability, the minimum income from AIGA should equal or more than the HH's income dependency.

Thus, we can set hypothesis as

$$H_0\text{: Min(HI: }\boldsymbol{hh}=\mathbf{5}) \geq FD[e \rightarrow HI](=tk.121035)$$

This asserts that there is no negative significant difference between the minimum incomes from AIGA and HH's income dependency.

4.2. AIGA interventions in the FDCs

In the areas of SUFAL projects regarding AIGA activities demonstrated, total number of FCV/VCV in the whole population was 426 of which the highest and the second highest number of 170 and 142 were counted in hill forest and coastal forest, respectively and the lowest number was 114 for sal forest. Again, sum of HH under FCV/VCF was estimated at 24710 in where the households according to descending were included 10156, 8500, and 6054 in coastal-forest, hill-forest, and sal-forest, respectively. Number of AIGA based on three ecosystems of coastal forest, hill forest and sal forest were identified as several sectors/divisions. Therefore, these classifications are (i) sub-sector specific, (ii) trade specific, (iii) processing specific, and (iv) service specific.

Table 6 shows the Coverage of AIGA in the forest ecosystems and describing the status of active (operative/running) AIGAs as per categories/groups under sectors (segments/divisions) for SUFAL Project. Many types of AIGAs and their positions according to the sectors defined through SUFAL Project were mentioned this section. Therefore, some AIGAs belonged to the **sub-sector specific** were (1) nursery, (2) homestead gardening (vegetables, fruits, bashak), (3) poultry/ duck/ pigeon rearing/ business, (4) cow/ goat/ sheep rearing/business, (5) fish culture/ fishing/fish drying, and (6) others (crop production/ tractor/ fertilizer/ water pump/ paddy-rice business/ vermi-compost/ fodder/ seasonal fruit business). Besides, **trade specific AIGIs** included (1) agricultural trades (crop/ vegetable/ fruits/ betel-leaf/ cow/ goat/ poultry/ duck/ pigeon/ fish), (2) other trading (timber/ stationary/ shoe/ cloth/ sand/ oil/ hardware/ cookeries/ grocery/ fishing-net). Also the AIGI groups identified for **processing/cottage specific** were (1) handicraft/ weaving/ handloom/ nakshi-kantha/ Puthir-mala/ fishing net knitting/ cap making/ carpentry, (2) sewing/ cloth making, (3) salt production, (4) others (cattle meat/ poultry meat/ fruits pickle). The last-one AIGA groups for **service specific** were (1) Shop (Grocery/tea stall/pharmacy/ hotel/Street-Food/cosmetics), (2) tailoring, (3) auto rickshaw/ rickshaw van/ tom-tom/ motor cycle rent/ boat/ cycle garage, (4) mobile/ TV/ fridge/ electric servicing/wielding/ masonry/ decoration services, and (5) others (scraps or bhangari/ street hawker/ mobile banking/ hairdresser).

Table 6 also shows that the coverage of the AIGAs regarding **sub-sector specific** as per descending order were calculated at 86.46%, 84.09% and 74.28% for coastal forest, hill forest and sal forest, respectively whereas for total rate of three forest was gained 82.53%. Similarly, it were 11.92%, 10.26%, 2.41% and 82.53% for the **trade specific AIGAs**, respectively. It were also estimated at 6.06%, 0.77%, 0.20% and 1.87% for the **processing/cottage specific AIGAs,** and 13.60%, 5.08%, 4.89% and 6.80% for **service specific AIGAs**, respectively.

Table 6: Coverage of AIGA in the forest ecosystems

Sl. No.	Sector	AIGA		AIGA in Forest Ecosystem (%)			
				Coastal forest	Hill forest	Sal forest	Total
3	Sub-sector specific	1	Nursery	0.00%	0.05%	1.32%	0.31%
		2	Homested gardening (vegetable, fruits, bashak)	11.79%	21.52%	7.89%	16.34%
		3	Poultry/duck/pigeon rearing/business	27.16%	16.43%	36.09%	23.13%
		4	Cow/Goat/pig/sheep rearing/business	28.19%	17.90%	19.54%	20.64%
		5	Fish culture/fishing/Fish drying	9.03%	3.97%	2.23%	4.77%

Sl. No.	Sector	AIGA		AIGA in Forest Ecosystem (%)			
				Coastal forest	Hill forest	Sal forest	Total
		6	Others (crop production/tractor/ fertilizer/ water pump/paddy-rice business/vermi-compost/ Fodder/seasonal Fruit business)	10.28%	24.22%	7.21%	17.34%
			Sub-Total	*86.46%*	*84.09%*	*74.28%*	*82.53%*
4	Trade specific	7	Agriculture Trader (Crop/vegetable/fruits/ betel-leaf/Cow/Goat/Poultry/duck/ pigeon/fish)	0.33%	0.63%	0.80%	0.59%
		8	Other Trader (timber/stationary/shoe/cloth/ sand/oil/ hardware/cookeries/grocery/ fishing-net)	2.07%	9.63%	11.13%	8.20%
			Sub-Total	*2.41%*	*10.26%*	*11.92%*	*8.80%*
1	Processing/ Cottage	9	Handicraft/weaving/Handloom/Nakshi kantha/Puthir mala/Fishing net knitting/Cap making/Carpentry	2.53%	0.61%	0.20%	0.97%
		10	Sewing/cloth making	2.53%	0.10%	0.00%	0.64%
		11	Salt Production	0.99%	0.00%	0.00%	0.23%
		12	Others (Cattle meat/Poultry meat/pickle)	0.00%	0.05%	0.00%	0.03%
			Sub-Total	*6.06%*	*0.77%*	*0.20%*	*1.87%*
2	Service Specific	13	Shop (Grocery/tea stall/pharmacy/ hotel/Street-Food/cosmetics)	2.52%	2.60%	0.12%	2.05%
		14	Tailoring	0.98%	0.26%	2.96%	1.01%
		15	Auto Rickshaw/Rickshaw van/Tom-Tom /Motor cycle rent/ boat/Cycle garage	0.76%	1.99%	9.36%	3.29%
		16	Mobile/TV/fridge/electric servicing / Wielding/masonry/decoration services	0.70%	0.02%	1.16%	0.42%
		17	Others (Scraps (*Bhangari*)/Street hawker/ Mobile banking/Hairdresser)	0.12%	0.01%	0.00%	0.03%
			Sub-Total	*5.08%*	*4.89%*	*13.60%*	*6.80%*
Grand Total				100.00%	100.00%	100.00%	100.00%

Source: Author's own calculation, 2024

Among the 4 sectorial distribution, the results in table 10 illustrated that the coverage rate (1.87%) of processing specific AGIAs by the patronization of SUFAL project was very ignorable level and also the development stages of trade specific AIGAs (8.80%) and service specific AGIAs (6.80%) were not so much good (well/satisfactory).

Now, it is necessary to identify that what AIGAs are principal in the study area as well as dominated in the AIGA peoples, which have the highest possibilities for three ecosystems (Sal-forest, Hill-forest, and Coastal-forest).

Based on the results of above Table 6, the study set 17 variables regarding sub categories of sectorial distribution of AIGAs for 3 study areas of coastal forest, hill forest and sal forest. The name of variable are: var1_home_g: 'Home gardening (vegetables, fruits, basak)', var2_chic_r: 'Chicken farming', var3_duck_r: 'Duck farming', var4_pige_r: 'Pigeon breeding/rearing', var5_cow_r: 'Cow rearing', var6_goat_r: 'Goat rearing', var7_fish_f: 'Fish farming', var8_fish_c: 'Fishing/ fish drying', var9_vege_b: 'Vegetable business', var10_live_b: 'Livestock business', var11_fish_b: 'Fish business', var12_hand_c: 'Handicraft/ weaving/ handloom/ nakshi-kantha/ Puthir mala/ fishing net knitting/ cap making/ carpentry', var13_sewi: 'Sewing/ cloth making', var14_shop: 'Shop business (grocery/ tea stall/ pharmacy/ hotel / street-food/ cosmetics)', var15_auto: 'Auto rickshaw/ rickshaw van/ tom-tom / motor cycle rent/ boat/ cycle garage', var16_mech: 'Mobile/ TV/ fridge/ electric repair servicing

/ welding/ masonry/ decoration service', and var17_proc: 'Processing (cattle meat/ poultry meat/ pickle processing)', shown in Table 11 below.

Result shows that the highest frequency of 31.35% was found in the share rate of home gardening (vegetables, fruits, basak), and the lowest rate was counted for vegetable business, livestock business, mobile/TV/fridge/electric repair servicing/wielding/masonry/decoration services, and processing (cattle meat/poultry meat/ pickle). Besides, the second biggest frequency of 24.30% was calculated for the AIGA of chicken farming and the frequency rates from the second highest as per descending order 14.63%, 9.83%, 5.50%, 3.33%, and 3.10% were computed for cow farming, duck farming, goat rearing, shop business (grocery/tea stall/pharmacy/ hotel /street food/ cosmetics), and fishing/fish drying, respectively while 2.17% was for fish farming and also auto rickshaw/rickshaw van/tom-tom/motor cycle rent/boat/cycle garage, 1.63% for pigeon breeding/rearing, 0. 0.93% for sewing/cloth making, and 0.23% for fish business and also handicraft/weaving/handloom/*nakshi kantha/putir* mala/fishing net knitting/cap making/ carpentry (Table 11).

Table 7: Definition of AIGA and their frequency in the study area

Variables on AIGA	Definition	Mean ± StdDev	Frequency (in %)			
			Coastal Forest	Hill Forest	Sall Forest	Grand Total
var1_home_g	Home gardening (vegetables, fruits, basak)	0.318 ± 0.718	22.72%	30.67%	40.00%	31.35%
var2_chic_r	Chicken farming	0.247 ± 0.431	28.45%	22.39%	21.62%	24.30%
var3_duck_r	Duck farming	0.100 ± 0.300	10.62%	10.43%	8.69%	9.83%
var4_pige_r	Pigeon breeding	0.017 ± 0.127	1.91%	0.92%	1.82%	1.63%
var5_cow_r	Cow rearing	0.149 ± 0.356	17.83%	15.34%	11.11%	14.63%
var6_goat_r	Goat rearing	0.056 ± 0.230	6.16%	3.37%	6.26%	5.50%
var7_fish_f	Fish farming	0.022 ± 0.147	2.97%	2.76%	1.01%	2.17%
var8_fish_c	Fishing/drying	0.031 ± 0.175	4.88%	5.21%	0.00%	3.10%
var9_vege_b	Vegetable business	0.002 ± 0.040	0.42%	0.00%	0.00%	0.15%
var10_live_b	Livestock business	0.002 ± 0.040	0.21%	0.31%	0.00%	0.15%
var11_fish_b	Fish business	0.002 ± 0.049	0.00%	0.92%	0.00%	0.23%
var12_hand_c	Handicraft/weaving/handloom/ nakshi kantha/putir mala/fishing net knitting/cap making/carpentry	0.002 ± 0.049	0.21%	0.00%	0.40%	0.23%
var13_sewi	Sewing/cloth making	0.009 ± 0.097	0.42%	0.31%	1.82%	0.93%
var14_shop	Shop (grocery/tea stall/pharmacy/hotel/street-food/cosmetics)	0.034 ± 0.181	2.34%	2.45%	4.85%	3.33%
var15_auto	Auto rickshaw/rickshaw van/ tom-tom /motor cycle rent/ boat/ cycle garage	0.022 ± 0.147	0.21%	4.91%	2.22%	2.17%
var16_mech	Mobile/TV/fridge/electric repair servicing /wielding/masonry/decoration services	0.002 ± 0.040	0.21%	0.00%	0.20%	0.15%
var17_proc	Processing (cattle meat/poultry meat/pickle)	0.002 ± 0.040	0.42%	0.00%	0.00%	0.15%

Source: Author's own calculation, 2024

Table 12 showed the proportion of variance of a variable explained by the common factor, called communality. The value of Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) is 0.703, which falls into the range of being high (i.e., higher than 0.5) and assured that the PCA analysis is appropriate for this data. The Bartlett's measure is found to be highly significant (p<0.0001) and alos suggest that the PCA analysis is appropriate.

Table 8: Eigenvalues and percentages of inertia for AIGA variables

Component	Initial Eigenvalues			KMO	Extraction (%)
	Eigenvalue	Inertia (%)	Cumulative %		
F1	2.518	14.813	14.813	0.833	14.813
F2	1.184	6.962	21.775	0.673	21.775
F3	1.109	6.521	28.296	0.682	28.296
F4	1.087	6.397	34.693	0.771	34.693
F5	1.054	6.201	40.894	0.710	40.894
F6	1.023	6.018	46.912	0.808	
F7	1.008	5.932	52.844	0.778	
F8	0.996	5.857	58.701	0.440	
F9	0.973	5.723	64.423	0.456	
F10	0.938	5.516	69.940	0.572	
F11	0.895	5.263	75.202	0.635	
F12	0.867	5.098	80.300	0.420	
F13	0.848	4.991	85.291	0.698	
F14	0.765	4.498	89.788	0.700	
F15	0.731	4.303	94.091	0.777	
F16	0.645	3.796	97.887	0.428	
F17	0.359	2.113	100.000	0.605	
Kaiser-Meyer-Olkin Measure				0.703	
Bartlett's sphericity test statistics	¬ Chi-square (Observed value)			1511.099	
	¬ Chi-square (Critical value)			164.216	
	¬ p-value			**< 0.0001*****	
	¬ alpha			0.05	

**** Significance at 1% level of confidence; Extraction method: Principal component analysis.*

A new set of 11 orthogonal variables (PCs) are generated by PCA (Table 2). The first principal component (PC) has the highest eigenvalue of 2.518 and accounted for 14.81% of the total variability of the data set. PC2 has the eigenvalue of 1.184 and accounted for 6.96% of the variance in the data. PC3 has the eigenvalue of 1.109 and accounted for 6.52% of the variance in the data. The last six PCs (i.e. PC12 to PC17) yielded progressively smaller eigenvalue and did not explain significant variability in the data set (24.79%). Therefore, according to Kaiser rule only the first five PCs explaining about 40.89% of the total variability are selected.

The number of components also can be determined at the point of Scree Plot, beyond which the remaining eigenvalues are all relatively small and of comparable size (Jollife, 2002; Peres-Neto et al., 2005). Figure 4 depicted that four variables are more appropriate (>30%) but we considered five variables which explained more (40.89%) of the total variability.

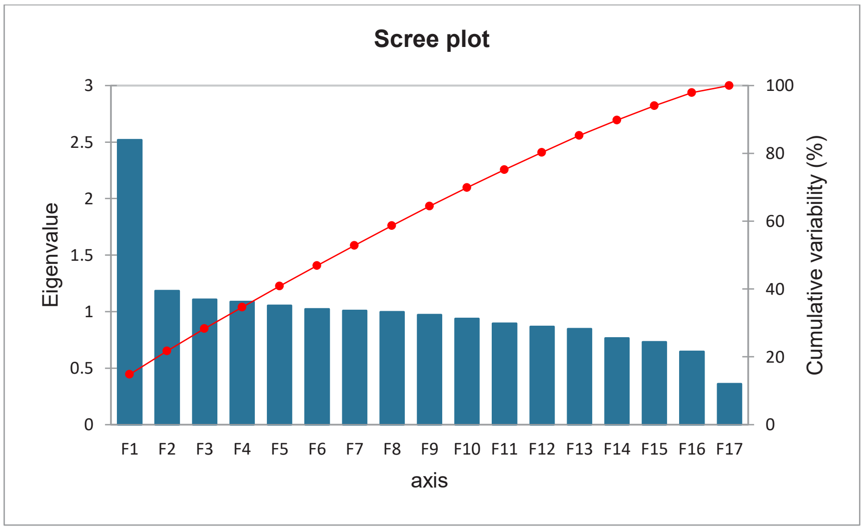

Figure 5: Scree plot of the PCs of AIGA variables

Table 9 presented the results of each variable's loading with eigenvectors on the five components extracted. The first principal component is positively correlated with four of the AIGA variables. Out of the variables the component1 seemed to significantly increase with increasing var2_chic_rearing, var3_duck_rearing, var5_cow_rearing, and var6_goat_rearing. The strongest variable in this component is chicken rearing. The second component is significantly increasing with var14_shop, while component3 shows a positive correlation with the variable of var7_fish_f arming and var11_fish_retailing business. Component 4 is primarily increasing with var4_pige_rearing and var17_meat processing business. The increasing trend in component5 is orchestrated by livestock business..

The values of the squared cosines (cos^2)[1] is shown in Table 9. A high cos^2 indicates a good representation of the variable on the PC where variable is positioned close to the circumference of the correlation circle, while a low cos^2 indicates that the variable is not perfectly represented by the PCs where the variable is close to the center of the circle. The component1 contributes highly to Chicken farming, Duck farming, Cow rearing, and Goat rearing, while component2 contributes most to Shop (grocery/tea stall/pharmacy/hotel/street-food/cosmetics) and Auto rickshaw/rickshaw van/ tom-tom /motor cycle rent/ boat/ cycle garage. Here, Mobile/TV/fridge/electric repair servicing /wielding/masonry/decoration services is contributes in component3.

Table 9: Principal coordinates and squared cosines of AIGA variables

Variables	Principal coordinates (Factor loadings)					Squared cosines				
	F1	F2	F3	F4	F5	F1	F2	F3	F4	F5
var1_home_g	0.255	-0.032	0.093	0.068	-0.264	0.065	0.001	0.009	0.005	**0.070**
var2_chic_r	**0.813****	-0.021	0.015	-0.078	0.076	**0.661**	0.000	0.000	0.006	0.006
var3_duck_r	**0.677****	-0.061	-0.059	-0.061	0.114	**0.458**	0.004	0.003	0.004	0.013
var4_pige_r	0.372	0.205	-0.047	**0.553****	0.105	0.139	0.042	0.002	**0.306**	0.011
var5_cow_r	**0.665****	-0.113	0.067	-0.037	0.118	**0.442**	0.013	0.004	0.001	0.014
var6_goat_r	**0.603****	-0.005	-0.141	-0.008	-0.315	**0.364**	0.000	0.020	0.000	0.099
var7_fish_f	0.244	-0.181	**0.552****	0.099	-0.001	0.059	0.033	**0.305**	0.010	0.000

[1] *The **factor loading** of a variable describes the correlation between it and a given principal component (PC). By squaring the factor loading for a variable, we also get its **squared loading** (also called **squared cosine** or **cos2**). This provides a measure of the **proportion** of variance in a variable that is captured by a PC. For each variable the sum of its squared loading across all PCs equals to 1. The squared loading between a quantitative variable and a factorial axis is equal to the squared correlation between the variable and the axis. Besides, the squared loading between a qualitative variable and a factorial axis is equal to the correlation ratio between the variable and the axis.*

Variables	Principal coordinates (Factor loadings)					Squared cosines				
	F1	F2	F3	F4	F5	F1	F2	F3	F4	F5
var8_fish_c	-0.013	-0.243	-0.348	-0.134	**0.399**	0.000	0.059	0.121	0.018	**0.160**
var9_vege_b	0.047	0.367	-0.020	-0.356	-0.487	0.002	0.135	0.000	0.127	**0.237**
var10_live_b	0.115	0.273	0.134	-0.484	**0.491**	0.013	0.074	0.018	0.234	**0.241**
var11_fish_b	0.179	-0.241	**0.581****	-0.022	-0.074	0.032	0.058	**0.338**	0.000	0.005
var12_hand_c	0.045	-0.025	-0.035	-0.034	-0.342	0.002	0.001	0.001	0.001	**0.117**
var13_sewi	0.290	-0.135	-0.473	-0.074	-0.216	0.084	0.018	**0.224**	0.005	0.047
var14_shop	0.292	**0.606****	0.062	-0.283	0.054	0.085	**0.367**	0.004	0.080	0.003
var15_auto	0.289	**-0.383**	-0.216	-0.069	0.078	0.083	**0.147**	0.047	0.005	0.006
var16_mech	0.016	-0.030	**0.065**	-0.009	0.044	0.000	0.001	**0.004**	0.000	0.002
var17_proc	0.164	0.480	-0.084	**0.534****	0.157	0.027	0.231	0.007	**0.285**	0.025

Source: Author's own calculation, 2024

*** Significantly Correlated (For this study, positive correlation values above 0.5 and negative values farthest from 0 are set to significant); Values in bold correspond for each variable to the factor for which the squared cosine is the largest.*

The factor score is used to classify AIGAs by plotting in two dimensions with PC1 (=F1) in the horizontal axis (x) and PC2 (=F2) in the vertical axis (y). The classification is based on the factor score, presented as Biplot[2] in Figure 5. The positive value direction of F1 and F2 showed Agro-based AIGAs such as poultry (native chicken, ducks, and pigeons), livestock (goats, cows) and non-Agro-based AIGAs grocery shop in market, tea stalling in market, fish retailing business, chicken meat processing retail shop business, tom-tom/rickshaw and TV/mobile/electric servicing.

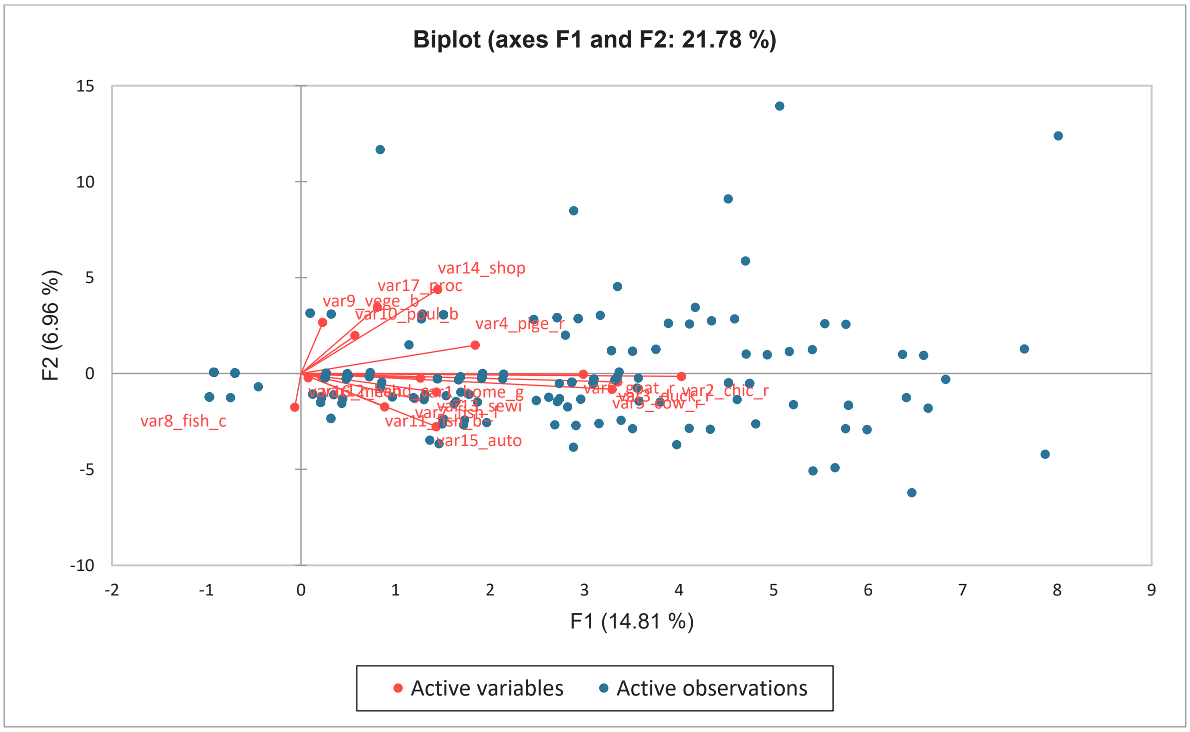

Figure 6: *Correlation circle (a) and biplot (b) of AIGA variables*

[2] The biplot was introduced by Gabriel (1971). It is a type of exploratory graph used in statistics, a generalization of the simple two-variable scatterplot.

The findings from principal component analyses indicated that Agro-based AIGAs (native chicken, ducks, and pigeons, goats, and cows) and non-Agro-based AIGAs grocery shop in market, tea stalling in market, fish retailing business, chicken meat processing retail shop business, tom-tom/rickshaw and TV/mobile/electric servicing activities will have the highest possibilities for three ecosystems (Sal-forest, Hill-forest, and Coastal-forest).

4.3. Income from sub-sectoral AIGAs: Production, marketing and value-chain

Agro-based AIGAs such as poultry (native chicken, ducks, and pigeons), livestock (goats, cows), crop farming, and aquaculture are vital in forest ecosystems. The study analysed Production, marketing and value-chain for 5 Agro-based AIGAs (native chicken, ducks, and pigeons, goats, and cows) for three ecosystems (Sal-forest, Hill-forest, and Coastal-forest). To make report in short only an analysis of the income from Agro-based AIGAs (native chicken) described, here:

4.3.1. AIGA: Native chicken rearing

Native chicken rearing involves raising indigenous breeds of chickens, which are typically more resilient and adaptable to local conditions than commercial breeds. These chickens are often raised for their meat and eggs, and are valued for their hardiness, disease resistance, and ability to thrive in small-scale, low-input environments. Native chicken rearing in Bangladesh's **Sal forest**, **Hill forest**, and **Coastal forest ecosystems** is a critical livelihood activity, particularly for rural and indigenous communities.

Native chicken rearing can serve as an **Alternative Income Generating Activity (AIGA)** for rural households by providing a supplementary source of income, food security, and potential for community-level entrepreneurship. The statistics of native chicken rearing, their Cost and Returns, Market Structure, Value chain, value addition and margins, possible Market chain options and price dynamics for native chicken rearing are discussed in the next sections.

4.3.1.1. Statistics of native chicken rearing

Three varieties of chicken i.e. native, sonali and broiler were reared in AIGA Households financial supported by SUFAL project. In Table 10, in total households of chicken rearing, the highest of 96.74% households were involved in the chicken rearing of native variety while sonali chicken was reared by the lowest household of 0.63%. Besides, as per flock size, AIGA Household based chicken farm were classified into three groups, such as, group1, group2, and group3. Number of rearing chicken was defined 20 to 50 in group1, 51 to 100 in group-2 and 101 to above in group3. In total chicken rearing households, the maximum part of 97.79% were involved in group1 whereas the same involvements in group2 and group3 were estimated only at 1.26% and 0.95%, respectively.

Table 10: *Number of chicken rearing in the HH*

AIGA	Category	Group	Definition	% of n	Mean ± StdDev
Chicken Rearing (n=366) [74.76%]	Variety wise	Native		96.74%	52.23 (± 12.661)
		Sonali		2.63%	99.00 (± 1.414)
		Broiler		0.63%	350.00 (± 212.132)
	Flock Size wise	Group-1	Number of chicken: 20 to 50	97.79%	41.34 (± 8.164)
		Group-2	Number of chicken: 51 to 100	1.26%	90.75 (± 13.985)
		Group-3	Number of chicken: 101 to above	0.95%	283.33 (± 189.297)
	All	Live birds		100.00%	54.91 (± 32.607)

Source: Author's own calculation, 2024

4.3.1.2. Cost and returns of native chicken rearing

Rearing of native chicken in households by FCV/VCF beneficiaries (members) was considered as one important AIGAs for SUFAL project. Moreover, for determining the profitability, cost and return of the AIGA is described in the part. In this case, three major costs i.e. (1) initial investment, (2) variable cost, and (3) fixed cost were identified the indicator of main costs for the AGIAs. The details of cost items are shown in Table-11. Results showed that the initial investment cost were estimated at tk. 2671.7 which is 6.47% of total cost, while variable cost, and fixed cost were tk. 36558.3 (88.47%) and tk. 2095.1 (5.07%), respectively. Thus, the total cost were found at tk 41325.1. The gross return of the chicken rearing was computed from the aggregate of all the line items of return sources. Besides, for calculating all the costs and returns, total 100 chickens as a flock size and 1 circle was counted (1 circle = 4 - 6 months) was considered.

Table 11: Cost and Returns of native chicken rearing in the HH

Indicators	Sl	Cost and Return Item	Unit	100 native chickens rearing in HH (1 circle = 4-6 months)			
				Qnt	Rate (tk)	Cost (tk)	% of Total
Initial Investment	1	Chicken Coop or Housing	Nos.	1	2158.3	2158.3	5.22%
	2	Tools and equipment	Set	1	513.5	513.5	1.24%
		Sub-Total				**2671.7**	6.47%
Variable Cost (VC)	3	Beginning stock/DOC/chick	Nos.	**100**	38.3	3831.0	9.27%
	4	Feed	Kg/bird	6.91	42.1	29091.1	70.40%
	7	Labour-HH	Man days	52	408.1	0.0	0.00%
	8	Labour-Hired	Man days	2	408.1	816.2	1.98%
	9	Healthcare and Vaccination	LS	1	497.3	497.3	1.20%
	10	Electricity	Monthly	4	201.7	806.7	1.95%
	11	Litter	LS	1	488.5	488.5	1.18%
	12	Repairing	LS	2	122.7	245.5	0.59%
	13	Transportation and Miscellaneous	LS	1	310.5	310.5	0.75%
	14	Marketing cost/toll	LS	1	471.4	471.4	1.14%
		Sub-Total				36558.3	88.47%
Fixed Cost (FC)	15	IOC	%		5%	1827.9	4.42%
	16	Depreciation of housing, tools and equipment	%		10%	267.2	0.65%
		Sub-Total				2095.1	5.07%
Total Cost (TC=VC+FC)						**41325.1**	**100.00%**
Returns (TR)	17	Egg: HH consume	Nos.	25	8.7	216.8	-

Indicators	Sl	Cost and Return Item	Unit	100 native chickens rearing in HH (1 circle = 4-6 months)			
				Qnt	Rate (tk)	Cost (tk)	% of Total
	18	Egg: Sold	Nos.	270	8.7	2340.9	-
	19	Egg: Hatching	Nos.	105	8.7	910.4	-
	20	Live bird: HH consume	Nos.	5	**585.0**	2924.9	-
	21	Live bird (matured): Sold	Nos.	**93**	585.0	54403.1	-
	22	Live bird (squabs): Sold	Nos.				-
	23	Death bird	Nos.	2	0.0	0.0	-
	24	**By-products: Chicken droppings, litter**	LS	-	-	200.0	
	25	Salvage value	%		90%	2204.6	-
		Gross Return (GR)				**63200.6**	-
Income/ Margins	26	Gross-Margin (GM=GR-VC)	tk/circle	-	-	21875.5	-
	27	Net-margin (NM=GR-TC)	tk/circle	-	-	20148.9	-
	28	MBCR (undiscounted) (=GR/VC)	ratio	-	-	1.53	-

Source: Author's own calculation, 2024

The gross return is calculated at tk. 63200.6, while the gross margin and net margin stood at tk. 21875.5 and tk. 20148.9 per month respectively, indicating that native chicken rearing in the HH in the study area is profitable. The undiscounted benefit-cost ratio is found at 1.53, showing that for every tk.1.00 investment on operating a grocery shop, people can received tk. 1.53 in a circle.

4.3.1.3. Structure of native chicken market

Five indicators were considered for identifying the structure of native chicken markets situated in the nearest areas of forest dependent community (Table 12). The five indicators were (1) AIGA products, (2) market for AIGA products, (3) Distance of markets, (4) Market competition, and (5) market demand and supply (Table-9). Data showed that Products from native chicken rearing was live birds (chicken), the variety was native, and average weight per live chicken was calculated at 1.10 kg to 1.70 kg. The nearest market for AIGA products was determined village market or union market of which 1 (one) was the nearest markets and 2 hat day were generally held in each markets. Again, distance of markets from AIGA households were identified 0.50 km for village level market and 0.50–1.00 km for union level market. The sellers and buyers gathered in the hat day in the markets were usually identified 40-60 persons and 100–150 persons that indicate the markets as oligopoly markets (oligopolistic competition). On the other side, weekly market demand and supply of products were estimated at 70,688.57 kg and 70,350 kg, respectively whereas deficit of product supply per week was counted at 338.43 kg having standard deviation ±270.04 kg.

Table 12: Structure of native chicken market which nearest in the FDC

Sl	Indicator	Line Item			Results	
1	AIGA Products	Products from AIGA		:	Live chicken (1.1-1.7 kg)	
		Variety			Native	
2	Market for AIGA Products	Name of nearest market		:	Village market/ Union market	
		Number of nearest markets		:	2	
		Hat Days/Week in a market		:	2	
3	Distance of Markets	Village level market		:	0.5 km	
		Union level market		:	0.5-1 km	
4	Market Competition	Number of buyer		:	40-60	
		Number of seller		:	100-150	
		Type of market competition	Perfect competition	:		
			Oligopoly	:	√	
			Monopoly	:		
			Monopolistic	:		
5	Market Demand and Supply	Market Demand		:	70,688.57 (±214.36)	Kg/week
		Market Supply		:	70,350.14 (±325.71)	Kg/week
		Deficit (-) / Surplus (+)		:	-338.43 (±270.04)	Kg/week (Deficit)

Source: Author's own calculation, 2024

4.3.1.4. Value chain, value addition and margins of native chicken

The actors in the value chain of the native chicken in the three forest ecosystem's farmers to central consumers are (i) forest area market actors: neighbor consumer, family consumer, faria, bapari/local trader, local arotdar, retailer, local rural consumer; (ii) regional market actors: wholesaler, retailer, hawker, local urban consumer; and (iii) central market actors: central arotdar, supplier, retailer, hawker, processor, super shop, central consumer (Figure 7). The results showed that the production cost at farm was estimated at tk. 413.3 and sold price at tk. 585.0 per chicken which was sold at tk. 646.7 to central consumer.

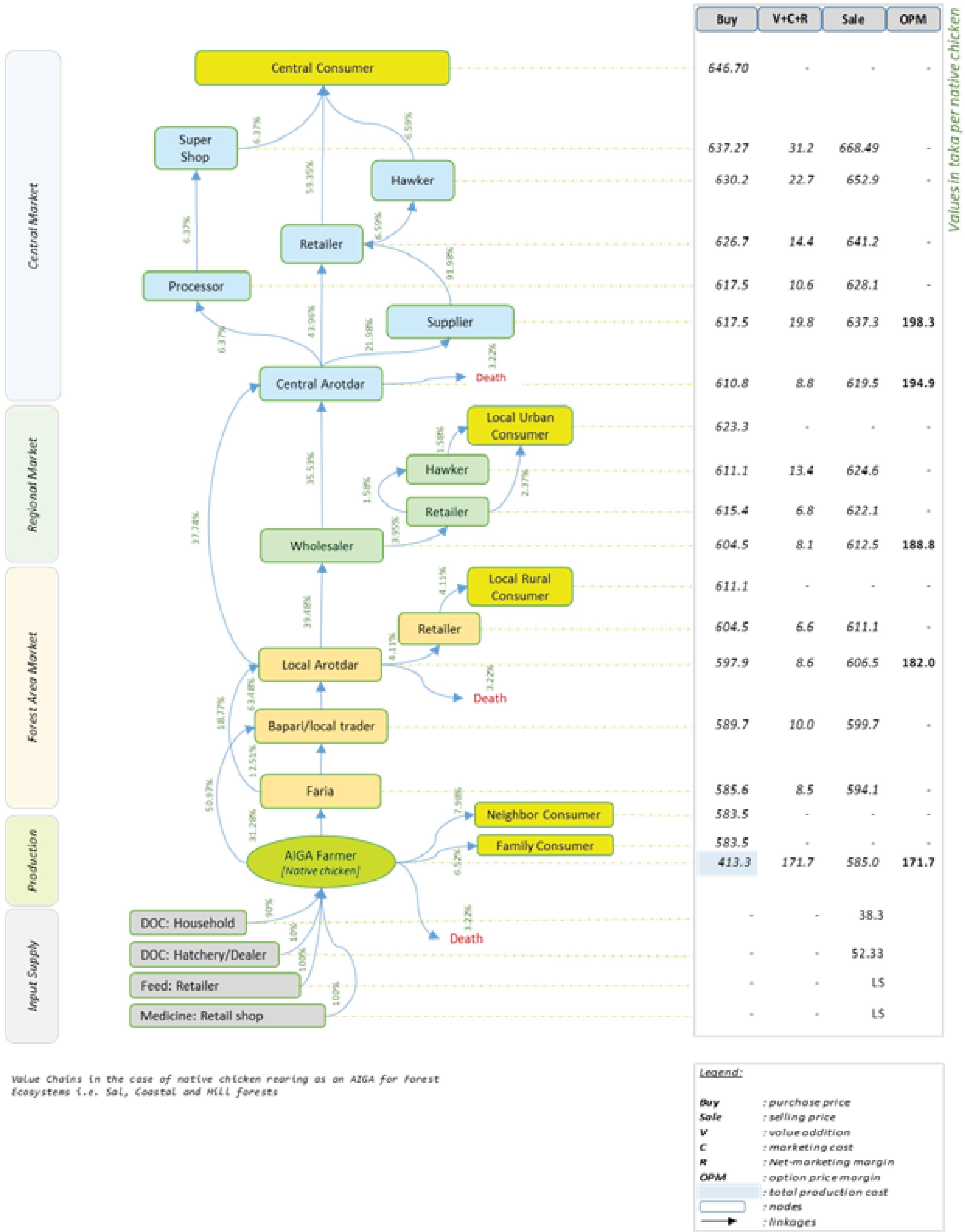

Figure 7: *Value chain of native chicken*

4.3.1.5. Market chain options and price dynamics for native chicken rearing

Figure 8 shows the market chain options for native chicken rearing and Table 13 illustrated the price dynamics for FDCs. Generally native chicken rearing farmers sold their chicken to neighbor and foria, at the price of tk. 585 in the forest area market. Value-chain in figure 9 indicating that farmers have four options to sold to local arotdar of forest area market at tk. 597, wholesaler of regional market at tk. 604, central arotdar of central market at tk. 610 and supplier of central market at tk. 617 which are 2.21%, 3.33%. 4.41%, and 5.56% increasing from the base price. At base price, the margin of farmers is found at tk. 171, and considering this, the option price margin will increase to 6.03%, 9.95%, 13.50%, and 15.49%, respectively.

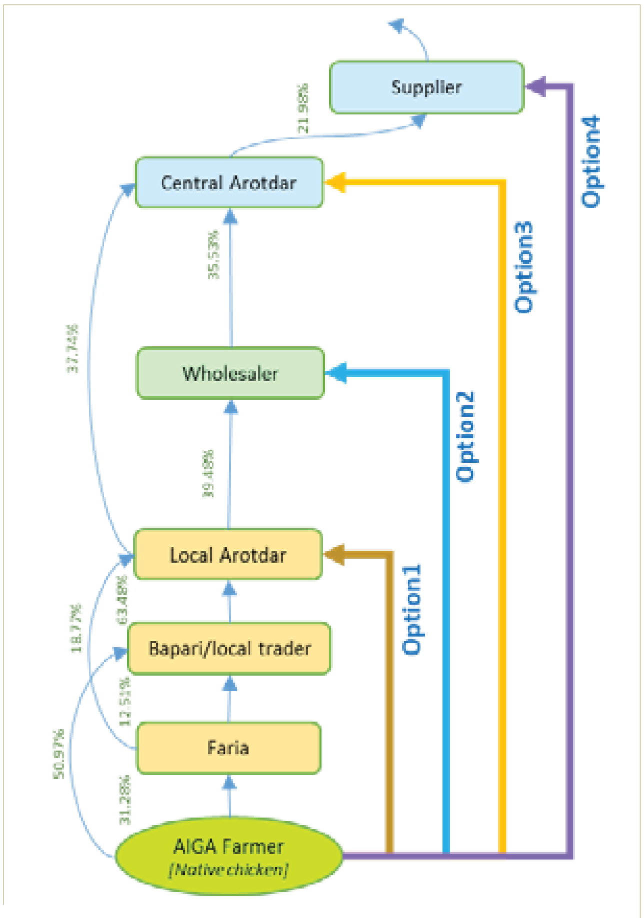

Figure 8: Market chain options for native chicken rearing farmers

Table 13: Market chain options and price dynamics for live chicken

Possible market to sold		Option No.	Option Price		OPM	
Market	Market Actors		Price (tk.)	Increase (%)	Margin (tk.)	Increase (%)
Forest Area Market	Foria, Neighbor	Base	585.0	-	171.7	-
"	Local Arotdar	Opt.1	597.9	2.21%	182.0	6.03%
Regional Market	Wholesaler	Opt.2	604.5	3.33%	188.8	9.95%
Central Market	Central Arotdar	Opt.3	610.8	4.41%	194.9	13.50%
"	Supplier	Opt.4	617.5	5.56%	198.3	15.49%

Source: Author's own calculation, 2024

4.3.1.6. Sustaining a household's livelihood through native chicken rearing

Income from native chicken rearing helps to sustain a household's livelihood. Native chicken rearing can provide consistent income, especially in rural areas where job opportunities may be limited. Selling eggs and meat can help cover essential household expenses like food, education, and utilities. The cost of setting up a small chicken rearing operation is relatively low, and chickens can be raised with minimal input. Chickens can also serve as a form of "savings" since they can be sold for cash in emergencies.

4.3.1.7. Challenges on native chicken rearing in forest ecosystems

Native Chicken Rearing in Bangladesh's **Sal forest, Hill forest,** and **Coastal forest ecosystems** is a critical livelihood activity**, have some Challenges**:

- Poultry are susceptible to diseases like Newcastle disease, avian influenza, and coccidiosis.
- Limited access to veterinary care and vaccinations.
- Poor healthcare services lead to high mortality rates during disease outbreaks.
- Harsh terrain and poor infrastructure limit market access and veterinary services.
- Prices of eggs and meat can fluctuate based on demand, seasonality, and local market conditions.
- Chickens are vulnerable to predators like foxes, mongooses, dogs, cats, and birds of prey, and theft can be an issue in some areas.
- Frequent cyclones and tidal surges destroy infrastructure and kill livestock.
- Conflict over forest resources due to expanding settlements and agriculture.

4.3.1.8. Remarks on native chicken rearing

The native chicken rearing business is relatively risk-resistant, as native chickens are hardy and require less attention compared to commercial breeds, with proper management, this activity can be a resilient and valuable part of a diversified household income strategy.

4.4. Income from non-sub-sectoral AIGAs: trading, processing and servicing

The study analyzed income from 6 non-sub-sectoral AIGAs (trading, processing and servicing specific), are: grocery shop in market, tea stalling in market, fish retailing business, chicken meat processing retail shop business, tom-tom/rickshaw and TV/mobile/electric servicing. To make report in short only an analysis of the income from non-agro-based AIGA (grocery shop in market) described, here:

4.4.1. AIGA: Grocery shop

A grocery shop is a small or medium-sized retail store that sells essential goods for daily use, including food, beverages, cleaning supplies, toiletries, and sometimes small household items. In the study area Grocery shops are integral to forest dependent communities, offering convenience and meeting the regular needs of individuals and families. Grocery shops can range in size from small neighborhood stores to large supermarkets or hypermarkets. Table 30 shows the cost, returns and profit margin of grocery shop.

Total cost (TC) of a grocery shop estimated at tk. 57132.9, consists sum of initial investment costs and daily operating costs. Initial investment cost is for setup costs includes space rental or ownership: rent for a shop space or constructing a small stall; furniture and fixtures: shelves, racks, counters, display boards, and storage units; basic equipment: cash register, weighing scale; decoration: minimal signage or shade; fan and lighting systems; inventory: initial stock of goods; and interest on operating capital (IOC). Monthly total initial investment costs is estimated at tk. 3387.9 which is 5.93% of total costs. Besides, daily operating costs includes restocking goods: regular purchase of inventory based on demand; labour; bags/polybags for customers; utilities: electricity, water, and other; market cost/toll; repair/replace of items; maintenance; and other miscellaneous. Monthly total initial investment costs were estimated at tk. 53745.0 which is 94.07% of total costs.

The source of returns from a grocery shop are Daily sales and some Waste-products. The gross return is calculated at tk. 63387.5, while the gross margin and net margin stood at tk. 9642.5 and tk. 6254.6 per month respectively, indicating that operating a grocery shop in the study area is profitable. The undiscounted benefit-cost ratio is found at 1.18, showing that for every tk.1.00 investment on operating a grocery shop, people can received tk. 1.18.

Table 14: Cost, returns and profit margin of grocery shop

Sl	Indicator	Unit	Unit Rate in Tk.	Monthly Tk.	Percent of total (%)
A	**Cost**				
A1	Initial Investment Costs				
1	Space Rental or Ownership: Rent for a shop space or constructing a small stall.	10 years	126500	1054.2	1.85%
2	Furniture and Fixtures: Shelves, racks, counters, display boards, and storage units.	5 years	7495	124.9	0.22%
3	Basic Equipment: Cash register, weighing scale	5 years	6650	110.8	0.19%
4	Decoration: Minimal signage or shade	5 years	7253	120.9	0.21%
5	Fan and Lighting systems	5 years	1840	30.7	0.05%
6	Inventory: Initial stock of goods	1 years	20000	1666.7	2.92%
7	IOC	%	0	279.7	0.49%
	Total Fixed Cost (FC)			**3387.9**	**5.93%**
A2	Variable Cost/ Operating Costs				0.00%
1	Restocking Goods: Regular purchase of inventory based on demand.	Weekly	11620	46480.0	81.35%
2	Labour-HH	Daily 1	0	0.0	0.00%
3	Labour-Hired	Daily 0	0	0.0	0.00%
4	Bags/polybags for customers.	Daily	125	3250.0	5.69%
5	Utilities: Electricity, water, and other	Monthly	775	775.0	1.36%
6	Market cost/toll	Daily	20	520.0	0.91%
7	Repair/replace of items, and maintenance	Monthly	1052	1052.0	1.84%
8	Miscellaneous	Weekly	417	1668.0	2.92%
	Total Operating Cost (OC)			**53745.0**	**94.07%**
B	Total Cost (TC)		FC+OC	**57132.9**	**100.00%**
C	**Returns**				
1	Daily sales	Daily	2436	63338.3	99.92%
4	Waste-products	Yearly	590	49.2	0.08%
	Gross Return (GR)			**63387.5**	**100.00%**
D	**Income**				
1	Gross-Margin (GM)	Monthly	GR-OC	9642.5	-
2	Net-margin (NM)	Monthly	GM-TC	6254.6	-
3	MBCR (undiscounted)	Monthly	GR/OC	1.18	-

Source: Author's own calculation, 2024

Income from a Grocery Shop may Sustains a forest dependent Household's Livelihood in Bangladesh. Daily sales provide consistent cash flow, allowing households to meet essential expenses such as food, rent, and education. The owner can access household essentials at cost, reducing their personal living expenses. Family members can work in the shop, saving on labor costs while contributing to the household income. Surplus earnings can be saved for emergencies or reinvested to expand the business by increasing inventory, improving infrastructure, or opening additional outlets. Essential goods like rice, flour, oil, and soap are always in demand, making the business less susceptible to economic downturns. Income can be used to pay for children's schooling, healthcare, and other long-term developmental needs for the family. The shop ensures access to food and essentials, especially during emergencies or natural disasters. Thus, operating a grocery shop is a sustainable and profitable livelihood option, especially in areas of sal, hill and coastal forest ecosystems with consistent foot traffic. With careful planning, customer trust, and proper inventory management, a grocery shop can provide steady income, support household needs, and serve as a foundation for financial growth and stability.

4.5. Livelihood sustainability of AIGA people

A livelihood can be classified as sustainable, when it is resilient in the face of external shocks and stresses, when it is not dependent upon external support, when it is able to maintain the long-term productivity of natural resources and when it does not undermine the livelihood options of others. For thus, in Bangladesh, if a forest dependent family can live their livelihood by an AIGA in a sustainable manner, then the household (HH) reduces their dependency on forest. Otherwise, they take switching decisions to forest & forest resources which again increase the forest loss. Empirically, livelihood sustainability refers to the capacity of individuals, households, and communities to maintain and improve their means of living in a way that preserves resources for future generations. It encompasses a balance between economic stability, environmental preservation, and social well-being, ensuring that livelihoods are resilient to shocks, adaptable to change, and equitable for all members of society. Thus, at first we need to identify the level of social, demographic and economic status of FDCs, then mapping the matrix of sustainability of AIGAs for the forest ecosystems.

4.5.1. Social, demographic and economic status of HHs in FDCs

The impact of socio-demographic status on livelihood sustainability is significant, as socio-demographic factors—such as age, gender, education, income level, household size, occupation, and geographic location—play a crucial role in shaping access to resources, opportunities, and resilience mechanisms. Here’s how these factors influence livelihood sustainability:

The study categorized the HH members, based on age in to four groups: (i) between 0 to 14, (ii) between 15 to 29, (iii) between 30 to 64, (iv) above 65. Results shown in Table 9, and illustrated that the percentage of group1 members is 29%, their average age is 8.27 with 4.04 standard deviation [29.24 (8.27 ± 4.04)], which is 31.61 (20.38 ± 3.88), 36.16 (41.61 ± 9.07), and 3.00 (73.00 ± 8.55) for others groups respectively. This result is similar to national figures (BBS, 2023).

Table 15: Age category of the HH members

Eco-system	Age Group	HH members in FDC [% (Ave ± StdDev)]			SYB 2023: National [% (Ave)]			HIES 2022: National
		Male	Female	Total	Male	Female	Total	
All Forest	0 to 14	29.03 (8.14 ± 3.96)	29.24 (8.27 ± 4.04)	29.13 (8.20 ± 4.00)	30.54%	28.88%	29.71%	28.14%
	15 to 29	31.18 (20.93 ± 3.97)	31.61 (20.38 ± 3.88)	31.39 (20.65 ± 3.93)	24.15%	27.49%	25.81%	65.67%
	30 to 64	35.08 (43.38 ± 9.37)	36.16 (41.61 ± 9.07)	35.62 (42.49 ± 9.26)	39.35%	39.40%	39.38%	
	65+	4.72 (67.89 ± 3.81)	3.00 (73.00 ± 8.55)	3.86 (69.87 ± 6.54)	5.93%	4.22%	5.08%	6.19%
	Total (Grand Total)	100.0 (27.31 ± 18.13)	100.0 (26.09 ± 17.26)	100.0 (26.70 ± 17.71)	100.00%	100.00%	100.00%	28.14%

Source: Author’s own calculation, 2024

Results on table 39 showed that proportion of male members is 48.35%, 53.32%, and 49.82% in the Coastal Forest, Hill Forest, and Sall Forest Ecosystem, while female share is 51.65%, 46.68%, and 50.18% respectively. In total, male is more (50.15%) than female (49.85%) which reverse to national figures.

Table 16: Gender status of the HH members

Ecosystem	HH members in FDC [%]			SYB 2022	
	Male	Female	All	Male	Female
Coastal Forest	48.35%	51.65%	43.72%	-	-
Hill Forest	53.32%	46.68%	27.88%	-	-
Sall Forest	49.82%	50.18%	28.40%	-	-
Total	50.15%	49.85%	100.00%	49.51%	50.49%

Source: Author's own calculation, 2024

The dependency ratio—the proportion of dependents (children aged 0–14 and elderly aged 60 and above) relative to the working-age population (15–59 years)—significantly impacts the livelihood sustainability of forest-dependent communities in Bangladesh. The Dependency ratio in the HH of forest-dependent communities in Bangladesh shown in Table 40, showed that dependency ratio is 38.75 in the HH of forest-dependent communities which is 28.62, 45.20, and 48.01 for Coastal Forest, Hill Forest, and Sall Forest Ecosystem. The Dependency ratio in the HH of forest-dependent communities is the lower than the national figure of Bangladesh (SYB, 2023; HIES, 2022).

Table 17: Demographic Ratio of the HH members

Indicator	Ecosystem	Ration		
		FDC	SYB 2023	HIES 2022
Dependency ratio	Coastal Forest	28.62	-	-
	Hill Forest	45.20	-	-
	Sall Forest	48.01	-	-
	All	38.75	53.35	52.3
Male-Female ratio (M:F)	Coastal Forest	0.94	-	-
	Hill Forest	1.14	-	-
	Sall Forest	0.99	-	-
	All	1.01	0.98	1.08

Source: Author's own calculation, 2024

Table 41 illustrated that in the HH of forest-dependent communities 22.84% members can read or write only. Among the others, Class I to V is 18.67%, Class V passed is 18.67%, Class VI to VIII is 16.36%, Class IX to SSC is 10.27%, Class XI to HSC is 5.41%, B.Sc./Honors. is 2.26%, Masters is 3.05%, and Madrasa is 2.48%. Regarding Literacy level the Child literacy rate (age 7 to 14) is 96.07%, Adult literacy rate (age 15 & above) is 73.32%, and Functional literacy rate (age 7+ above) is 62.71%. This result is higher than the national figures for Child literacy rate is (72.97%), Adult literacy rate is (60.77%), but lower than the Functional literacy rate (74.66%).

Table 18: Literacy level of the HH members

Sl	Education		Literacy level Coastal Forest	Hill Forest	Sall Forest	Grand Total
1	Can read or write only		14.79%	27.53%	29.42%	22.84%
2	Primary	Class I to V	21.37%	17.59%	15.96%	18.67%
3		Class V passed	19.59%	21.41%	14.62%	18.67%
4	School	Class VI to VIII	16.58%	17.40%	15.00%	16.36%
5		Class IX to SSC	10.96%	8.41%	11.15%	10.27%
6	College	Class XI to HSC	4.66%	4.21%	7.69%	5.41%
7	Graduate	B.Sc./Honors.	2.47%	1.34%	2.88%	2.26%
8	Post-graduate	Masters	5.21%	0.38%	2.69%	3.05%
9	Madrasa		4.38%	1.72%	0.58%	2.48%
10	Others		0.00%	0.00%	0.00%	0.00%
11	Literacy level	Child literacy rate (age 7 to 14)	95.88%	95.00%	97.67%	96.07%
12		Adult literacy rate (age 15 & above)	83.20%	68.78%	65.11%	73.32%
13		Functional literacy rate (age 7+ above)	69.57%	53.33%	66.67%	62.71%
14	P&HC, BBS, 2023	Child literacy rate (age 7 to 14)	-	-	-	72.97%
15		Adult literacy rate (age 15 & above)	-	-	-	60.77%
16		Functional literacy rate (age 7+ above)	-	-	-	74.66%

Source: Author's own calculation, 2024

Table-9 shows the occupation of the HH members, and illustrated that in the HH of forest-dependent communities 13.92% are employed in Crop production, 7.74% employed in Cow/Goat rearing, 17.62% employed in Chicken/duck/Pigeon rearing, 1.12% employed in Fish farming, 1.91% employed in Shop , 2.81% employed in Rickshaw/van/auto puller, 5.72% employed in Business, 0.34% employed in Piker/Bapari, 11.22% employed in Service/job, and 37.6% employed in Others (not employed, students, childs, etc.).

Table 19: Occupation of the HH members

Sl	Occupation		Employment of HH members Coastal Forest	Hill Forest	Sall Forest	Grand Total
1	Crop production		14.78%	10.70%	16.00%	13.92%
2	Cow/Goat rearing		6.38%	7.38%	9.82%	7.74%
3	Chicken/duck/Pigeon rearing		10.43%	19.56%	24.73%	17.62%
4	Fish farming		0.58%	1.48%	1.45%	1.12%
5	Shop		1.45%	0.74%	3.64%	1.91%
6	Rickshaw/van/auto puller		2.90%	1.11%	4.36%	2.81%
7	Business		3.77%	3.32%	10.55%	5.72%
8	Piker/Bapari		0.87%	0.00%	0.00%	0.34%
9	Service/job		12.17%	5.90%	15.27%	11.22%
10	Others (not employed, students, childs, etc.)		46.67%	49.82%	14.18%	37.60%
11	Earning members	Numbers HH members are earning (%)	42.90%	78.97%	88.00%	67.79%
12		Average number Per HH	1.69	1.52	1.42	1.57

Source: Author's own calculation, 2024

Table-9 shows the assets of the HH members, and illustrated the distribution of access to Home Ownership, Toilets, Drinking Water Purification methods, Main House Infrastructure, Light Source, Source of Drinking Water, and Source of Cooking Fuel of the forest-dependent communities. The household assets of forest-dependent communities in Bangladesh play a significant role in determining their livelihood sustainability. Table 43 shows ownership of HH, their assets and livelihood condition.

Table 20: Ownership of HH, their assets and land use condition

Livelihood Indicator	**Options & Status (%)**							
	opt1	**opt2**	**opt3**	**opt4**	**opt5**	**opt6**	**opt7**	**opt8**
Home Ownership	Own	Rent	Other					
	80.19%	1.19%	18.62%					
Toilets	Septic Tank/ Latrine	Pit Latrines	Hanging Latrines	Open Spaces/ Shrubs				
	81.15%	13.37%	3.34%	2.15%				
Drinking Water Purification	Boiling	Alum	Purification Tablet	Filter	Nothing			
	4.77%	0.72%	0.24%	1.67%	92.60%			
Main House Infrastructure	Jhupri	Golpata	Tin/Tali	Semi-paka	Paka/Tiles	Others		
	2.86%	7.16%	67.06%	16.23%	2.63%	4.06%		
Light Source	Electricity	Hurricane	Candle	Solar Power	Biogas	Other		
	91.17%	3.10%	2.63%	1.67%	0.95%	0.48%		
Source of Drinking Water	Tube Well	Well	Pond	River/Canal	Rain Water	Electric Motor	Others	
	68.02%	0.24%	0.00%	2.39%	2.39%	26.49%	0.48%	
Source of Cooking Fuel	Wood	Bamboo	Jute Stick	Dung	Leaves	Gas	Crop By-Products	Others
	51.79%	3.82%	6.44%	8.11%	15.04%	13.37%	0.24%	1.19%

Source: Author's own calculation, 2024

4.5.2. Sustainable level of AIGAs for sustainable livelihood in FDCs

From results of the above tables, the study assuming that if a forest dependent family can live their livelihood by an AIGA in a sustainable manner, then the household (HH) reduces their dependency on forest. Otherwise, the HH takes a switching decision to another AIGAs or to forest, which again increases the forest loss. According to study survey 2024 conducted by the research team the average size of households stood at 5.09 for three forest ecosystems, and the average household expenditure per month is tk. **21867.2** in 2024 means annually tk. **262406.4**. The result from the study emphasizes the fact that for five-member households in the forest ecosystems in Bangladesh, the annual income should be at least Tk. **262406.4** per year. Since HHs recover tk. 29170.6 from their own source and tk. 112201.3 earn from different non-AIGA income sources per year, thus, if a family earns remaining amount of expenditure tk. 121034.5 per annum from any AIGA to cover the living cost of that family, he will cover his household living expenditure, and therefore, the AIGA will be sustainable. He will reduce their dependency on forest ecosystems.

From the table 9 it is identified that only the AIGAs on Cow rearing, Fish retailing business, and Tom-tom/rickshaw pedaling return more or equal income of that amount, individually. In that case, the study analyse the income of the HHs who will operating two AIGAs simultaneously. In the sub-sectoral context, the study found three option:

i. Chicken rearing with Pigeons rearing

ii. Duck rearing with Pigeons rearing

iii. Pigeons rearing with Goat rearing

In the non-sub-sectoral context, the study found that only the option of Duck rearing with Meat Processing is not feasible. Except this, all other options of combinations of sub-sectoral AIGAs with any non-sub-sectoral AIGAs are feasible earn required income.

Table 21: Difference of HH income and Expenditure

AIGA Name	Nos.	Difference of HI and HE					
		For Single AIGA	Income balance for double AIGA				
			Chicken rearing	Duck rearing	Pigeons rearing	Cow rearing	Goat rearing
Sub-Sectoral AIGA							
Chicken rearing	100	-72677.0					
Duck rearing	100	-96821.6	-48464.1				
Pigeons rearing	100	-23545.3	24812.2*	667.7*			
Cow rearing	5**	**139769.9**	188127.4	163982.8	237259.1		
Goat rearing	10	-68356.3	-19998.8	-44143.3	29133.0	192448.1	
Non-Sub-Sectoral AIGA							
Grocery Shop in Market	1	-32190.6	16166.8*	-7977.7	65298.6*	228613.8	20487.6*
Tea Stalling in Market	1**	**23136.6**	71494.0	47349.5	120625.8	283941.0	75814.8
Fish retailing business	1**	**206086.5**	254443.9	230299.4	303575.7	466890.9	258764.7
Meat Processing	1	-20784.8	27572.6*	3428.1*	76704.4*	240019.6	31893.4*
Tom-tom/rickshaw	1**	**84257.8**	132615.2	108470.7	181747.0	345062.2	136936.0
TV/mobile/electric servicing	1	-3783.6	44573.9*	20429.3*	93705.6*	257020.8	48894.6*

Source: Author's own calculation, 2024

* *: Significant when people operating double AIGA*

** *: Significant when people operating even single AIGA*

4.5.3. Options for livelihood sustainability of FDC people

Results in table 47 showed that if a farmer want to operate only a single sub-sectoral AIGA at small scale for living their livelihoods is a sustainable manner, he/she should take decision for Chicken rearing or Cow rearing, only. Ant the flock and herd size should be minimum 212 and 3, respectively in the case of soled to nearest forest market. If they can create a link to Regional Market and Central Market for Chicken rearing the flock size will be minimum 199 and 195, respectively.

For single AIGA of Duck rearing, Pigeons rearing, and Goat rearing the size is higher than their capacity. In that case they can take a decision for double AIGA at a time. Break-even number of flock or herd size are given in below table.

Table 22: Break-even-points for sustainable AIGAs

Sector	AIGA Name	Nos.	Min(N), where: HI=HE							
			Single AIGA			Double AIGA: sold to nearest market				
			Forest Market	Regional Market	Central Market	chicken rearing	Duck rearing	Pigeons rearing	Cow rearing	Goat rearing
Sub-Sectoral AIGA	1. Chicken rearing	100	212	199	195	-	264	75	any	14
	2. Duck rearing	100	428	373	360	177	-	100	any	18
	3. Pigeons rearing	100	125	112	109	57	98	-	any	70
	4. Cow rearing	5	3	3	3	any	any	any	-	any
	5. Goat rearing	11	23	23	23	133	250	70	any	-
Sub-Sectoral AIGA	6. Grocery Shop	1	(-)			73	128	33	any	7
	7. Tea Stalling in Market	1	1			any	any	any	any	any
	8. Fish retailing business	1	1			any	any	any	any	any
	9. Meat Processing	1	(-)			52	89	any	any	5
	10. Tom-tom/rickshaw	1	1			any	any	any	any	any
	11. TV/mobile/electric servicing	1	(-)			20	31	4	any	2

Source: Author's own calculation, 2024

From the above table 47, the study identified 15 sustainable options for given quantity and 36 options for any quantity of flock/herd sizes. Five options are single AIGAs like Minimum 212 native chicken rearing; or, Minimum 3 cow rearing; or, Minimum a Tea Stalling in Market; or, Minimum a Fish retailing business; or, Minimum a Tom-tom/rickshaw peddling. Two options are related to sub-sectoral double AIGAs like 100 chickens rearing + minimum 75 pigeons rearing; and 100 chickens rearing + minimum 14 goat rearing. Regarding sub-sectoral with non-sectoral AIGA the study found 7 options. These are Grocery Shop + minimum 73 native chicken rearing; or, Grocery Shop + minimum 33 pigeons rearing; or, Grocery Shop + minimum 7 goat rearing; or, Meat Processing retail shop + minimum 52 native chicken rearing; or, Meat Processing retail shop + minimum 5 goat rearing; or, TV/mobile/electric servicing + minimum 20 native chicken rearing; or, TV/mobile/electric servicing + minimum 4 pigeons rearing; or, TV/mobile/electric servicing + minimum 2 goat rearing Remaining four options on "any one of ten AIGA with minimum herd/flock-size" with 3 cow rearing; or, A Tea Stalling in Market; or, A Fish retailing business; or, A Tom-tom/rickshaw + any one of ten AIGA with minimum herd/flock-size. The list is given below Table 48.

Table 23: List of AIGA options for livelihood sustainability

Options	AIGA Combinations	Options Nos.
Option1	Minimum 212 native chicken rearing	1
Option2	Minimum 3 cow rearing	1
Option3	Minimum a Tea Stalling in Market	1
Option4	Minimum a Fish retailing business	1
Option5	Minimum a Tom-tom/rickshaw	1
Option6	100 chickens rearing + minimum 75 pigeons rearing	1
Option7	100 chickens rearing + minimum 14 goat rearing	1

Options	AIGA Combinations	Options Nos.
Option8	Grocery Shop + minimum 73 native chicken rearing	1
Option9	Grocery Shop + minimum 33 pigeons rearing	1
Option10	Grocery Shop + minimum 7 goat rearing	1
Option11	Meat Processing retail shop + minimum 52 native chicken rearing	1
Option12	Meat Processing retail shop + minimum 5 goat rearing	1
Option13	TV/mobile/electric servicing + minimum 20 native chicken rearing	1
Option14	TV/mobile/electric servicing + minimum 4 pigeons rearing	1
Option15	TV/mobile/electric servicing + minimum 2 goat rearing	1
	Total	15
Option16	3 cow rearing + any one of ten AIGA with minimum herd/flock-size	36
	A Tea Stalling in Market + any one of ten AIGA with minimum herd/flock-size	
	A Fish retailing business + any one of ten AIGA with minimum herd/flock-size	
	A Tom-tom/rickshaw + any one of ten AIGA with minimum herd/flock-size	
	Total	51

Source: Author's own calculation, 2024

There are some factors Affecting BEPs for AIGAs. Among them, five factors are (i) market Access: The availability of buyers and fair pricing significantly impacts BEPs; (ii) training and Skill Levels: Poor skills can increase costs or reduce productivity; (iii) initial Investment: Lower fixed costs lead to faster break-even; (iv) time to Revenue Generation: Activities like timber production may take years, delaying break-even; and (v) environmental Sustainability: Overharvesting or mismanagement can increase future costs. With proper planning and community involvement, achieving BEPs for AIGAs becomes more feasible while maintaining the sustainability of Bangladesh's forest ecosystems.

4.5.4. Viability of AIGA options under risk and uncertainties

The viability of Alternative Income-Generating Activities (AIGAs) in the context of Bangladesh's forest ecosystems depends on ecological, economic, and social factors. The study found seven risk and uncertainties on AIGAS, are purchase price, price of feed, labour wage, repairing cost by climate hazards, transportation cost by market distance, sale price, and mortality rate. The stochastic distribution of risks and uncertainties embedded with AIGA are shown in Table 49.

Table 24: Stochastic distribution of risks and uncertainty embedded with AIGA

Risks and Uncertainties:	Unit	Mean, StdDev			
		Chicken	Duck	Pigeon	Cow
Purchase price	tk./piece	38.31, 1.114	44.92, 1.813	300.5, 5.214	34260, 1532.103
Price of feed	tk./kg	52.1, 2.502	52.1, 2.517	52.1, 2.021	22050, 13.204
Labour wage	tk./manday	408.12, 10.024	408.12, 10.101	408.12, 8.975	-
Repairing cost by Climate Hazards	tk.	122.73, 9.821	52.8, 10.495	342.5, 11.201	520, 49.781
Transportation cost by market distance	tk.	310.49, 2.768	200, 12.231	405.5, 9.685	-

Sale price	tk./piece	584.98, 5.411	548.25, 4.226	145.5, 3.3942	72450, 3200.108
Mortality rate	percent	0.022, 0.00031	0.023, 0.00042	0.021, 0.00012	-

Source: Author's own calculation, 2024

The study incorporated the risk and uncertainties in to the income model for option 1 (Minimum 212 native chicken rearing) and option 8 (Grocery Shop + minimum 73 native chicken rearing) with different scenarios. The study run the results by applying Monte-Carlo Simulation technique with 1000 iterations. Figure 13 shows the QQ plot of 4 stochastic distribution of risks and uncertainties for option 1, indicating the data is normally distributed. Similar result found for the option 8 shown in Figure 14.

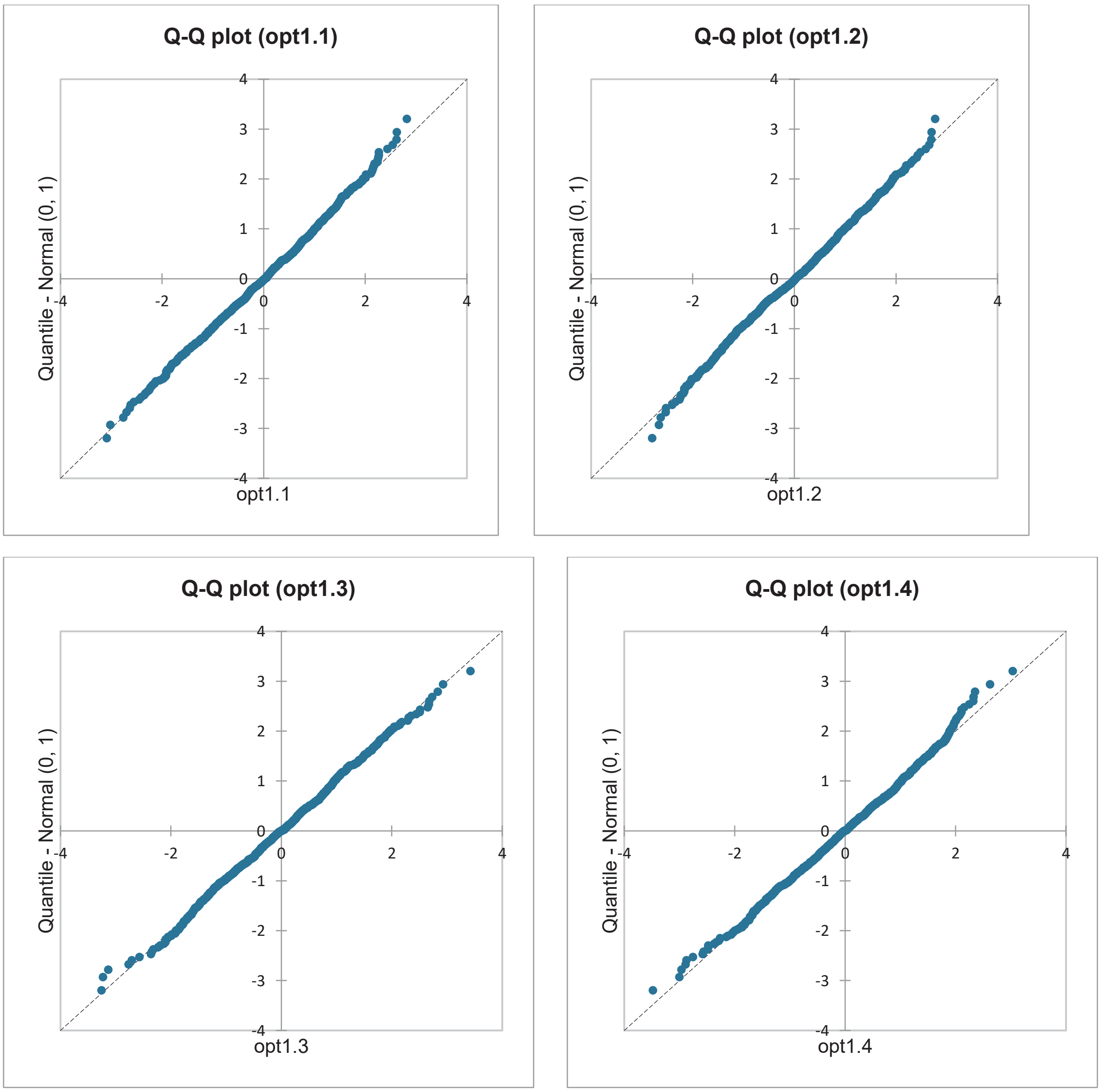

Figure 9: *QQ plot of 4 stochastic distribution of risks and uncertainties for option 1*

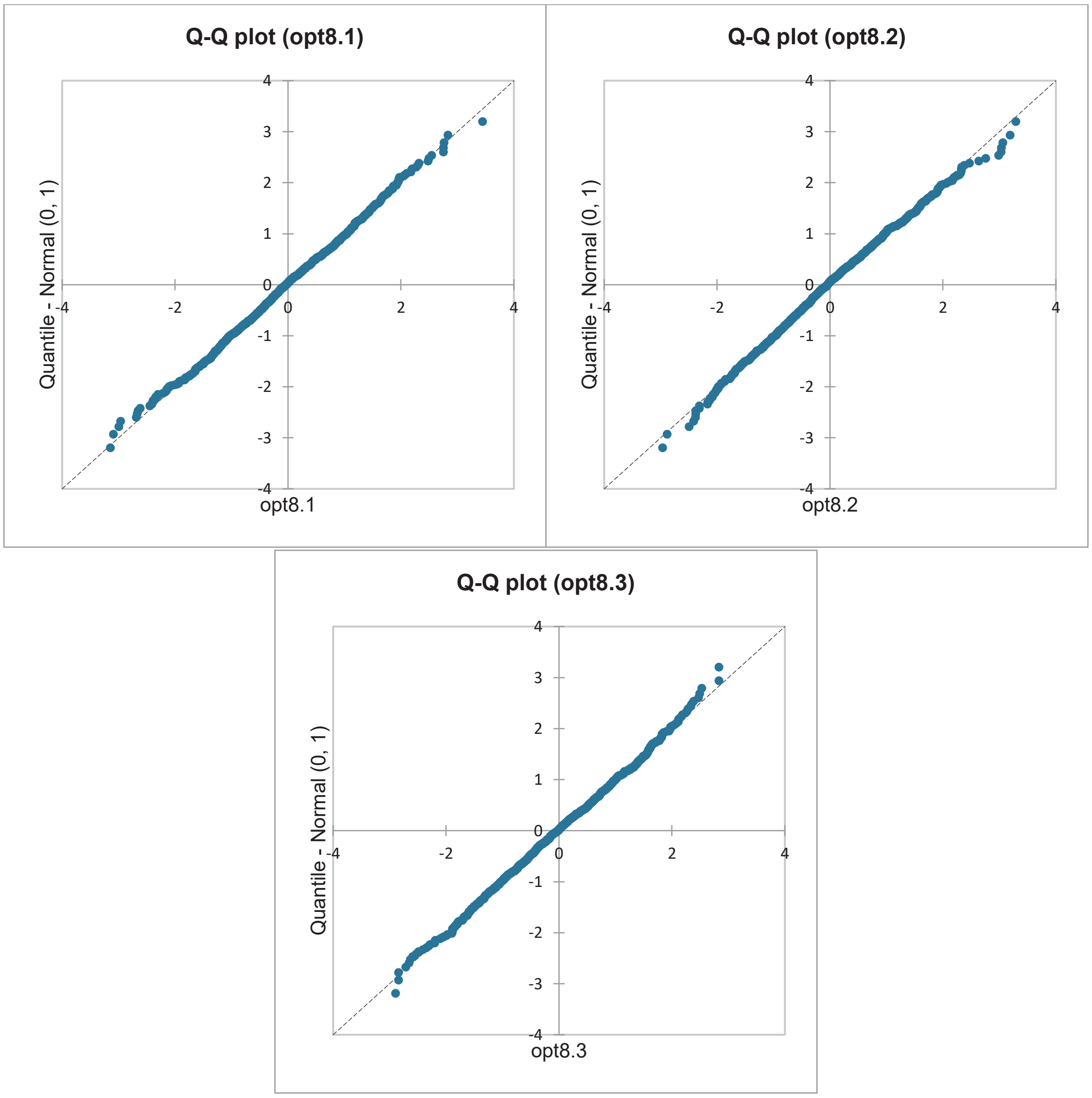

Figure 10: *QQ plot of 3 stochastic distribution of risks and uncertainties for option 8*

Simulation results of the options 1 with 4 scenario and option 8 with 3 scenarios are shown in Table 50. Result shows that, considering risk and uncertitinies an AIGA people with native chicken rearing will not sustain with the flock size of 212, 237, even 262 which is 50 nos. more the deterministic number. In that case the Probability of loss are found at 100.00%, 100.00% and 84.50%. This option 1 is sustainable with the flock size at 287 which is 75 more than the deterministic number as it shows 0.00% probability of loss. Here, mean income is found at tk. 134108, Std. deviation is 716, Maximum and Minimum income is tk. 112956 and tk. 108235, Kurtosis is -0.1490 and Skewness is -0.1331. Similar result is found for option 8where flock size is more than the deterministic number with 0.00% probability of loss.

Table 25: Simulation results of the options 1 with 4 scenario and option 8 (target income= tk.121034.5)

Statistic	Option1 Only native chicken rearing				Option8 Grocery Shop + Native chicken rearing		
Scenarios: N=	212	237	262	287	73	98	123
Iteration	1000	1000	1000	1000	1000	1000	1000
Mean	89465	103769	118590	134108	110486	121226	132643
Std. deviation	2049	2224	2510	2782	716	927	1155
Maximum	95248	109931	127194	142560	112956	124279	135919
Minimum	83145	97547	110419	124428	108235	118479	129304
Kurtosis	-0.2002	-0.3403	-0.0002	-0.1490	0.0391	0.0630	-0.2190
Skewness	-0.1047	-0.0016	0.0157	-0.1331	-0.0244	0.1806	-0.0099
Coefficient of Variation, CV	2.2901	2.1431	2.1169	2.0747	0.6485	0.7648	0.8706
Confidence level (95%)	401.57	435.87	492.04	545.33	140.43	181.71	226.33
Upper value	89867	104205	119082	134653	110627	121408	132870
Lower value	89064	103333	118098	133562	110346	121045	132417
Jarque-Bera	3.4953	4.8268	0.0413	3.8774	0.1629	5.6035	2.0141

Source: Author's own calculation, 2024;

Therefore, sub sectoral AIGA should be more than the break-even number for sustaining the livelihoods. Recommended Strategy for AIGA Implementation may would be-

- Avoid reliance on a single AIGA to mitigate risks.
- Test AIGAs on a small scale before wider adoption.
- Continuously assess ecological and economic impacts.
- Integrate AIGAs into broader conservation goals, such as REDD+ initiatives.
- Engage NGOs, government bodies, and private sector players for funding and training.

By addressing these factors, Bangladesh can implement viable AIGAs that simultaneously promote forest conservation and improve community livelihoods, which also have come constraints.

4.6. Constraints to sustainability of AIGAs

The constraints to the sustainability of Alternative Income Generating Activities (AIGA) in the forest ecosystems of Bangladesh are multifaceted and involve a range of environmental, economic, social, and institutional challenges. Despite the potential benefits of AIGAs, such as reducing dependence on traditional forest-based livelihoods and promoting conservation, several factors hinder their long-term sustainability in forest ecosystems.

4.6.1. Major problems

To analyses the measures, the study identified existing constraints in the forest dependent communities in Bangladesh's forest ecosystems. The constraints are then categorized to six groups, are environmental constraints, economic constraints, social constraints, institutional constraints, technical constraints, and political constraints, shown in Table 51, below.

Table 26: Constraints to Sustainability of AIGA

Constraints	Variable	Definition and measurement	Mean	StdErr	StdDev
Environmental Constraints	Var_climate	Climate change impacts	4.064	0.169	1.170
	Var_diversity	Depletion of species diversity	2.122	0.129	0.897
Economic Constraints	Var_**finance**	**Limited access to financial resources**	4.157	0.134	0.929
	Var_markets	Dependence on local markets or small-scale value chains	4.742	0.317	2.195
	Var_price	Price volatility	3.724	0.144	1.000
	Var_**transaction**	**High transaction costs**	4.042	0.094	0.650
Social Constraints	Var_**Culture**	**Community and cultural resistance**	2.355	0.139	0.965
	Var_**gender**	**Gender inequality**	3.071	0.148	1.023
	Var_skills	Lack of technical skills and knowledge	4.983	0.065	0.449
Institutional Constraints	Var_governance	Lack of strong governance structures and effective law enforcement	2.929	0.150	1.038
	Var_**Institute**	**Fragmented policy and institutional support**	1.427	0.117	0.812
	Var_**support**	**Lack of long-term support**	4.959	0.045	0.311
Technical Constraints	Var_technology	Lack of access to modern technologies	4.081	0.053	0.364
	Var_**practice**	**Overdependence on traditional practices**	2.007	0.052	0.359
Political Constraints	Var_**land**	**Land tenure and ownership issues**	3.989	0.027	0.185
	Var_**policy**	**Policy instability**	1.003	0.003	0.021

Source: Author's own calculation, 2024

The study is used Wilcoxon sign-rank test to examine the constraints to the sustainability of Alternative Income Generating Activities (AIGA) in the forest ecosystems of Bangladesh. The data of the constraints to the AIGA consists of a categorical scale which represents the importance of the identified constraints' factors. The important category is expressed from not at all important (scale=1), somewhat important (scale=2), important (scale=3), very important (scale=4), and extremely important (scale=5). Thus, the average score is 3.00 based on likert-scale. Figure 15 shows the scatter plot of constraints indicating normal distribution.

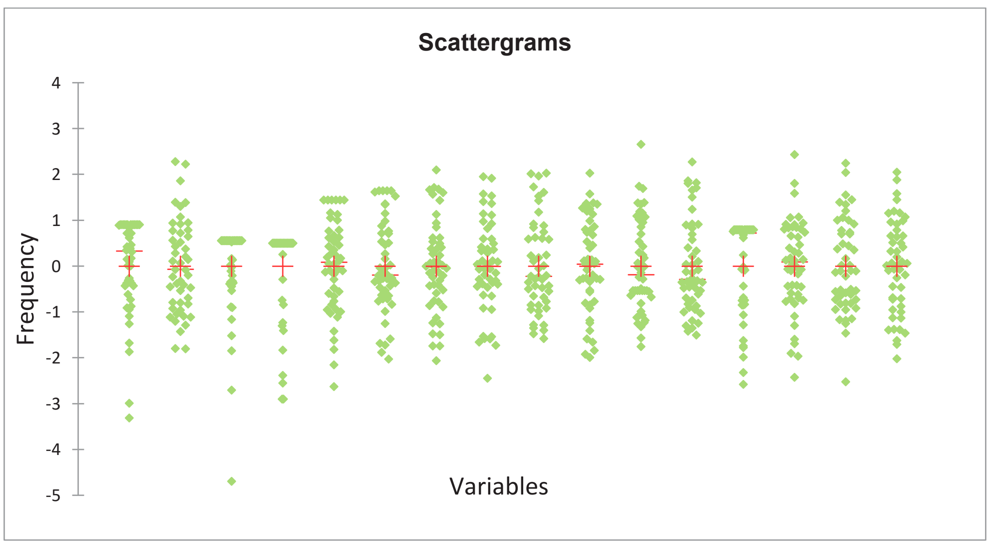

Figure 11: *Scatter plot of distribution of constraints to sustainability of AIGA*

From the analysis of the interview results, sixteen (16) statements are identified as constraints to the sustainability of AIGA, shown in Table 52. Score results of the constraints indicated that fourteen (14) constraints are significant, of which, nine (9) are found at higher than average score (3.00) followed by five (5) are found at lower.

Table 27: Mean important scores of constraints motivating to contract sale

Constraints	Mean score	Prob >|t|
Var_skills	4.983***a	0.000
Var_support	4.959***a	0.000
Var_markets	4.742***a	0.000
Var_finance	4.157***a	0.000
Var_technology	4.081***a	0.000
Var_climate	4.064***a	0.000
Var_transaction	4.042***a	0.000
Var_land	3.989*a	0.090
Var_price	3.724***a	0.000
Var_gender	3.071	0.316
Var_governance	2.929	0.680
Var_Culture	2.355**b	0.010
Var_diversity	2.122***b	0.000
Var_practice	2.007***b	0.000
Var_Institute	1.427***b	0.000
Var_policy	1.003***b	0.000

Source: Author's own calculation, 2024

a: *Mean score indicated significant higher mean than 3 (average score) on the basis of a Wilcoxon sign-rank test.*
b: *Mean scores indicated significant lower mean than 3 (average score) on the basis of a Wilcoxon sign-rank test.*
* *Significant at the 10% level;*

** *Significant at the 5% level;*

*** *Significant at the 1% level.*

Regarding higher mean score, eight (8) constraints i.e. Var_skills, Var_support, Var_markets, Var_finance, Var_technology, Var_climate, Var_transaction, and Var_price are found significant at 1% level, while only Var_land is found at 10% level.

On the other hand, among the lower mean scores, four constraints i.e. Var_diversity, Var_practice, Var_Institute, and Var_policy are found significant at 1% level, while Var_Culture is found significant at 5% level.

Lack of technical skills and knowledge (Var_skills) is found as a major issue (score=4.983) to sustainability of AIGA. Lack of technical skills and knowledge about sustainable practices for new AIGAs is a common constraint. Many forest-dependent communities have limited access to training in alternative agricultural practices, eco-friendly techniques, or value-added processing (e.g., packaging or branding). This lack of capacity-building and technical assistance makes it difficult for rural populations to succeed in more diverse or specialized AIGAs.

Lack of long-term support (Var_support) is also very impotant (4.959). Many AIGAs are implemented as short-term projects with limited sustainability. Inadequate follow-up support, monitoring, and evaluation after initial implementation often result in a lack of long-term success. Without sustained technical support, market linkages, and financial services, AIGAs fail to develop into sustainable businesses or practices, leading to the eventual abandonment of these activities.

Dependence on local markets or small-scale value chains (Var_markets) consists score at (4.742). AIGAs in forest ecosystems often depend on local markets or small-scale value chains. However, the lack of reliable market access, infrastructure, and fair pricing mechanisms makes it difficult for communities to maximize income from their activities.

Limited access to financial resources (Var_finance) is a constraints (4.157), like many rural communities in Bangladesh have limited access to financial resources and credit. This hampers their ability to invest in or expand alternative livelihoods, such as setting up sustainable farming systems or businesses that rely on forest resources. While some microfinance programs exist, they often fail to meet the specific needs of forest-dependent communities or are inaccessible due to bureaucratic hurdles or lack of financial literacy.

Lack of access to modern technologies (Var_technology) also an majore issue (4.081). Communities may lack access to modern technologies that could help improve the productivity, efficiency, and sustainability of alternative livelihoods. For example, the lack of access to better farming techniques, processing technologies for NTFPs, or renewable energy solutions (e.g., solar-powered irrigation) hinders the scalability of AIGAs. Without access to appropriate tools, techniques, and training, the productivity and profitability of AIGAs remain limited.

Climate change impacts (Var_climate) is very important issue (4.064). Climate change impacts, such as irregular rainfall patterns, rising temperatures, and extreme weather events (e.g., floods, droughts, and cyclones), affect forest productivity and the availability of resources required for AIGAs. Changes in weather patterns also affect crops, livestock, and other resources that are integral to alternative livelihoods, disrupting the stability of AIGAs.

High transaction costs (Var_transaction) is an issue with score of (4.042). The high cost of transportation, marketing, and accessing suppliers for alternative livelihood inputs increases the operational costs for rural producers. This discourages investment in higher-value AIGAs such as ecotourism, handicrafts, or agroforestry.

Land tenure and ownership issues (Var_land) also agreat concern (3.989). Land tenure issues remain a major constraint in the sustainable management of forest resources. Without clear ownership or legal access to forest land, communities are often hesitant to invest in long-term sustainable practices for fear of losing their land rights or access to resources. Disputes over land ownership and the encroachment of commercial interests into forest areas can lead to conflicts that undermine the implementation of AIGAs.

Price volatility (Var_price) is positive but least constraint (3.724). Price volatility, especially for NTFPs like honey, bamboo, or medicinal plants, makes it challenging for households to plan and stabilize their income over time.

Among the lower mean scores, Community and cultural resistance (Var_culture) is major concern (2.355). Some communities may have cultural or traditional attachments to forest-based livelihoods (e.g., fishing, logging, or fuelwood collection). Transitioning to alternative livelihoods may face resistance due to these cultural practices and beliefs. Lack of awareness about alternative income-generating opportunities or inadequate community involvement in decision-making processes can lead to reluctance in adopting sustainable AIGAs.

Depletion of species diversity (Var_diversity) is also an issue (2.122). The depletion of species diversity in forest ecosystems (including plants, animals, and insects) limits the potential for sustainable AIGAs like eco-tourism, wildlife-based products, and biodiversity conservation activities. Loss of key species, such as certain medicinal plants or fish species, reduces opportunities for communities to generate income.

Overdependence on traditional practices (Var_practice) is a graet issues 2.007). Traditional practices that are not aligned with sustainable resource management (e.g., slash-and-burn agriculture or unsustainable harvesting of forest products) can undermine the potential of AIGAs. Communities may lack awareness of more sustainable, modern practices that can help diversify their income while preserving forest ecosystems.

Fragmented policy and institutional support (Var_Institute) least but important issue (1.427). There is often a lack of coordination among government agencies, NGOs, and local communities regarding the development of AIGAs in forest ecosystems. This fragmented approach leads to inefficiencies and gaps in the support provided to rural communities.

Policy instability (Var_policy) is a common constraint (1.003). Shifts in government policies, especially regarding forest management, land use, and community rights, can disrupt the continuity of AIGA initiatives. Policy changes can lead to uncertainty, limiting the confidence of local communities to invest in and sustain alternative income activities. Inadequate integration of community needs in national forest policies leads to dissatisfaction and a lack of commitment to long-term sustainability from local stakeholders.

Overcoming these challenges requires a holistic approach that combines community empowerment, capacity building, improved governance, stronger market linkages, and long-term financial and technical support. Effective policy frameworks, integrated forest management practices, and a focus on gender inclusivity will be key to ensuring the success and sustainability of AIGAs in these ecosystems.

4.6.2. Deep-dive to problems facing by AIGA-HHs in FDCs

Overall, in the Forest Ecosystems the top-ten problems are Lack of capital contributing (24.57%) of the total, then Natural hazard contributing (2.59%), then Poverty status/poor HH contributing (15.95%), then Lack of place for livestock rearing/crop production contributing (10.34%), then More diesease but no proper remidies and vaccin contributing (3.88%), then Lack of proper transportation facility contributing (1.29%), then Lack of suitable market and marketing system contributing (7.76%), then Lack of training and guidelines contributing (7.33%), then Higher input price contributing (1.72%), and Lack of subsidy or low rate debt contributing (2.59%).

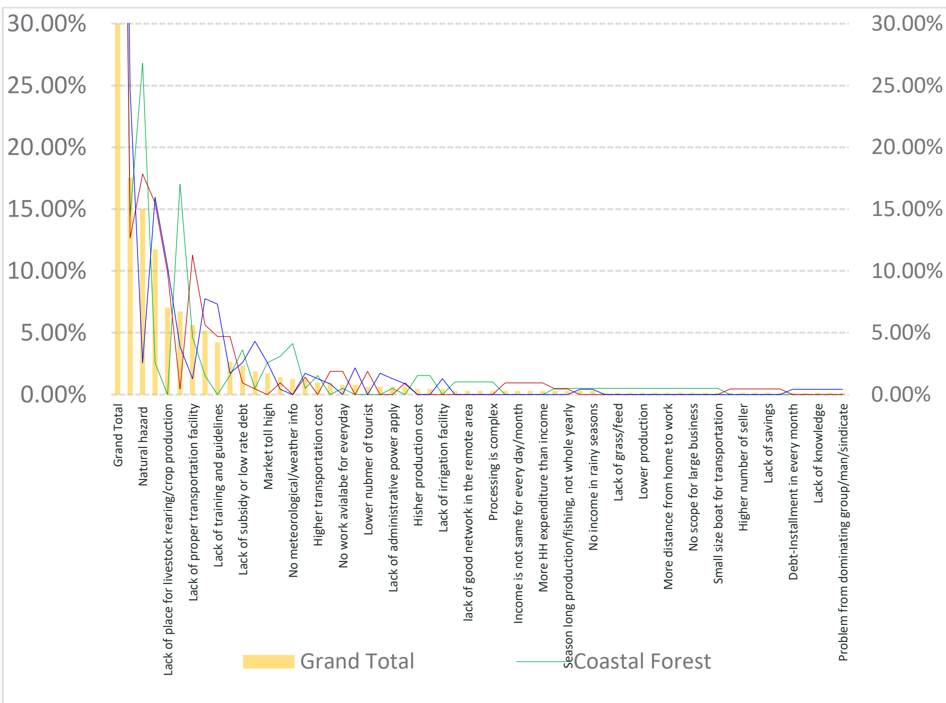

Figure 12: *Problems facing by AIGA-HHs in FDCs*

4.7. Conclusions and policy suggest

4.7.1. Summary

A number of studies of different AIGAs for forest ecosystems have been done in country and abroad and investigated forest people's livelihood, contributions, returns, production, sustainability, risks' effects as well as factors to expansion of AIGAs and their marketing systems.

Based on the research questions, total eight (8) districts: Dhaka, Mymensingh, Tangail, Sylhet, Chattogram, Cox's Bazar, Bhola and Patuakhali have been selected purposively for the study area.

Before sampling design for this research, at first we the research team preliminary visited study fields/areas.

Preliminary Field visit and review of SUFAL documents showed that the SUFAL project considered 4 broad categories of AIGAs, namely Production (crops, fisheries & livestock based AIGAs), Processing (cap making, handicraft, etc.), Trade (retailing, wholesaling, etc.) and Services (barbering, etc.).

Using Probability Proportional to Size (PPS) sampling technique the samples are distributed to selected 8 districts of 3 ecosystems respectively.

A Methodology Validation Workshop for the research project has been conducted. The Title was "Methodology Validation Workshop". Chief Guest was Md. Amir Hossain Chowdhury, Chief Conservation of Forest. Chairperson was Mr. Gobinda Roy, Project Director, SUFAL Project. Venue was Karobi Hall, Bana Bhaban, Agargaon, Dhaka. Date was 02/04/2024.

the coverage of the AIGAs regarding sub-sector specific as per descending order were calculated at 86.46%, 84.09% and 74.28% for coastal forest, hill forest and sal forest, respectively whereas for total rate of three forest was gained 82.53%. Similarly, it were 11.92%, 10.26%, 2.41% and 82.53% for the trade specific AIGAs, respectively. It were also estimated at 6.06%, 0.77%, 0.20% and 1.87% for the processing/cottage specific AIGAs, and 13.60%, 5.08%, 4.89% and 6.80% for service specific AIGAs, respectively.

The PCA shows that the component1 contributes highly to Chicken farming, Duck farming, Cow rearing, and Goat rearing, while component2 contributes most to Shop (grocery/tea stall/pharmacy/hotel/street-food/cosmetics) and Auto rickshaw/rickshaw van/ tom-tom /motor cycle rent/ boat/ cycle garage. Here, Mobile/TV/fridge/electric repair servicing /wielding/masonry/decoration services is contributes in component3.

Agro-based AIGAs such as poultry (native chicken, ducks, and pigeons), livestock (goats, cows), crop farming, and aquaculture are vital in forest ecosystems.

The gross return for native chicken rearing is calculated at tk. 63200.6, while the gross margin and net margin stood at tk. 21875.5 and tk. 20148.9 per month respectively, indicating that in the HH in the study area is profitable. The undiscounted benefit-cost ratio is found at 1.53, showing that for every tk.1.00 investment on operating a grocery shop, people can received tk. 1.53 in a circle.

The actors in the value chain of the native chicken in the three forest ecosystem's farmers to central consumers are (i) forest area market actors: neighbor consumer, family consumer, faria, bapari/local trader, local arotdar, retailer, local rural consumer; (ii) regional market actors: wholesaler, retailer, hawker, local urban consumer; and (iii) central market actors: central arotdar, supplier, retailer, hawker, processor, super shop, central consumer. The actors in the value chain of the native chicken in the three forest ecosystem's farmers to central consumers are (i) forest area market actors: neighbor consumer, family consumer, faria, bapari/local trader, local arotdar, retailer, local rural consumer; (ii) regional market actors: wholesaler, retailer, hawker, local urban consumer; and (iii) central market actors: central arotdar, supplier, retailer, hawker, processor, super shop, central consumer.

Value-chain map indicating that farmers have four options to sold to local arotdar of forest area market at tk. 597, wholesaler of regional market at tk. 604, central arotdar of central market at tk. 610 and supplier of central market at tk. 617 which are 2.21%, 3.33%. 4.41%, and 5.56% increasing from the base price. At base price, the margin of farmers is found at tk. 171, and considering this, the option price margin will increase to 6.03%, 9.95%, 13.50%, and 15.49%, respectively.

Costs and returns also estimated of six non-sectoral AIGAs, are: grocery shop in market, tea stalling in market, fish retailing business, chicken meat processing retail shop business, tom-tom/rickshaw and TV/mobile/electric servicing.

Total cost (TC) of a grocery shop estimated at tk. 57132.9. The undiscounted benefit-cost ratio is found at 1.18, showing that for every tk.1.00 investment on operating a **grocery shop**, people can received tk. 1.18.

Estimated income from the above result tables are summarized that a AIGA people living in the forest dependent community under Sal-forest, Hill-forest and Coastal-forest ecosystems in Bangladesh earned tk. 19841.50 as his/her income for one year from 50 Chicken rearing in their households. This amount under sub-sectoral AIGAs are tk. 5017, tk. 238301, tk. 154851, and tk. 25054, from 35 Duck rearing, 20 Pigeon rearing, 3 Cow rearing, and 5 Goat rearing, respectively. Among the non-sectoral AIGAs the Trade specific AIGAs are Grocery Shop, Tea Stalling and Fish retailing resulted the income amount at tk. 88843.85, tk. 144171.06, and tk. 327120.97, respectively. Under Processing specific AIGAs people can earn tk. 100249.66 from Meat Processing retail shop business. Tom-tom/rickshaw pedaling and TV/mobile/electric servicing business are Service Specific AIGAs by which forest dependent people can earn income about tk. 205292.25 and tk. 117250.90, respectively.

Thus, income earned from AIGAs under SUFAL Project is about tk. 1190.08 crore. This amount is direct impact of AIGA intervention on the FDC's HH income. There is also follow-up income means non-projected people taking decision to follow the activities as a sustainable better alternatives for their livelihoods. The follow-up income for AIGA is estimated at tk. 2169.02 crore.

Most of HH in the forest ecosystems (25.71%) are with 5 members, while nationally 4 members family is more about 30.30% (Population and housing Census, 2023). Male and female is almost same i.e. 2.58 and 2.51, respectively.

The total expenditure was estimated at tk. 21867.2 which is lower than the national figure (26842) according to HEIS-2022. Based on field survey, it was also estimated that people cover tk. 2,430.9 from their own source, thus they need to purchase items by tk. 19436.32.

The average size of households stood at 5.09 for three forest ecosystems, and the average household expenditure per month is tk. **21867.2** in 2024 means annually tk. **262406.4**. The result from the study emphasizes the fact that for five-member households in the forest ecosystems in Bangladesh, the annual income should be at least Tk. **262406.4** per year. Since HHs recover tk. 29170.6 from their own source and tk. 112201.3 earn from different non-AIGA income sources per year, thus, if a family earns remaining amount of expenditure tk. 121034.5 per annum from any AIGA to cover the living cost of that family, he will cover his household living expenditure, and therefore, the AIGA will be sustainable. He will reduce their dependency on forest ecosystems.

it is identified that only the AIGAs on Cow rearing, Fish retailing business, and Tom-tom/rickshaw pedaling return more or equal income of that amount, individually.

In the non-sub-sectoral context, the study found that only the option of Duck rearing with Meat Processing is not feasible. Except this, all other options of combinations of sub-sectoral AIGAs with any non-sub-sectoral AIGAs are feasible earn required income.

If a farmer want to operate only a single sub-sectoral AIGA at small scale for living their livelihoods is a sustainable manner, he/she should take decision for chicken rearing or Cow rearing, only. Ant the flock and herd size should be minimum 212 and 3, respectively in the case of soled to nearest forest market. If they can create a link to Regional Market and Central Market for Chicken rearing the flock size will be minimum 199 and 195, respectively.

For single AIGA of Duck rearing, Pigeons rearing, and Goat rearing the size is higher than their capacity. In that case they can take a decision for double AIGA at a time.

the study identified 15 sustainable options for given quantity and 36 options for any quantity of flock/herd sizes. Five options are single AIGAs. Two options are related to sub-sectoral double AIGAs. Regarding sub-sectoral with non-sectoral AIGA the study found 7 options.

The study found seven risk and uncertainties on AIGAS, are purchase price, price of feed, labour wage, repairing cost by climate hazards, transportation cost by market distance, sale price, and mortality rate.

Regarding higher mean score, eight (8) constraints i.e. Var_skills, Var_support, Var_markets, Var_finance, Var_technology, Var_climate, Var_transaction, and Var_price are found significant at 1% level, while only Var_land is found at 10% level.

On the other hand, among the lower mean scores, four constraints are Var_diversity, Var_practice, Var_Institute, and Var_policy are found significant at 1% level, while Var_Culture is found significant at 5% level.

In the Forest Ecosystems the top tem problems are Lack of capital contributing (24.57%) of the total, then Natural hazard contributing (2.59%), then Poverty status/poor HH contributing (15.95%), then Lack of place for livestock rearing/crop production contributing (10.34%), then More diesease but no proper remidies and vaccin contributing (3.88%), then Lack of proper transportation facility contributing (1.29%), then Lack of suitable market and marketing system contributing (7.76%), then Lack of training and guidelines contributing (7.33%), then Higher input price contributing (1.72%), and Lack of subsidy or low rate debt contributing (2.59%).

4.7.2. Recommendations and suggestions

The study reveals that only cow rearing, fish retailing business, and Tom-tom/rickshaw pedaling generate more or equal income. In non-sub-sectoral contexts, duck rearing with meat processing is not feasible. However, all other combinations of sub-sectoral AIGAs with non-sub-sectoral AIGAs are feasible. Farmers should choose chicken rearing or cow rearing for sustainable livelihoods. The study identified 15 sustainable options for flock/herd sizes and 36 options for any quantity of flock/herd sizes. Risks and uncertainties on AIGAs include purchase price, feed price, labor wage, repairing cost by climate hazards, transportation cost by market distance, sale price, and mortality rate. The recommended strategy for AIGA implementation is to avoid reliance on a single AIGA, test AIGAs on a small scale, assess ecological and economic impacts, integrate AIGAs into broader conservation goals, and engage NGOs, government bodies, and private sector players for funding and training.

4.7.3. Policy implications, guideline, and strategy

The proposed study will not formulate any policy on forest ecosystems, but identify measures for sustainable AIGAs, but will find out the exit plan for ongoing SUFAL project or next project activities to keep the AIGAs sustainable to reduce the FDC's reliance on forest ecosystems of Bangladesh.

It is expected to enhance the knowledge on livelihood of forest communities, their participation on alternative income generating activities (AIGAs), marketing systems of AIGA commodities, and the constraints that need to be addressed essentially and effectively. The study will identify the measures for sustainable AIGAs, by which SUFAL as well as forestry will take the right decision in taking initiatives in formulating policy with the ultimate goal of protection of Bangladesh's forest ecosystem.

The proposed study will not formulate any policy on forest ecosystems, but identify measures for sustainable AIGAs. The Forest Policy 2016 (draft) proposed some mitigation and adaptation policies and practices (section 5.4) for protection of Bangladeshi forest ecosystems, where distinct focus issues were on natural forests (sal forest, hill forest and mangroves), forest communities, AIGAs, and market value chains. Special consideration also focuses on exit strategy (section 5.4.18) in terms of project implementation. Considering the stated issues, the research will identify what sustainable measures need to be included in the forest policy. The identified measures also will be helpful to design exit plan/strategy for SUFAL projects to keep their AIGAs sustainable in the long run.

Through these findings the project will help in the development of skills and knowledge in both DAE and BFD stakeholders. The scientific training of the research team and the resultant reports will cover the latest methods in AIGA's livelihood sustainability, market linkages, value chain, survey design, data handling and analysis. Handbooks, articles and project reports will offer a valuable accumulation of knowledge documents which the BFD staffs, DAE, donor agencies, Bangladesh Forest Research Institute, Universities, IUCN, and international collaborators can use for further research ecosystem management and biodiversity conservation and for effective decision making in Sal, Hill and Coastal forests resource management.

4.7.4. Limitations and Further research

This study was not designed to reveal every aspect of AIGs for forest ecosystems, therefore, in spite of the significance of this research, it is worthwhile to recognize some limitations. Firstly, the study incorporated only five AIGAs regarding sub-sectoral for only three forest ecosystems which enable further study with additional options in relation to AIGAs using data from other parts of the country.

Secondly, the study used a cross-sectional data that tracks the experience of the farmer at a given time. But the motivation of AIGA farmers' participation is a dynamic phenomenon which changes over time. As a consequence, further research is recommended for considering the time-varying dimensions of factor relationships. Other research also could generate valuable panel data by using the survey data from this study as a baseline and re-interviewing the AIGA farmers who participated in this study; thus, the livelihood sustainability of AIGA could be measured in a more stable way.

Thirdly, the study assessed viability only from AIGA farmers' viewpoint. To identify whether gap exist between farmers and buyers, future research is suggested to measure this dimension from buyers' viewpoint.

Research could also focus on tracing and analyzing the constraints to improving the profitability, viability, and inclusivity of AIGA.

Lastly, this research did not have detailed asset data for previous years to determine whether changes in assets could be attributed to participation in the marketing contracts.

Therefore, other studies with more rigorous analysis are recommended to address the limitations.

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Determining soil respiration rate and assessing abundance of microbial composition in rhizosphere of Sal (Shorea robusta Gaertn.) and selected associates tree species of Sal Forests, Bangladesh.

by

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CHAPTER I

1 INTRODUCTION

1.1 Background and context

The Sal Forests have a reasonably huge but interrupted distribution within the drier central and northerly parts of mainland of Bangladesh. Those Forests in most cases arise within the Gazipur, Tangail, Mymensingh, Sherpur, Cumilla, Dinajpur, and Rangpur districts. A maximum of the Sal Forests lies inside the districts of greater Mymensingh and Tangail, the most important belt, also known as "Madhupur Garh" (Banglapedia 2008).

About 86% of Sal Forest land is located in this central part and the leftover 14% of Sal Forest belongs to the northern part of the country (Alam *et al.*2008). The Sal Forest ecosystem supports a wealthy and diverse variety of flora which incorporates 221 plant species (Green 1981, Khan 2007).

The structure and composition of Forests are strongly related to topographic factors (Currie 1991). Phyto-sociological analysis helps in understanding the structure and composition of plant communities (Braun-Blanquet 1965) and thus have huge implications in the conservation and management of Sal Forests (Campbell 1994).

Soil respiration refers to the production of CO_2 through the biological movement of soil organisms, which include plant roots, microbes, and soil animals (Martin Rubio and Rodriguez 2017).

Soil respiration is a fundamental system for the flow of carbon in Forest ecosystems. A big amount of carbon is launched into the environment as CO_2 during the decomposition of litter and CO_2 is also launched through the respiration of living roots (Bowden 1993).

The rhizosphere generally refers to the portion of soil found adjacent to the roots of living plants and the width of the rhizosphere zone has been shown to extend from 2 to 80 mm or 8cm away from the root surface (Koo *et al.*2005).

The microbial population is usually better in rhizosphere soil than in bulk soil and is species specific. Rhizosphere soil comprises several assemblies of microorganisms. Microorganism produces a few chemical materials that have an influence on the growth and improvement of the plant and vice-versa.

Different workers have concentrated in part on this subject matter but in the context of Bangladesh's Sal Forests, data is also not available representing works especially about microbial diversity and respiration of rhizosphere soil have been done in relation to Sal and Sal associates tree species.

Authentic research work is required inside the Sal Forests to find out the linkage between plants and rhizosphere soil respiration rate and microbial composition to understand the function of Sal Forest ecosystems. It will increase our expertise in the ecosystem function of Sal Forests which would assist to formulate proper management policy and conservation of this vital Forest by emphasizing the protection of keystone plant species.

1.2 Problem statement

Bangladesh is additionally one of the most densely populated countries in the world with limited natural Forest area. Increased population, rapid industrialization, and urbanization have created pressure on the natural Sal Forests (Kashem *et al.* 2015) and caused change in species composition (Ahmed *et al.* 2015).

Central regions of the Sal Forests have been decreased due to some natural calamities and anthropogenic activities, consequently the community structure of Sal Forests is being changes (Ahmed *et al.* 2015) that are subsequently changing the population structure of micro flora of soil, while authorities try to reforest the areas with some fast-growing species (Hossain 2005).

The knowledge on soil respiration rate and microbial composition in rhizosphere and their relationship with Sal and Sal associates tree species, and the carbon sequestration potential of different tree species, the right tree species selection for a given site for maintaining a healthy balance of carbon storage and release, and soil quality and health which can lead to the plant productivity of Sal and associates tree species of Sal Forests are still inadequate in Bangladesh.

Plants and soil biota have a strong functional relationship as they are the primary producers and decomposers (Wardle 2002). Organic carbons and nitrogen are provided by the plants for the biota of the soil through litter and root exudates whereas microbial communities release carbon and nitrogen that are essential for the growth of plants.

The effects of Sal and Sal associates tree species on the diversity of rhizosphere soil microbial communities and relationship with rhizosphere soil respiration have not been focused by many studies. Despite its importance in the Forests, Forests species and biodiversity, and habitat conservation, no substantial data is available in the relevant field in Bangladesh. A proper research work in the Sal Forests is essential to make sure concrete findings.

1. 3 Objectives

1.3.1 Specific objectives are as follows:

1. To quantify rhizosphere soil respiration rate of Sal and selected associates tree species of Sal Forests.
2. To analyze the abundance of microbial (Bacterial and Fungal) composition in the rhizosphere soil and their relationship between different selected tree species of Sal Forests.
3. To provide conservation recommendations towards rhizosphere soil respiration rate for Sal Forests.

1.3.2 Research questions are as follows:

1. What are the rhizosphere soil respiration rates of Sal and selected associates tree species of Sal Forests?
2. What is the abundance of microbial (Bacterial and Fungal) composition in the rhizosphere soil of different selected tree species of Sal Forests and how they vary?
3. What are the relationships among rhizosphere soil respiration rate, selected tree species and microbial composition in Sal Forests, and how can the findings of this study be applied to improve Forest management practices and conservation efforts for Sal Forests?

CHAPTER II

2. LITERATURE REVIEW

2.1 Existing literature review

Soil respiration refers to the production of CO_2 by the biological activity of soil organisms, making it a critical component of carbon flux in forest ecosystems (Martín Rubio & Rodríguez, 2017). Large amounts of carbon are released into the atmosphere as CO_2 during litter decomposition, alongside CO_2 emissions from living organisms' respiration (Bowden *et al.*1993). Soil respiration plays a significant role in the global carbon cycle, contributing approximately 50-75% of total terrestrial respiration (Zhou *et al*. 2012).

Soil respiration is often used as an indicator of soil quality and fertility (Haney *et al*. 2008). The rhizosphere, defined as the soil zone adjacent to plant roots, can extend from 2 to 80 mm or 0.2 to 8 cm from the root surface (Koo *et al*. 2005). Despite its importance, research on rhizosphere soil respiration in Bangladesh is scarce, with limited available data. (Propa *et al*. 2021) detailed soil sampling procedures for measuring rhizosphere soil respiration in Sal forests and explored relationships with environmental variables.

Rahman and Vacik (2010) analyzed plant species distribution in protected areas, finding that Sal (*Shorea robusta*) accounted for 98.5% of the core zone in Bhawal National Park and 59.5% in Madhupur National Park. Similarly, Wu *et al*. (2016) examined microbial community abundance in the rhizospheres of various mangrove species, emphasizing their role in mangrove ecosystem productivity. Shao *et al.* (2021) further demonstrated that rhizosphere soil respiration and microbial communities are significantly influenced by deciduous tree species.

Anderson (1982) was among the first to describe soil as a complex ecosystem teeming with organisms that release CO_2 through organic matter oxidation. Measuring CO_2 evolution provides a reliable means of quantifying soil respiration (Rs), with chemical titration offering a useful approach for comparing microbial activity across different soils. Haney *et al.* (2008) proposed an equation for calculating soil CO_2 respiration in mg CO_2 per g soil.

Recent studies have further explored the environmental and biological factors influencing soil respiration. Castaño *et al.* (2017) found that seasonal variations in soil moisture and temperature significantly impact the ectomycorrhizal fungus *Lactarius vinosus*, which, in turn, influences soil respiration. Similarly, Castanha *et al.* (2018) demonstrated that soil heating, rhizosphere presence, and depth regulate root litter decomposition through moisture mediation.

In tropical and subtropical regions, precipitation patterns strongly influence soil respiration. Chakravarthy *et al.* (2024) observed correlations between soil respiration, rainfall, and soil moisture at multiple temporal scales in a seasonal wet tropical forest. Talukder *et al.* (2016) also highlighted the impact of rainfall on sediment organic matter distribution along Bangladesh's Chittagong Coast.

Microbial communities in the rhizosphere play a crucial role in soil respiration dynamics. Wan *et al*. (2019) reported that organic matter manipulation alters seasonal microbial composition and enzyme activities in subtropical forests, while Wang *et al*. (2019) found that soil moisture modulates microbial control over carbon decomposition. Additionally, Ulbrich *et al.* (2022) noted that root exudates and rhizosphere bacterial communities shift depending on plant-neighbor context, suggesting complex interactions between plant species and soil microbes.

Soil respiration is also affected by tree species composition and litter decomposition. Makita and Fujii (2015) demonstrated that microbial respiration rates differ depending on the tree species from which decomposing leaves and fine roots originate. Tomar and Baishya (2020) further highlighted that seasonal variation and moisture regimes regulate soil respiration, enzyme activity, and microbial biomass carbon in semi-arid forests.

The interactions between soil microbes, root exudates, and plant growth further illustrate the complexity of soil respiration. Macías-Rodríguez *et al.* (2018) found that *Trichoderma atroviride* enhances tomato plant development by altering root exudation patterns, which in turn stimulate beneficial fungal growth and bio-control activity.

Lastly, soil structure and organic carbon content also influence respiration rates. Mestdagh *et al.* (2006) reported that variations in organic carbon concentration and bulk density impact respiration rates in Flemish grassland soils, demonstrating the importance of soil physicochemical properties in carbon cycling.

These findings collectively underscore the complexity of soil respiration, influenced by a combination of biological, chemical, and environmental factors. Understanding these dynamics is crucial for assessing soil health, carbon sequestration, and overall ecosystem function.

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CHAPTER III

3. METHODOLOGY

3.1 Study areas

3.1.1 Location of study areas

Naturally mostly grown Sal forests are situated in the central part of Bangladesh. The study was carried out in the Sal dominating two National Parks of the central part of Bangladesh. Among the two study sites of the research project, the first site namely Madhupur National Park (23º50'N-24º50'N and 89º54'E-90º50'E) is located in Tangail, and Mymensingh Districts with an area 8436.13 ha. The second site namely Bhawal National Park (23º55′N-24º00′N and 90º20′E-90º25′E) is located in Gazipur District with an area 5022 ha (Figure 1).

3.1.2 Climate of study areas

The climate of both parks is generally moderate. The temperature rises up to 37 °C in May and drops down to minimum 10 °C in January. Average temperatures were recorded at 25.4 °C and the average total rainfall was estimated at 2366 mm (Salam and Pramanik, 2018). June to September is the monsoon season with the most rainfall. The humidity varies between 60 and 86%, the duration of sunshine ranges from 5-9 hours and average maximum wind speed.

3.1.3 Topography of study areas

The topography of both parks comprises low and high land, while soil is poor in nutrients, acidic and red to brown in color (Rahman *et al*. 2010). The soils are also characterized by low organic matter and low fertility (Alam 1995). The soil is loamy, clay and sandy loam at various places. The altitude rises to 15 m (49 ft) above mean sea level. The topography of park is characterized by plain land or low hills locally known as 'Chalas', rising 3.0-4.5 m above the surrounding paddy fields, which are intersected by numerous depressions or ‘Baids’.

3.1.4 Vegetation of study areas

Phytogeographically both the parks belong to same agro-ecological zone and classified under tropical moist deciduous forests. *Shorea robusta* is the dominant species of these forests and usually forms 75% to 25% of the upper canopy in the natural habitat (Alam 1995). Floristic composition of different Sal forests indicated that these ecosystems have the richest plant diversity in Bangladesh. They are the habitats of different types of plants including tree, shrub, climber and herb (Alam 1995, Choudhury 2004). In past, both the parks were included within a continuous Sal *(Shorea robusta)* belt and consisted of same species composition (Alam 1995). With the increasing population both park areas are facing tremendous human pressures. Human pressure is more severe in Bhawal National Park than the Madhupur National Park due to its location near to the capital of Bangladesh (Rahman and Vacik 2009). The plants diversities of these parks are unknown to the outsiders and not well documented. On the other hand, there is no information whether the species composition and diversity of both parks are remaining on a comparable level like in the past or the parks show a different picture today.

Rahman and Vacik (2010) revealed that a total number of 129 species were recorded in the core zone of Madhupur National Park from which 65 were represented by tree species, 15 by shrub species, 26 by climbers and 23 by herbs. The Bhawal National Park inventory yielded a total of 43 plant species, out of which 22 were represented in the tree group, 10 in the shrubs group, 6 in the climbers group and 5 in the herbs group. Species overlap between Bhawal and Madhupur National Park was high 75% of Bhawal National Park.

The overall species composition revealed that both the national parks are dominated by *Shorea robusta*. Both the national parks were supposed to be mixed natural forests with a total share of 75% to 25% by Sal (*S. robusta*) and the rest by other deciduous species like *Adina cordifolia, Albizia procera, Bombax ceiba, Butea monosperma, Lagerstroemia parviflora, Dillenia pentagyna, Garuga pinnata, Hymenodictyon orixensis, Semecarpus anacardium, Miliusa velutina, Schleichera oleosa* (Ismail and Mia 1973).

The relative abundance of Sal (*S. robusta*) was 98.5% in the core zone of the Bhawal National Park, where 59.5% in the Madhupur National Park (Rahman and Vacik 2010).

3.1.5 Map of study areas

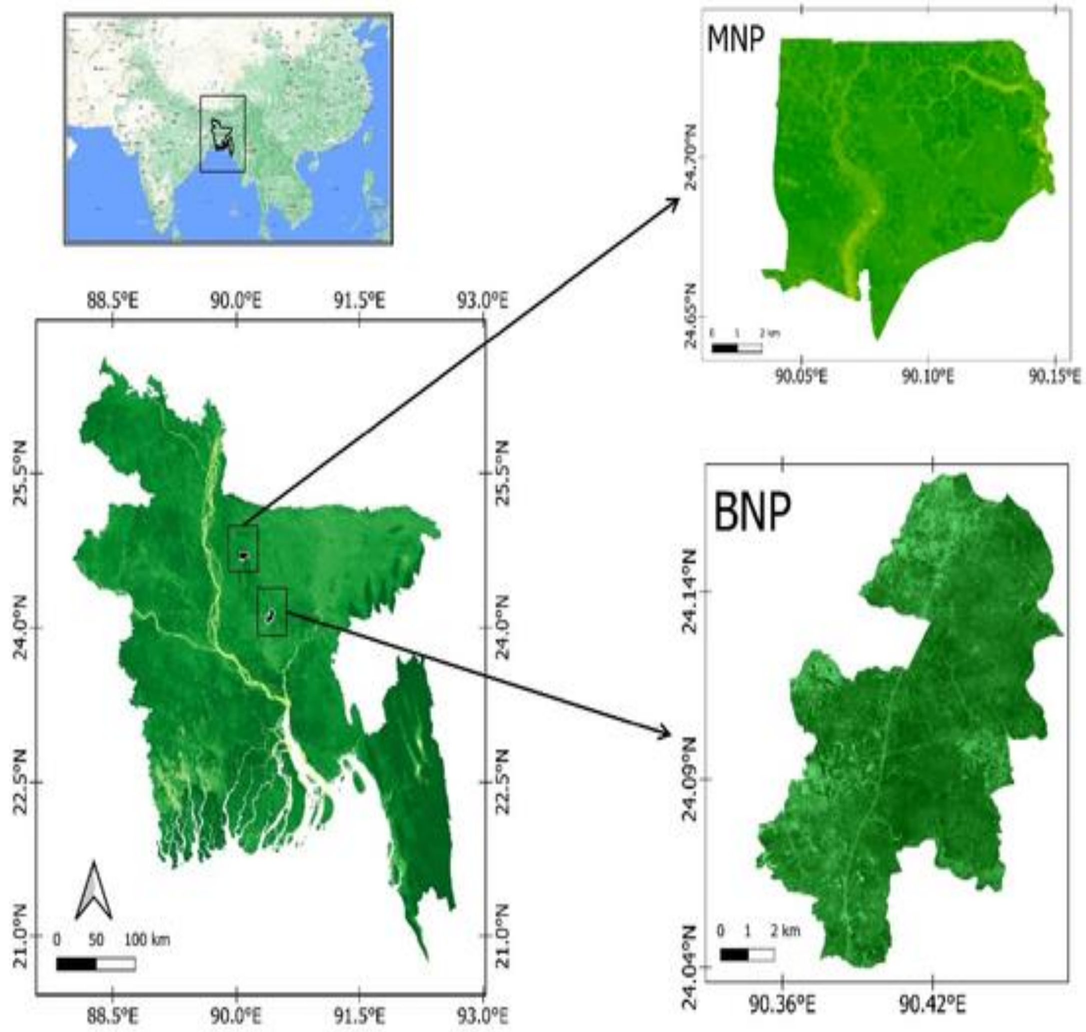

Figure 1. Location map of study area-Madhupur and Bhawal National Parks (Source: M.R.Karim *et.al* 2022).

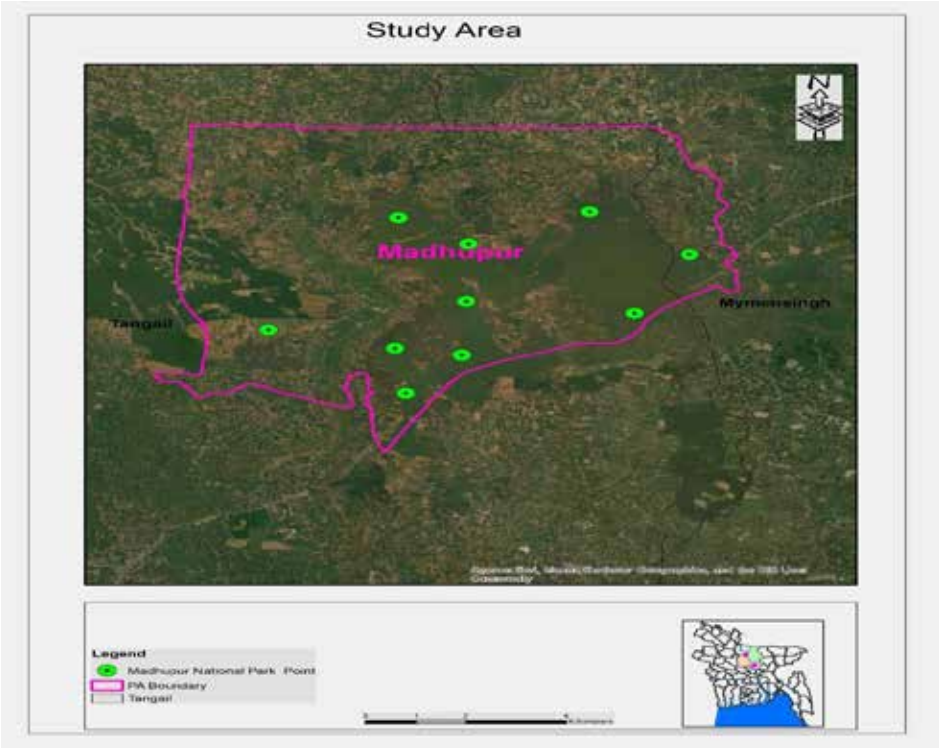

Figure 2a. Map of the study area -Madhupur National Park with Sampling Locations.

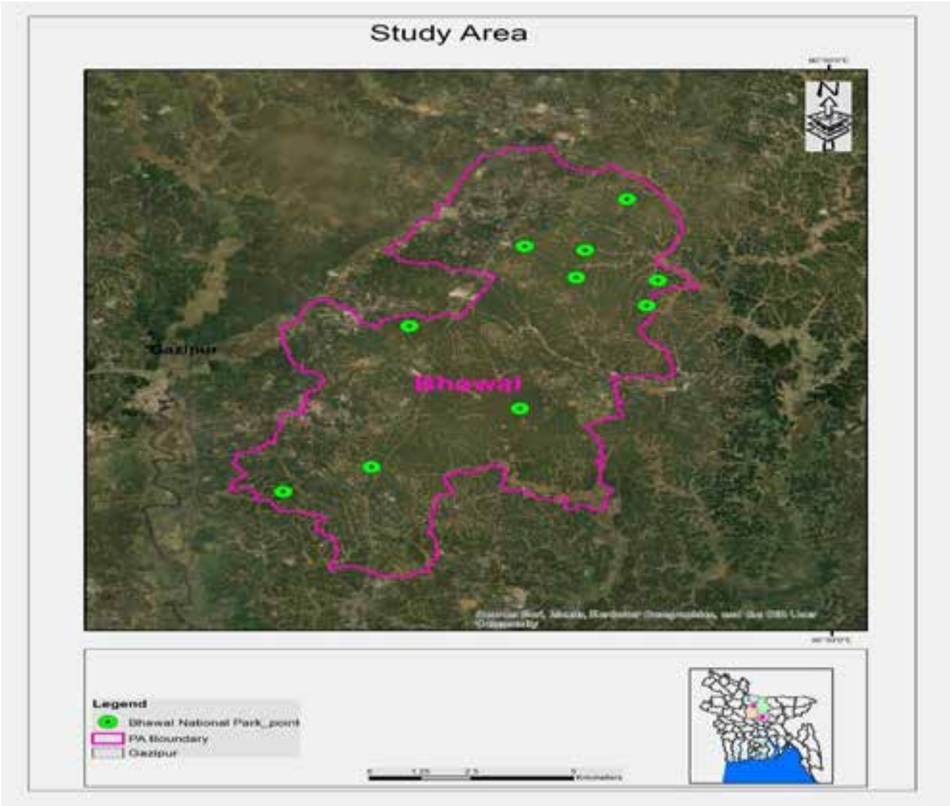

Figure 2b. Map of the study area -Bhawal National Park with Sampling Locations.

3. 2 Research Approach and Methods

3.2.1 Conceptual Design of Research Approach and Methods

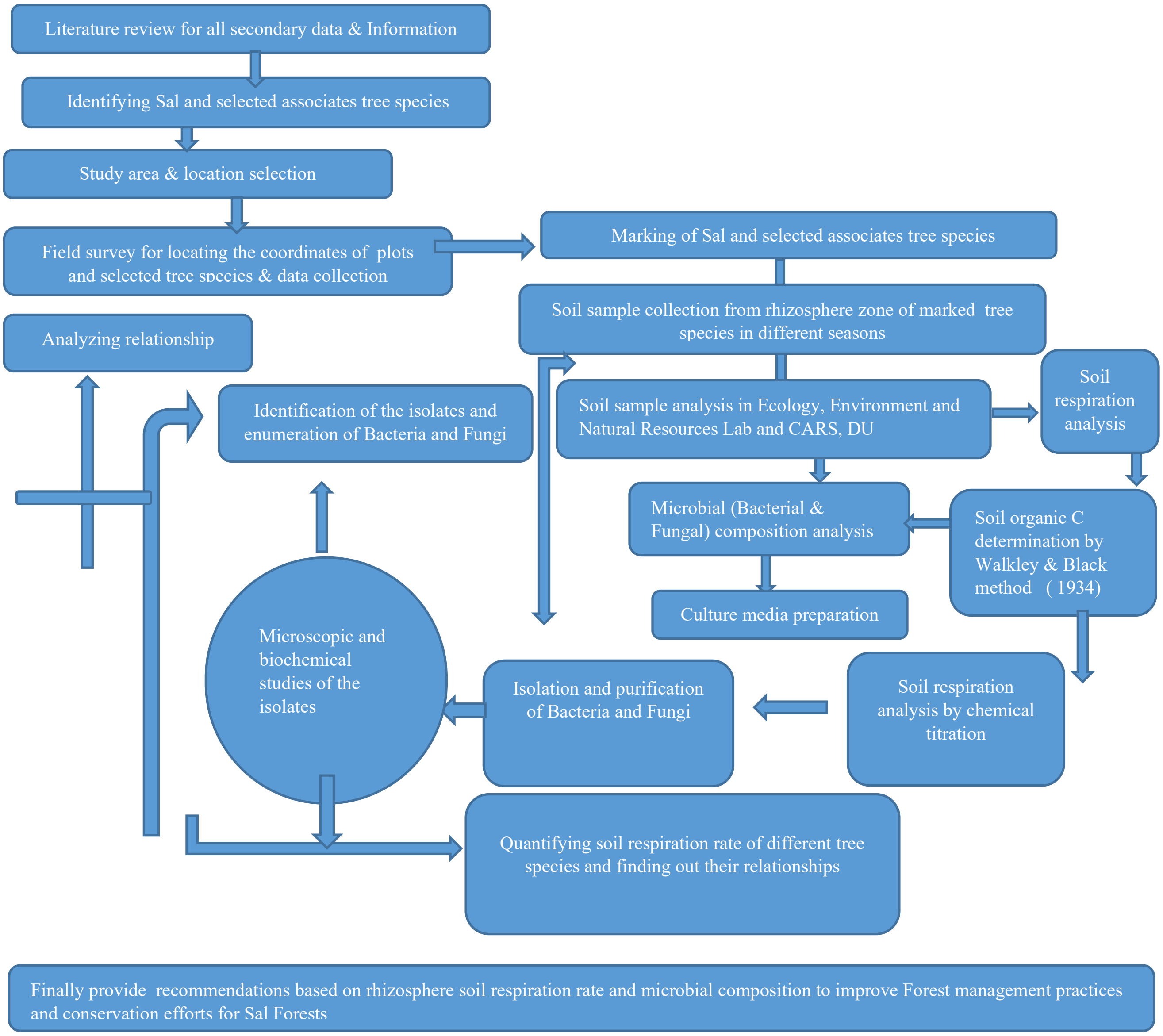

Figure 3. Schematic representation of the conceptual design of research approach and methods leading to get the expected results.

3.2.2 Research Approach

The proposed research is totally field and Laboratory oriented. At first, all secondary data and information were collected from a literature review about Sal Forests and then field surveys were conducted with the help of appropriate equipment and procedures described in different literatures on selected locations for identifying and marking Sal and selected associates (07 Spp.) tree species, and collecting soil samples. Through field surveys, collected soil samples analyzed for microbial abundance and soil respiration rate by different methods using instruments and chemicals in the Ecology, Environment and Natural Resource Laboratory, Department of Botany and CARS, University of Dhaka. Finally analyzed and determined values of different principal components to compare descriptive statistics and one-way and two-way ANOVA tests were performed using 14

Minitab software and then the relationship among them was found out. The whole research work was performed by a research team. The Research team consists of a Principal Investigator, a Co-principal Investigator, a Research Associate and a Research Assistant.

3.2.3 Research Methods

The following steps were applied for research works

3.2.3.1 Identifying and marking of Sal and selected associates tree (07 Spp.) species

The study was conducted in Madhupur and Bhawal National Parks (Figure 2a, 2b). A vegetation survey was carried out for identifying and marking of Sal and associates tree (07 Spp.) species in the different locations of study areas. At first, Stratified sampling was done in study areas on the basis of land cover. Then Ten 10m×10m quadrats/plots were randomly established in the 10 locations within low, medium and high dense vegetation of each of two study areas. Sal and associates tree (07 Spp.) species were selected on the basis of relative abundance of each species (Rahman and Vacik 2010). Each and every tree species was in height of 1.5-2m. Selected tree species were also marked with color and details of the sampling plot locations along with the corresponding coordinates were mentioned. If any targeted tree species was not be found in the plot, then the tree species situated outside the studied plots was also considered. All these activities were completed in the 1st & 2nd field visits of each of two study areas.

Figure 4. Photographs of selected tree species Left to Right (Sal, Bohera, Ban Chalta, Kanchan, Sidur, Datoi & Kumvi) in Madhupur & Bhawal National Parks

3.2.3.2 Soil samples collection

Intact soil cores were collected from the rhizosphere of the marked Sal and associates tree species (1.5m-2m height) of Madhupur and Bhawal National Parks in different seasons per year. Undisturbed soil cores (4×4×6 cm^3) were collected vertically alongside the plant base using a stainless-steel core soil sampler/augur. The soil samples were collected from the two parts of the soil profile namely upper (0–15 cm) and lower (15-30 cm) layers of soil attached to the root (from root surface to 8 cm) at around the stem of tree (07 Spp.) specie- *Shorea robusta* (Sal), *Terminalia bellerica* (Bohera), *Dillenia pentagyna* (Ban Chalta), *Bauhinia pentandra* (Kanchan), *Mallotus philippensis* (Sidur), *Grewia nervosa* (Datoi) and *Careya arborea* (Kumvi) as rhizosphere soil (Wu *et al*. 2016 and Propa *et al.*2021, Koo *et al.*2005). Before core collection, the uppermost layer of litter with visible un-decomposed material (leaves) was excluded. Thus, a total number of 840 soil samples (7 tree species × 2 depths × 20 locations of the two study areas × 3 seasons) were collected from the fields in different seasons. Collected soil samples were kept in air-tight aseptic plastic bags to avoid loss of soil moisture and finally carried to the Ecology, Environment and Natural Resources Laboratory and CARS, Dhaka University for further analysis.

3.2.3.3 Soil Organic C determination

At first augur volume was calculated by equation of Sahu *et al.* (2016) for the determination of soil bulk density. Percentage of organic carbon (OC) of the soil was determined by Walkley and Black method (Walkley and Black 1934). For determination Percentage of organic carbon, the following formula was used.

$$\% \text{ of organic carbon} = \{(B-T) \times 0.003 \times 1.3 \times 100\}/W$$

Where, B = Amount in ml of N FeSO4 solution required in this experiment (for blank)

T = Amount in ml of N FeSO4 solution required in experiment with soil

W = Weights of soil taken

For determination of soil OM following formula was used.

$$\% \text{ of total OM} = \% \text{ of organic carbon} \times 1.72 \text{ (Van Bemmelen factor)}$$

Finally, soil organic carbon (SOC) stock was estimated using the following formula as described by Donato *et al.* (2011) and Sahu *et al.* (2016) and the amounts were converted into tons per hectare.

$$\text{SOC (t/ha)} = \text{Bulk density (g/cm}^3\text{)} \times \text{soil depth (cm)} \times \text{organic carbon (\%)}$$

3.2.3.4 Soil respiration analysis

Soil was teeming with organisms that release CO_2 as organic matter was oxidized. Through measuring the rate of CO_2 evolution, the rate of soil respiration (Rs) could be determined. The rate of CO_2 evolution was determined by the conversion to CO^{3-} in the presence of excess OH^-. In this reaction excess OH^- was consumed, so that if the initial and final amounts of OH^- was known by chemical titration, the amount of CO_2 was calculated (Anderson 1982 and Haney *et al*. 2008, Propa *et al*.2021). A control vial with no soil was included in the incubation to correct for the CO_2 in the jar at the initiation of the incubation chemical titration for measuring soil CO_2 respiration is an effective means whereby different soils can be compared for microbial activity. Then an equation was employed to arrive at mg CO_2 per g soil (Haney *et al.* 2008).

3.2.3.5 Analysis of soil microbial (Bacterial and Fungal) abundance

For rhizosphere soil Bacteria and Fungi study following methods were applied:

3.2.3.5.1 Preservation of the samples

Collected soil samples were preserved in a refrigerator at 4°C before and the after the microbial analysis.

3.2. 3.5.2 Media and techniques for the enumeration and isolation of Bacteria and Fungi

Nutrient Agar (NA) and Potato Dextrose Agar (PDA) medium were used for the enumeration and isolation of bacteria and fungi present in soil samples of study areas. The pH of the medium was adjusted to 7.2 for the samples of study areas. Serial dilution plate technique (Green beg *et al.* 1980) was applied for the isolation of bacteria and fungi. After 48 hrs of incubation the plates having well discrete colonies were selected for counting. The selected plates were placed on a colony counter (Digital colony counter DC-80SK 1000086, Kayagaki, Japan) and developed colonies were counted. Well separate bacterial and fungal colonies were selected and isolated immediately after counting.

3.2.3.5.3 Isolation and purification of Bacteria and Fungi

Based on their colonial morphology different colonies were selected for isolation. The selected colonies were marked and studied following standard manual (Eklund and Lankford 1967, Bryan 1950).Then the marked and observed bacterial and fungal colonies were transferred on nutrient agar slant for further studies. The isolated organisms were purified by repeated streaking on the agar plates. Dilution plate technique was also applied for the purpose of purification.

3.2.3.5.4 Morphological observation of the isolates

For the identification of selected bacterial and fungal isolates, following morphological characters were studied and the results were recorded. The bacterial and fungal colony on the plating medium was morphologically studied.

3.2.3.5.5 Enumeration and Identification of the isolates of Bacteria and Fungi

Following Bergey's Manual of Systematic Bacteriology (Sneath *et al.*1986) and Compendium of Soil Fungi (Domsch *et al.*1994) bacterial and fungal isolates were identified. Finally bacterial and fungal were counted of rhizosphere soil samples of targeted tree species of study areas.

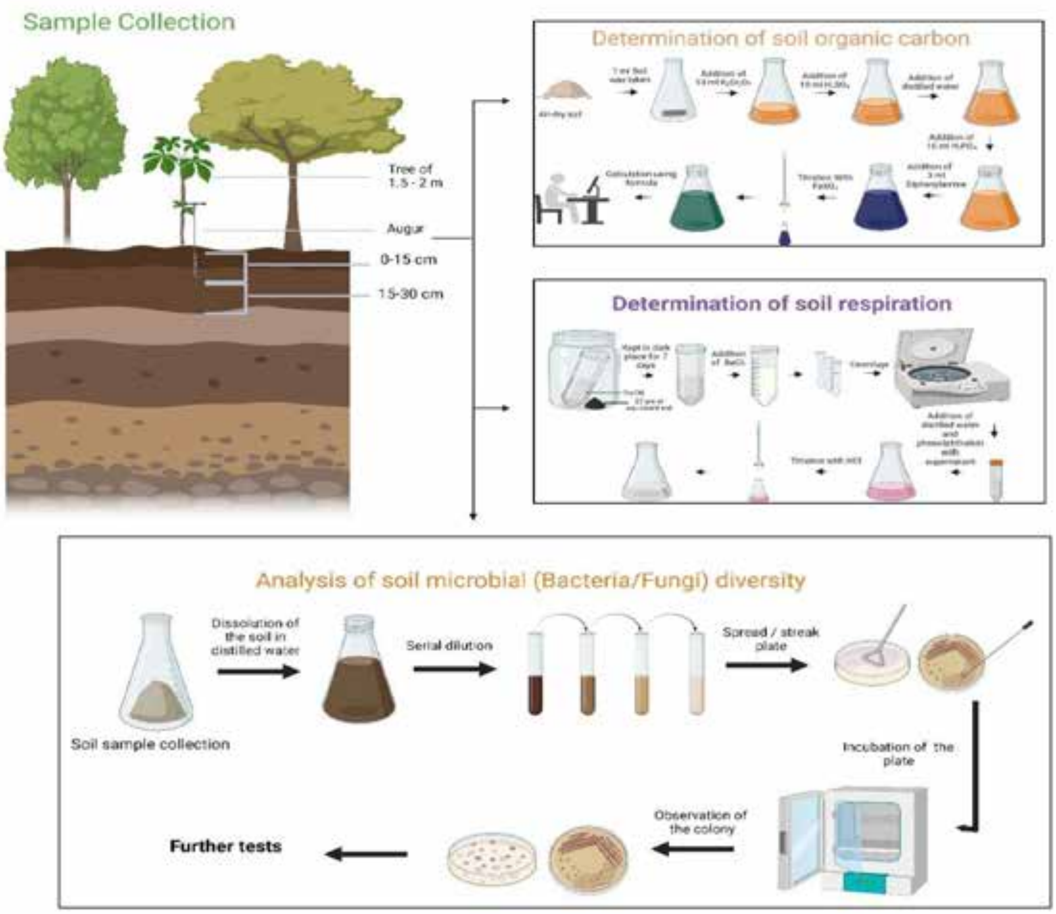

Figure 5. Schematic illustration showing the conceptual flow of the soil sample collection and analysis process.

3.2.4 Statistical analysis

To compare the amount of SOC and Rs between the different locations, upper- and lower-layers descriptive statistics and one-way & two-way ANOVA were performed using Minitab 14 software for normal distribution. Regression analysis, correlation and cluster analyses were done using same software.

3.3 The Environmental and Social safeguards policy

Environmental and Social safeguards were ensured during field surveys, Laboratory activities and other required aspects. During field surveys, it was made sure to wear appropriate clothing and gear such as long pants, sturdy boots and hats to protect from the sun, and to bring insect repellent and sunscreen. It was also aware of surroundings and to watch out for any hazards-uneven terrains, poisonous plants or dangerous animals and additionally to have first aid kit on hand. During sample analysis activities in Laboratory health safety measure was ensured. Lab employees were always wear appropriate personal protective equipment (PPE) such as gloves, Lab coats. Lab equipment were regularly inspected and maintained to ensure; it is in good working order. All hazardous materials were properly labeled and stored in designated areas. These protections were help to prevent accidental exposure or contamination or malfunctions. During transportation, transports were properly maintained and in good condition, licensed and qualified drivers were confirmed to operate vehicles, secured all equipment and supplies, and was observed all traffic laws & regulation.

CHAPTER IV

4. RESULTS AND DISCUSSIONS

4.1 Bulk Density (BD)

The analysis of variance (ANOVA) indicated that soil bulk density (BD) was significantly influenced by forest site ($F = 101.62$, $P < 0.001$), season ($F = 33.69$, $P < 0.001$), and plant species ($F = 21.65$, $P < 0.001$) (Table 1). BNP (0.73 ± 0.06 g/cm^3) exhibited significantly higher BD compared to MNP (0.65 ± 0.05 g/cm^3), suggesting greater soil compaction in BNP (Table 2). This difference may be attributed to variations in soil texture, organic matter content, and land-use history (Mestdagh *et al.* 2006). Seasonal variations in BD indicate that after rainy rainfall may have contributed to temporary reductions in BD in winter (Figures 5 and 6) (Talukder *et al.* 2016). Among plant species, *B. pentandra* had the highest BD 0.76 ± 0.06 g/cm^3) while *M. philippensis* (0.62 ± 0.05 g/cm^3) had the lowest (Figures 5, 6 and Table 3), likely due to differences in root biomass and litter decomposition rates (Castanha *et al*. 2018).

The bulk density of the rhizosphere soils of different plant species followed the order: *B. pentandra* (0.76 ± 0.06) > *T. bellerica* (0.72 ± 0.07) > *S. robusta* (0.70 ± 0.05) > *G. nervosa* (0.70 ± 0.06) > *C. arborea* (0.68 ± 0.08) > *D. pentagyna* (0.64 ± 0.04) > *M. philippensis* (0.62 ± 0.05) g/cm^3 (Table 3).

4.2 Organic Carbon (OC)

Forest site, season, and plant species significantly influenced soil organic carbon ($F = 20.15$, $P < 0.001$ for forest; $F = 11.02$, $P < 0.001$ for season; $F = 5.03$, $P = 0.001$ for plant species) (Table 1). BNP (0.82 ± 0.18 %) had higher OC than MNP (0.69 ± 0.08 %) (Table 2), suggesting better carbon retention due to lower decomposition rates (Wang *et al.* 2017). Seasonal variations in OC indicate that rainy conditions enhance organic matter input, whereas dry seasons may lead to higher decomposition (Figures 7, 8 and 14) (Wan *et al.* 2019). Plant species with higher leaf litter production, such as *B. pentandra* (0.90 ± 0.27 %) exhibited higher OC, whereas species with lower decomposition resistance, such as *M. philippensis* (0.69 ± 0.08 %) had lower OC (Table 3) (Wang *et al.* 2017).

The organic carbon concentrations of the rhizosphere soils of different plant species followed the order: *B. pentandra* (0.90 ± 0.27) > *G. nervosa* (0.87 ± 0.08) > *C. arborea* (0.72 ± 0.14) > *D. pentagyna* (0.72 ± 0.09) > *T. bellerica* (0.70 ± 0.12) > *S. robusta* (0.69 ± 0.10) > *M. philippensis* (0.69 ± 0.08) % (Table 3).

4.3 Soil Organic Carbon (SOC)

SOC showed strong dependence on forest site ($F = 40.42$, $P < 0.001$), season ($F = 14.50$, $P < 0.001$), and plant species ($F = 7.20$, $P < 0.001$) (Table 1). BNP (10.32 ± 3.90 t/ha) had higher SOC than MNP (6.63 ± 1.05 t/ha), reflecting its greater organic matter accumulation and lower microbial decomposition rates (Table 2 and Figure 15). Seasonal variations revealed that soil organic carbon (SOC) levels were highest during the winter season compared to summer and rainy seasons (Figures 9, 10 and 15). These fluctuations were likely influenced by litter fall patterns, microbial activity, and the availability of soil moisture. (Wang *et al.* 2019). Among plant species, *B. pentandra* had the highest SOC, while *M. philippensis* had the lowest (Table 3). These findings suggest that tree species play a vital role in carbon sequestration by influencing litter decomposition and root exudates (Yan *et al.* 2018).

The soil organic carbon content of the rhizosphere soils of different plant species followed the order: *B. pentandra* (10.32 ± 3.90) > *G. nervosa* (9.21 ± 1.71) > *C. arborea* (7.46 ± 2.26) > *S. robusta* (7.48 ± 1.61) > *T. bellerica* (7.55 ± 1.80) > *D. pentagyna* (6.77 ± 1.05) > *M. philippensis* (6.63 ± 1.05) t/ha (Table 3).

Among the study sites, Bhawal National Park (9.12 ± 2.68) exhibited a higher soil organic carbon stock compared to Madhupur National Park (6.71 ± 0.92) t/ha (Table 2).

4.4 Soil Respiration (Rs)

Soil respiration was significantly influenced by forest site ($F = 260.11$, $P < 0.001$), season ($F = 32.03$, $P < 0.001$), and plant species ($F = 9.34$, $P < 0.001$) (Table 1). Rs was higher in MNP (76.985 ± 3.92 mg CO_2/g soil) compared to BNP (67.77 ± 3.30 mg CO_2/g soil) (Table 2), likely due to increased microbial activity and root respiration associated with greater soil moisture and organic matter decomposition (Tomar *et al.* 2020).

Seasonal variations in Rs suggest that microbial respiration is enhanced during winter season (Figures 11, 12 and 16). However, during the rainy season, excessive moisture can create anaerobic conditions that may suppress microbial respiration. Consequently, Rs tends to be higher in winter than in the rainy season, as excess soil moisture gradually decreases after the rains, allowing the soil to reach an optimal temperature for microbial activity, thereby increasing the Rs rate (Chakravarthy *et al*. 2024). Among plant species, *D. pentagyna* (76.01 ± 4.99 mg CO_2/g soil) exhibited the highest Rs, while *B. pentandra* (69.57 ± 6.92 mg CO_2/g soil) had the lowest (Table 3 and Figure 17), reflecting differences in root respiration and microbial activity associated with species-specific litter decomposition rates (Makita and Fujii 2015).

The soil respiration rate of the rhizosphere soils of different plant species followed the order: *D. pentagyna* (76.01 ± 4.99) > *M. philippensis* (74.02 ± 5.47) > *C. arborea* (73.38 ± 7.62) > *S. robusta* (71.85 ± 5.43) > *T. bellerica* (70.99 ± 5.71) > *G. nervosa* (70.36 ± 4.19) > *B. pentandra* (69.57 ± 6.92) mg CO_2/g soil (Table 3 and Figure 17).

Among the study sites, Madhupur National Park (76.985 ± 3.92 mg CO_2/g soil) exhibited a higher soil respiration compared to Bhawal National Park (67.77 ± 3.30 mg CO_2/g soil) (Table 2).

The regression analysis presented in Figure 19 illustrates the relationship between SOC and Rs. The negative slope of the regression equation (Rs = 87.59 - 1.790 SOC) suggests that an increase in SOC is associated with a decrease in soil respiration. This inverse relationship is statistically significant ($p < 0.0001$), with an R-squared value of 57.6%, indicating that SOC accounts for approximately 57.6% of the variation in soil respiration. The decline in soil respiration with increasing SOC could be attributed to several factors. Higher SOC levels may indicate the presence of more stable organic matter fractions, which are less readily decomposed by microbial activity. Additionally, increased SOC can enhance soil aggregation, potentially reducing oxygen diffusion and microbial respiration rates. This trend is consistent with previous studies that suggest that labile carbon fractions contribute more significantly to soil respiration than recalcitrant organic matter.

Despite the strong correlation, the remaining 42.4% of unexplained variation in soil respiration may be influenced by other soil properties, such as microbial biomass, moisture content, and temperature. Further research incorporating these variables could provide a more comprehensive understanding of the mechanisms driving soil respiration dynamics in relation to SOC.

4.5 Abundance of Bacteria in Rhizosphere Soils

ANOVA results showed that bacterial abundance was significantly influenced by forest site ($F = 71.86$, $P < 0.001$), season ($F = 160.40$, $P < 0.001$), and plant species ($F = 71.86$, $P < 0.001$) (Table 1). Bacterial count was generally higher in MNP than BNP across all seasons, suggesting that MNP provides more favorable conditions for bacterial proliferation (Table 4 and 5). Seasonal variations were significant, with the highest bacterial populations recorded during the rainy season (Table 4 and 5), attributed to increased soil moisture, organic matter decomposition, and favorable temperatures (Wu *et al.* 2016). Among plant species, *Careya arborea*, *B. pentandra*, and *M. philippensis* exhibited the highest bacterial abundance, while *S. robusta* and *T. bellerica* had lower counts (Table 4 and 5), indicating that species-specific root exudates play a role in shaping bacterial communities (Ulbrich *et al.* 2022).

4.6 Abundance of Fungi in Rhizosphere Soils

Unlike bacteria, fungal abundance was not significantly influenced by forest site ($F = 0.92$, $P = 0.497$) or plant species ($F = 0.92$, $P = 0.497$), but was significantly affected by season ($F = 8.66$, $P < 0.001$) (Table 1). Fungal populations peaked in the rainy season and were lowest in summer (Table 4 and 5), likely due to higher humidity and organic matter decomposition enhancing fungal growth (Castaño *et al.* 2017). The lack of significant differences between BNP and MNP suggests that fungal communities may be more resilient to variations in forest site than bacteria. However, species-specific influences were observed, with *D. pentagyna*, *B. pentandra*, and *G. nervosa* showing higher fungal counts (Table 4 and 5), likely due to higher root exudation of carbohydrates, which promote fungal colonization (Macías-Rodríguez *et al.* 2018).

Microscopic examination of rhizosphere soil samples revealed the presence of various fungal species, each with distinct morphological characteristics (Figure 23). *Aspergillus* exhibited septate hyphae with conidial heads forming radiating chains. *Colletotrichum* was identified by its cylindrical conidia and melanized appressoria. *Alternaria* displayed dark-colored, multicellular conidia with transverse and longitudinal septa. *Saccharomyces cerevisiae* appeared as single-celled, oval to spherical structures capable of budding. *Penicillium* was characterized by branched conidiophores with brush-like conidial arrangements. *Trichoderma* showed fast-growing, greenish colonies with clustered phialides. Fusarium was recognized by its banana-shaped, septate macroconidia. *Mucor* formed broad, coenocytic hyphae with spherical sporangia at the tips. *Rhizopus* had stoloniferous hyphae with sporangia producing non-septate spores. *Absidia* resembled Rhizopus but displayed slightly curved sporangiophores and pyriform sporangia.

4.7 Hierarchical cluster analysis

The hierarchical cluster analysis (HCA) of rhizosphere soil properties, including bulk density (BD), organic carbon (OC), soil organic carbon (SOC), and soil respiration (Rs), reveals distinct groupings among plant species (Figure 20 and 21). The dendrogram indicates three major clusters, where *B. pentandra* and *G. nervosa* form a closely related group, suggesting similar effects on soil properties, likely characterized by higher BD, OC, SOC and lower Rs, which promote soil health. *C. arborea*, *S. robusta*, and *T. bellerica* cluster together, reflecting moderate BD, OC and SOC, contributing to stable soil respiration. In contrast, *D. pentagyna* and *M. philippensis* form a separate group, likely associated with lower BD, OC, SOC and higher Rs, which may negatively impact carbon sequestration. These results highlight the significant influence of plant species on soil properties, *with B. pentandra* and *G. nervosa* being particularly beneficial for maintaining soil quality. The findings suggest that selecting appropriate plant species can improve soil carbon storage and microbial functions, emphasizing their role in sustainable forest management and ecological restoration efforts.

4.8 Seasonal Variations and Plant-Specific Effects

The seasonal differences in bacterial and fungal abundance suggest that moisture availability plays a crucial role in microbial proliferation. The higher microbial abundance in the rainy season can be attributed to increased organic matter decomposition, higher soil moisture, and optimal temperatures, which promote microbial activity. Conversely, the lower microbial counts observed in the summer season suggest that water stress and high temperatures suppress microbial growth and activity.

Among plant species, *D. pentagyna, C. arborea, M. philippensis*, and *B. pentandra* consistently supported higher bacterial and fungal populations in both forest sites. These species may contribute to a more favorable rhizosphere environment through root exudates, organic matter inputs, and litter decomposition, which enhance microbial growth (Wan *et.al.* 2019). In contrast, *S. robusta* and *T. bellerica* exhibited comparatively lower bacterial and fungal counts, potentially due to differences in root exudation patterns, soil texture, or microbial competition.

4.9 Microbial Interactions and Their Influence on Soil Respiration

Microbial communities, including fungi and bacteria, play a crucial role in regulating soil respiration by driving organic matter decomposition and nutrient cycling. The analysis revealed a positive correlation ($r = 0.478$, $p = 0.001$) between soil respiration and fungal count (log-transformed) (Figure 22), indicating that an increase in fungal populations is associated with higher soil respiration. Fungi contribute significantly to carbon cycling by breaking down complex organic compounds, thereby enhancing microbial respiration in soil ecosystems.

Similarly, bacterial count (log-transformed) exhibited a positive correlation ($r = 0.481$, $p = 0.001$) with fungal count (Figure 22), suggesting an interdependent relationship between these microbial groups. Both bacteria and fungi play complementary roles in organic matter decomposition and nutrient cycling, with their positive correlation potentially driven by mutualistic interactions or overlapping ecological niches in the soil environment.

The strongest correlation ($r = 0.967$, $p = 0.000$) was observed between soil respiration and bacterial count (bottom-right scatter plot) (Figure 22), highlighting bacterial activity as a major driver of soil respiration. Bacteria are essential in the mineralization of organic carbon, leading to CO_2 release. The high correlation coefficient suggests that bacterial abundance significantly influences soil respiration rates, reinforcing the critical role of microbial biomass in soil carbon dynamics.

Overall, these findings emphasize the intricate microbial interactions that regulate soil respiration. The significant relationships between fungal and bacterial populations further suggest that microbial diversity and abundance are key factors controlling soil carbon fluxes. These results align with previous studies highlighting the importance of microbial communities in maintaining soil health and ecosystem stability. Future research should explore the mechanistic pathways through which microbial diversity influences carbon cycling across different environmental gradients.

Table 1. Effects of Forest Site, Seasonality, and Plant Species on Soil Bulk Density, Organic Carbon, Soil Organic Carbon and Respiration, and Bacterial and Fungal amounts in a Tropical Deciduous Sal Forest.

	Bulk density (g/cm^3)		
	Forest Site	**Season**	**Plant**
F value	101.62	33.69	21.65
p value	0.000***	0.000***	0.000***
	Organic carbon (%)		
	Forest Site	Season	Plant
F value	20.15	11.02	5.03
p value	0.000***	0.000***	0.000**
	Soil organic carbon (t/ha)		
	Forest Site	Season	Plant
F value	40.42	14.50	7.20
p value	0.000***	0.000***	0.000***
	Soil respiration (mg CO_2/g soil)		
	Forest Site	Season	Plant
F value	260.11	32.03	9.34
p value	0.000***	0.000***	0.000***
	Bacteria amount (CFU/g soil)		
	Forest Site	Season	Plant
F value	71.86	160.40	71.86
p value	0.000***	0.000***	0.000***
	Fungal amount (CFU/g soil)		
	Forest Site	Season	Plant
F value	0.92	8.66	0.92
p value	0.497^{ns}	0.000***	0.497^{ns}

p < 0.001 (***) and ns indicate statistically significant differences based on ANOVA results.

Table 2. Bulk density(BD), Organic carbon(OC), Soil organic carbon(SOC) stock and Soil respiration(Rs) of rhizosphere soil of Bhawal National Park (BNP) and Madhupur National Park(MNP).

Forest Site	**Bulk Density (g/cm^3)**	**Organic Carbon (%)**	**Soil Organic Carbon (t/ha)**	**Soil Respiration (mg CO_2/g soil)**
BNP	0.73 ± 0.06	0.82 ± 0.18	9.12 ± 2.68	67.77 ± 3.30
MNP	0.65 ± 0.05	0.69 ± 0.08	6.71 ± 0.92	76.985 ± 3.92

Table 3. Bulk density (BD), Organic carbon(OC), Soil organic carbon(SOC) stock and Soil respiration(Rs) of rhizosphere soil of selected plant species.

Plant Species	**Bulk Density (g/cm^3)**	**Organic Carbon (%)**	**Soil Organic Carbon (t/ha)**	**Soil Respiration (mg CO_2/g soil)**
Bauhinia pentandra	0.76 ± 0.06	0.90 ± 0.27	10.32 ± 3.90	69.57 ± 6.92
Careya arborea	0.68 ± 0.08	0.72 ± 0.14	7.46 ± 2.26	73.38 ± 7.62
Dillenia pentagyna	0.64 ± 0.04	0.72 ± 0.09	6.77 ± 1.05	76.01 ± 4.99
Grewia nervosa	0.70 ± 0.06	0.87 ± 0.08	9.21 ± 1.71	70.36 ± 4.19
Mallotus philippensis	0.62 ± 0.05	0.69 ± 0.08	6.63 ± 1.05	74.02 ± 5.47
Shorea robusta	0.70 ± 0.05	0.69 ± 0.10	7.48 ± 1.61	71.85 ± 5.43
Terminalia bellerica	0.72 ± 0.07	0.70 ± 0.12	7.55 ± 1.80	70.99 ± 5.71

Table 4. Abundance of bacteria and fungi of rhizosphere soil of different selected plants of Bhawal National Park in three different seasons, where CFU = Colony Forming Unit

Plant name	Layer	Bacteria amount (CFU/g soil)			Fungal amount (CFU/g soil)		
		Winter	Summer	Rainy	Winter	Summer	Rainy
Shorea robusta	U	6.2×10^5	2.7×10^5	2.9×10^6	1.3×10^5	5.2×10^4	5.6×10^6
	L	1.9×10^5	6.8×10^4	6.8×10^5	4.1×10^4	1.4×10^4	1.6×10^5
Terminalia bellerica	U	4.7×10^5	1.7×10^5	1.9×10^6	1.9×10^5	6.8×10^4	7.0×10^5
	L	4.8×10^5	1.8×10^5	2.0×10^6	8×10^4	2×10^4	2.2×10^5
Careya arborea	U	6.8×10^5	2.9×10^5	3.0×10^5	8×10^4	1.7×10^4	1.9×10^5
	L	1.8×10^6	7.4×10^5	7.7×10^6	4×10^4	1.9×10^4	2.0×10^5
Bauhinia pentandra	U	9×10^5	3.5×10^5	3.8×10^6	5×10^4	2.3×10^4	2.5×10^5
	L	5.0×10^5	2.1×10^5	2.4×10^6	1.4×10^5	1.1×10^5	1.4×10^6

Grewia nervosa	U	3.6×10^5	1.2×10^5	1.3×10^6	1.1×10^5	1×10^5	1.3×10^6
	L	1.6×10^5	7.6×10^4	7.8×10^5	4×10^4	1.9×10^4	2.1×10^5
Dillenia pentagyna	U	3.3×10^5	1.3×10^5	1.5×10^6	1.7×10^5	5.6×10^4	5.7×10^5
	L	2.7×10^5	1.4×10^5	1.6×10^6	1×10^5	2.9×10^4	3.0×10^5
Mallotus philippensis	U	9.1×10^5	4.3×10^5	4.5×10^6	1×10^5	3.9×10^4	4.0×10^5
	L	5.5×10^5	2.9×10^5	3.1×10^6	8×10^4	3.3×10^4	3.5×10^5

Table 5. Abundance of bacteria and fungi of rhizosphere soils of different selected plants of Madhupur National Park in three different seasons, where CFU = Colony Forming Unit

Plant name	Layer	Bacteria amount (CFU/g soil)			Fungal amount (CFU/g soil)		
		Winter	Summer	Rainy	Winter	Summer	Rainy
Shorea robusta	U	2.9×10^6	8.7×10^5	8.9×10^6	2×10^4	1.1×10^4	1.1×10^5
	L	2.1×10^6	7.9×10^5	8.0×10^6	1.9×10^5	5.1×10^4	5.1×10^5
Terminalia bellerica	U	1.5×10^6	6.5×10^5	6.7×10^6	3×10^4	2×10^4	2×10^5
	L	1.1×10^6	6.2×10^5	6.4×10^6	2.5×10^5	6.5×10^4	6.5×10^5
Careya arborea	U	1.7×10^6	5.8×10^5	5.9×10^6	3×10^4	1×10^4	1×10^5
	L	1.1×10^6	5.0×10^5	5.1×10^6	4×10^4	1×10^4	1×10^5
Bauhinia pentandra	U	2.1×10^6	7.8×10^5	7.9×10^6	1×10^5	6.1×10^4	6.1×10^5
	L	1.9×10^6	6.8×10^5	7.0×10^6	4×10^4	2.1×10^4	2.1×10^5
Grewia nervosa	U	1.2×10^6	4.2×10^5	4.3×10^6	1.1×10^5	1.1×10^5	1.1×10^6
	L	$2.\times10^6$	3.9×10^5	4.0×10^6	5×10^4	2.1×10^4	2.1×10^5
Dillenia pentagyna	U	7.8×10^5	1.1×10^5	1.2×10^6	1.3×10^5	1.1×10^5	1.1×10^6
	L	2.1×10^5	1.0×10^5	1.1×10^6	4.3×10^5	2.5×10^5	2.5×10^6
Mallotus philippensis	U	3.2×10^6	9.3×10^5	9.4×10^6	8.7×10^4	3.2×10^4	3.2×10^5
	L	2.1×10^6	8.8×10^5	8.9×10^6	3.2×10^4	1.7×10^4	1.7×10^{5}`

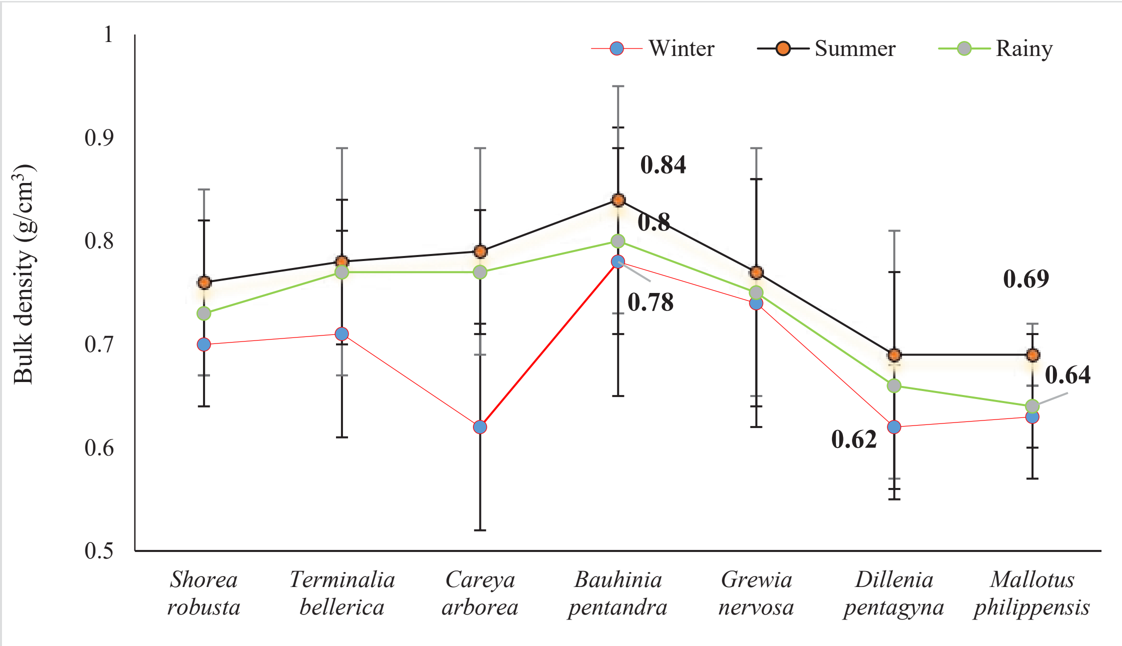

Figure 6. Seasonal variations in the Bulk density (BD) of rhizosphere soil for selected plant species in Bhawal National Park.

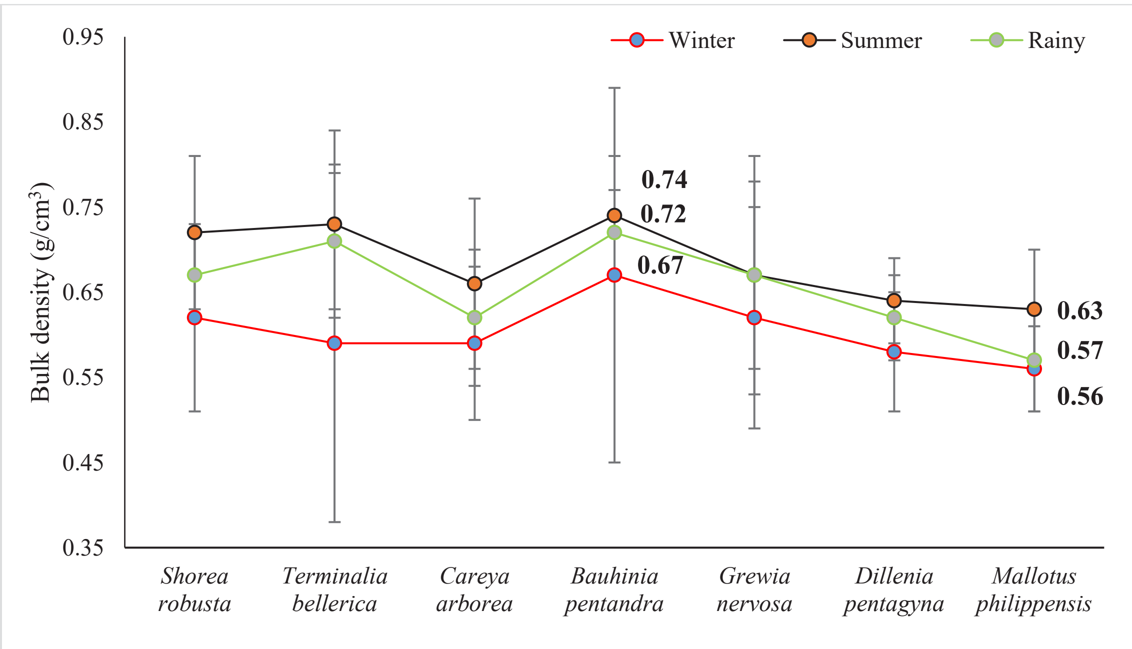

Figure 7. Seasonal variations in Bulk density (BD) of rhizosphere soil for selected plant species in Madhupur National Park.

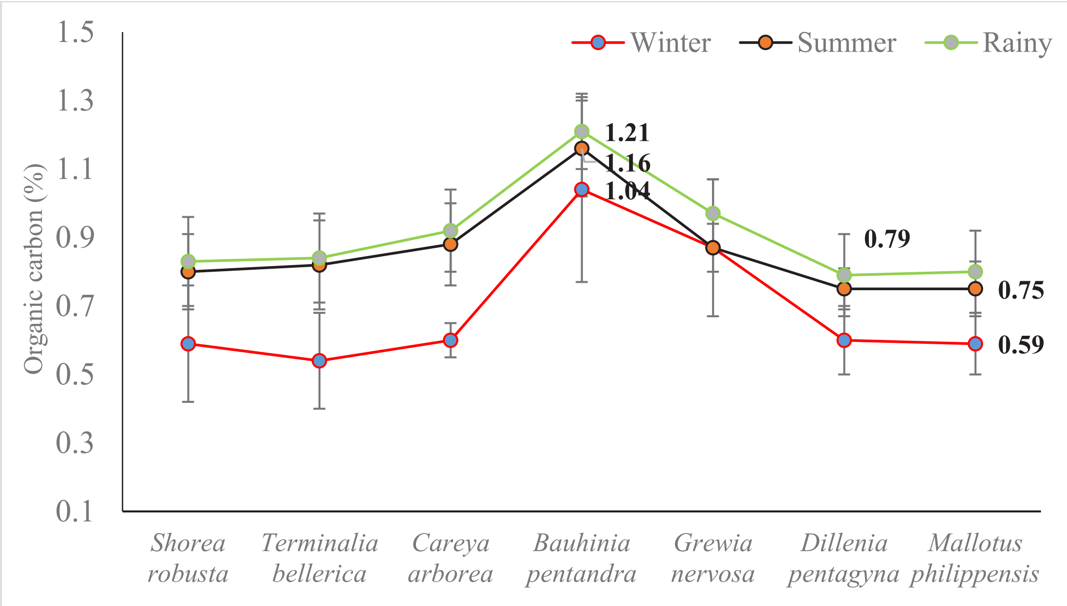

Figure 8. Seasonal variations in the Organic carbon (OC) of rhizosphere soils for selected plant species in Bhawal National Park.

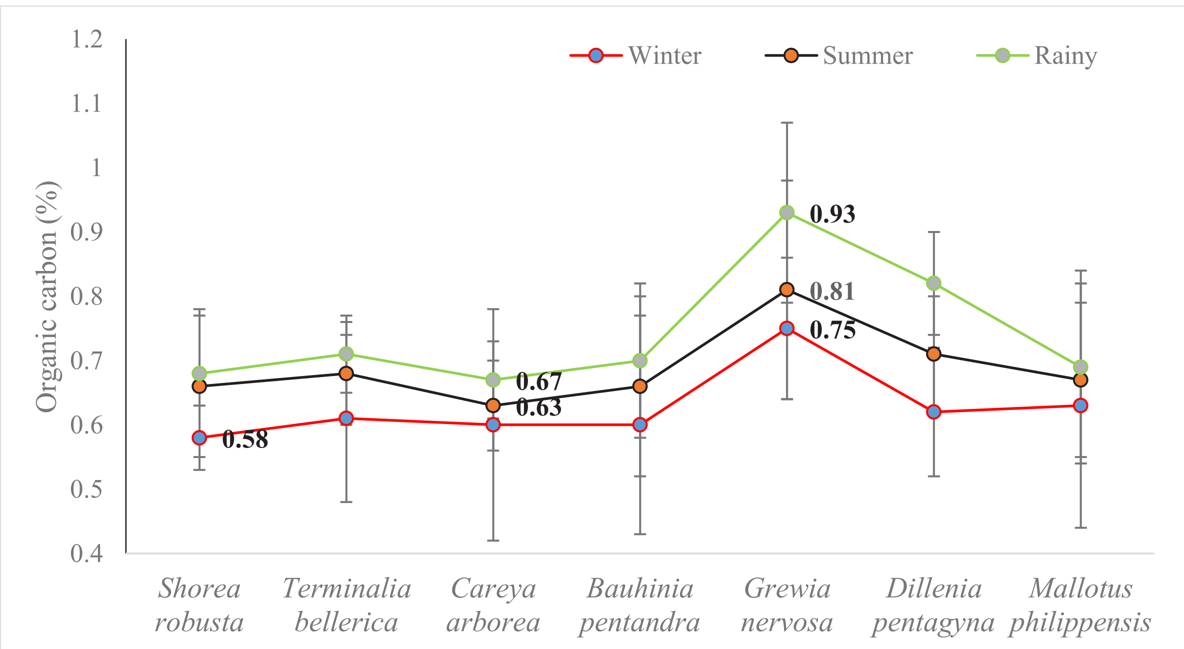

Figure 9. Seasonal variations in Organic carbon (OC) of rhizosphere soils for selected plant species in Madhupur National Park.

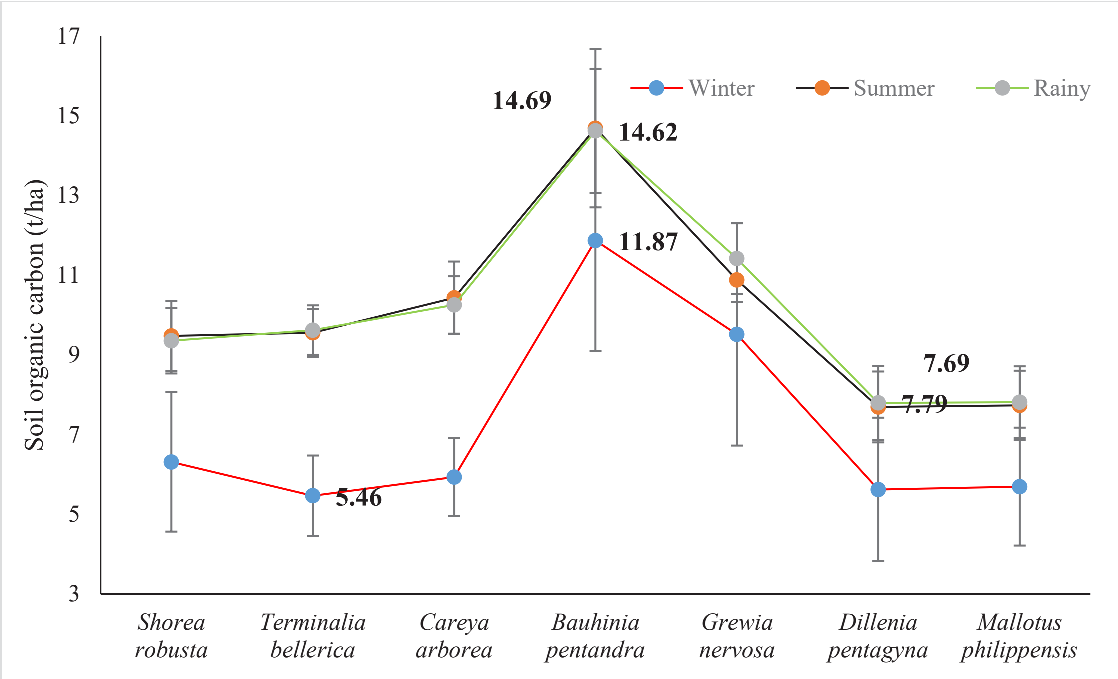

Figure 10. Seasonal variations in Soil organic carbon (SOC) of rhizosphere soils for selected plant species in Bhawal National Park.

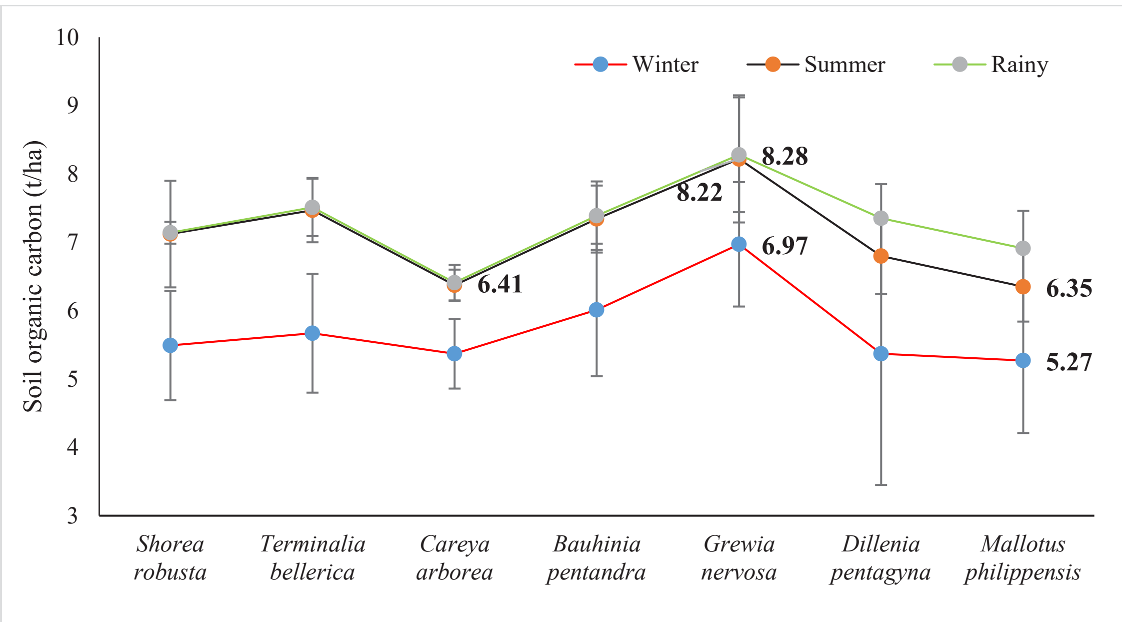

Figure 11. Seasonal variations in Soil organic carbon (SOC) of rhizosphere soils for selected plant species in Madhupur National Park.

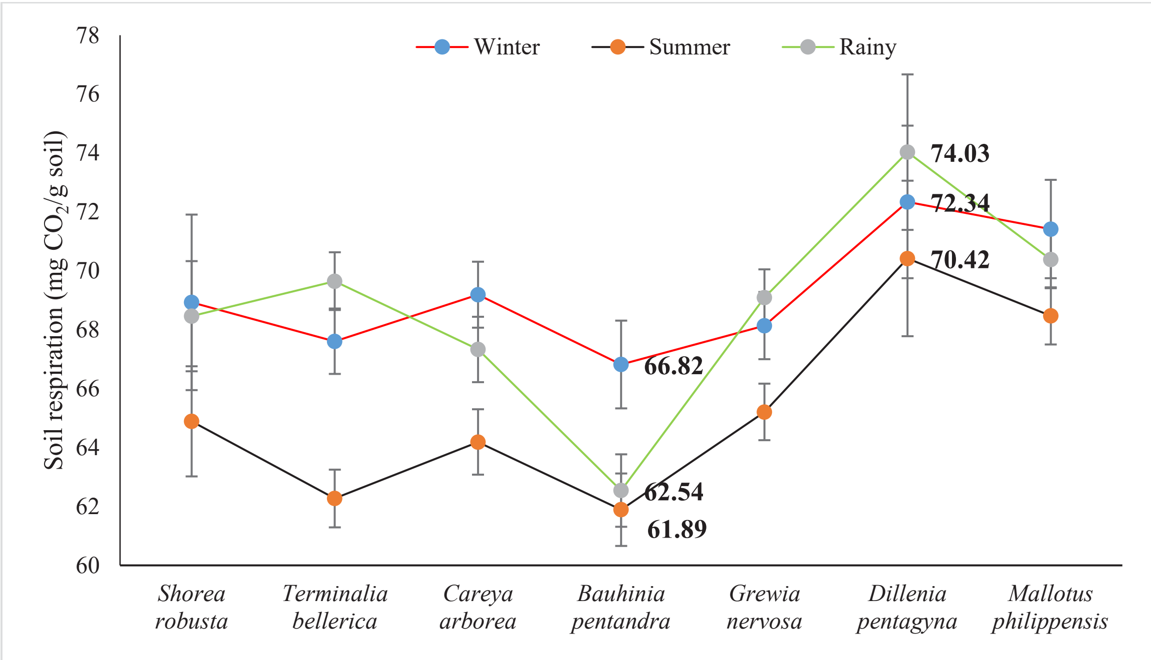

Figure 12. Seasonal variations in Soil respiration (Rs) of rhizosphere soils for selected plant species in Bhawal National Park.

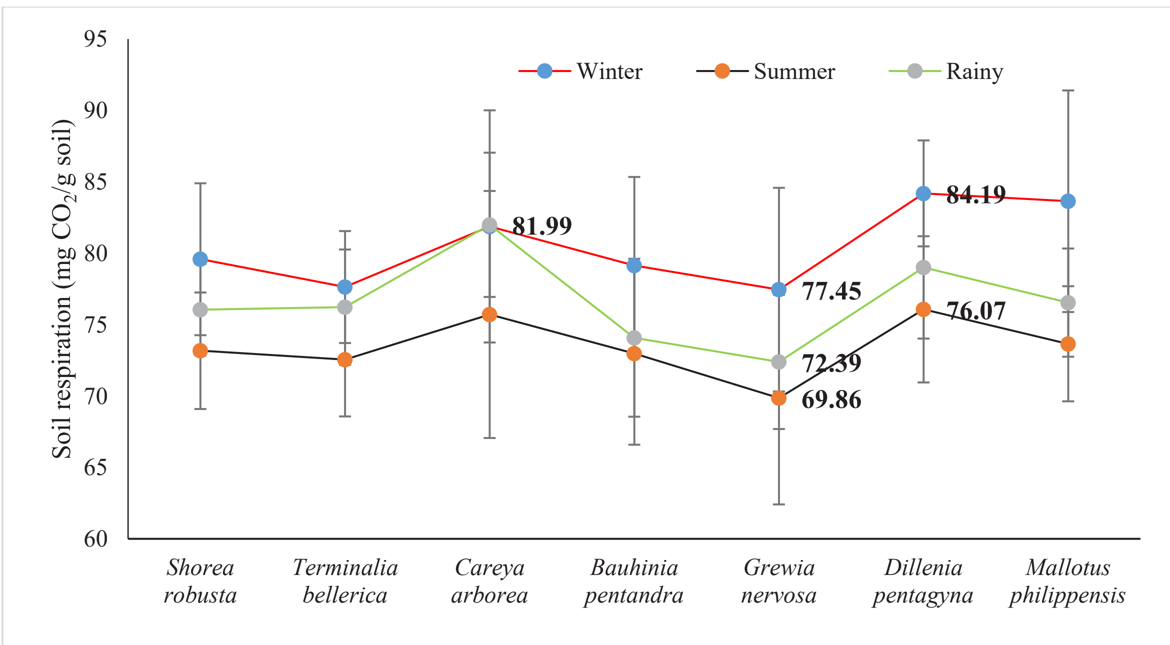

Figure 13. Seasonal variations in Soil respiration (Rs) of rhizosphere soils for selected plant species in Madhupur National Park.

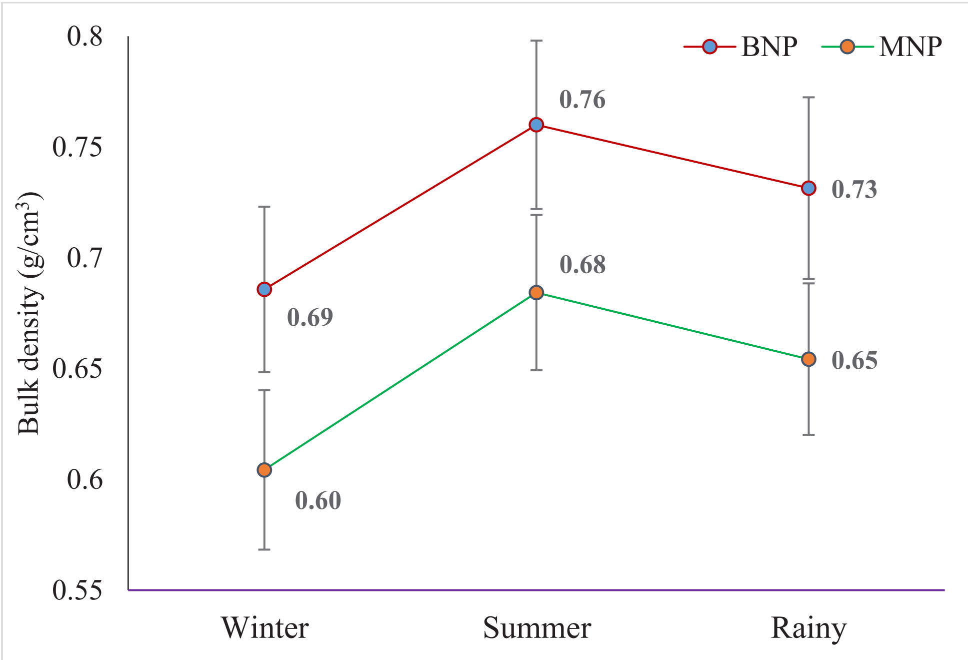

Figure 14. Seasonal variations in Bulk density (BD) of rhizosphere soil in Bhawal and Madhupur National Parks.

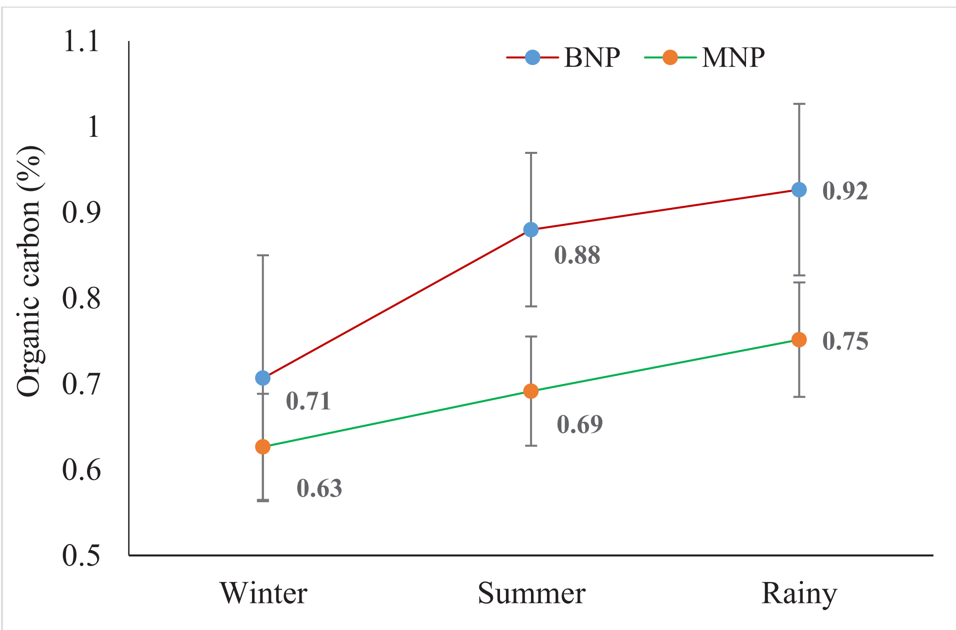

Figure 15. Seasonal variations in Organic carbon (OC) of rhizosphere soil in Bhawal and Madhupur National Parks.

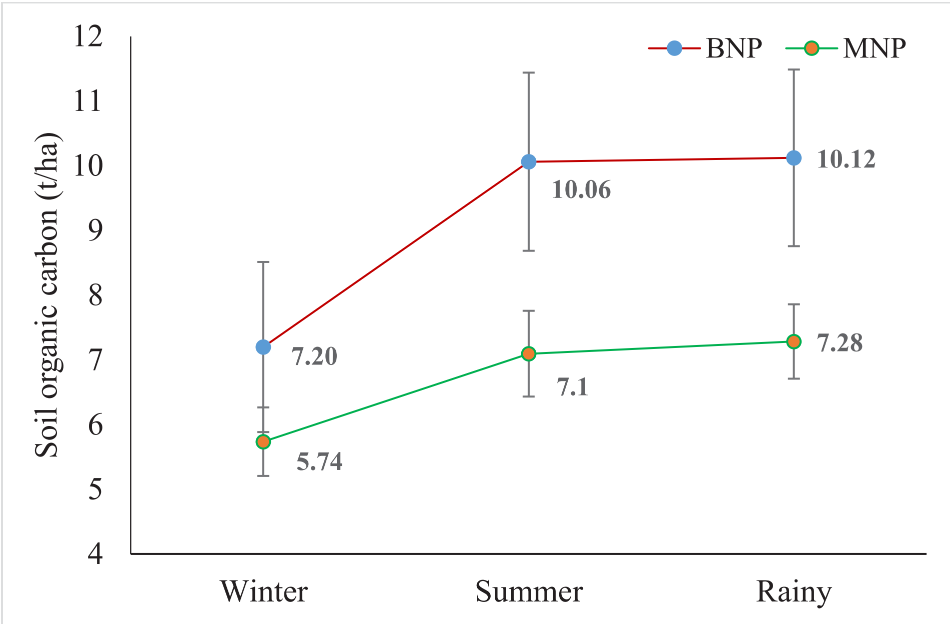

Figure 16. Seasonal variations in Soil organic carbon (SOC) of rhizosphere soil in Bhawal and Madhupur National Parks.

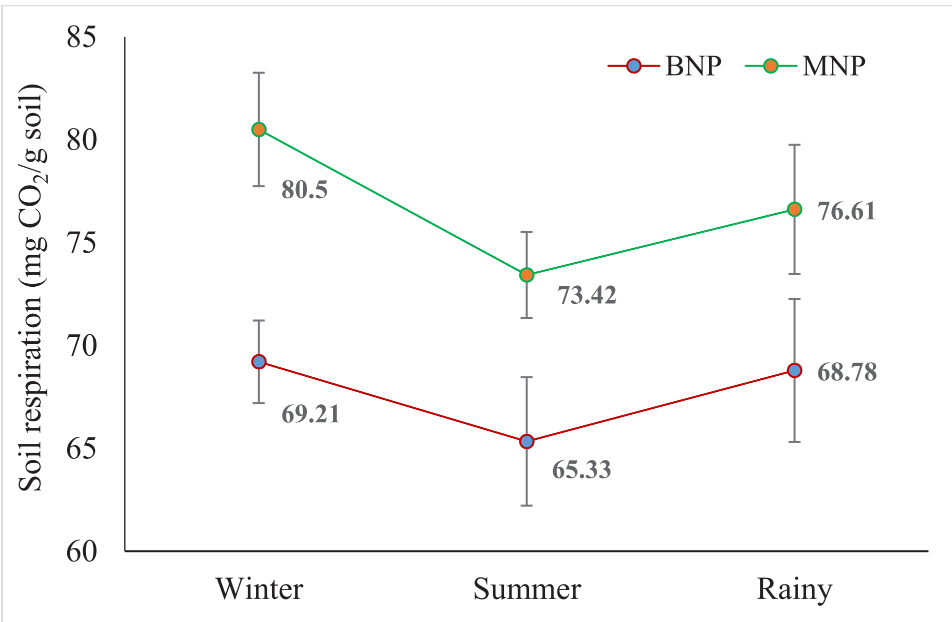

Figure 17. Seasonal variations in Soil respiration (Rs) of rhizosphere soil in Bhawal and Madhupur National Parks.

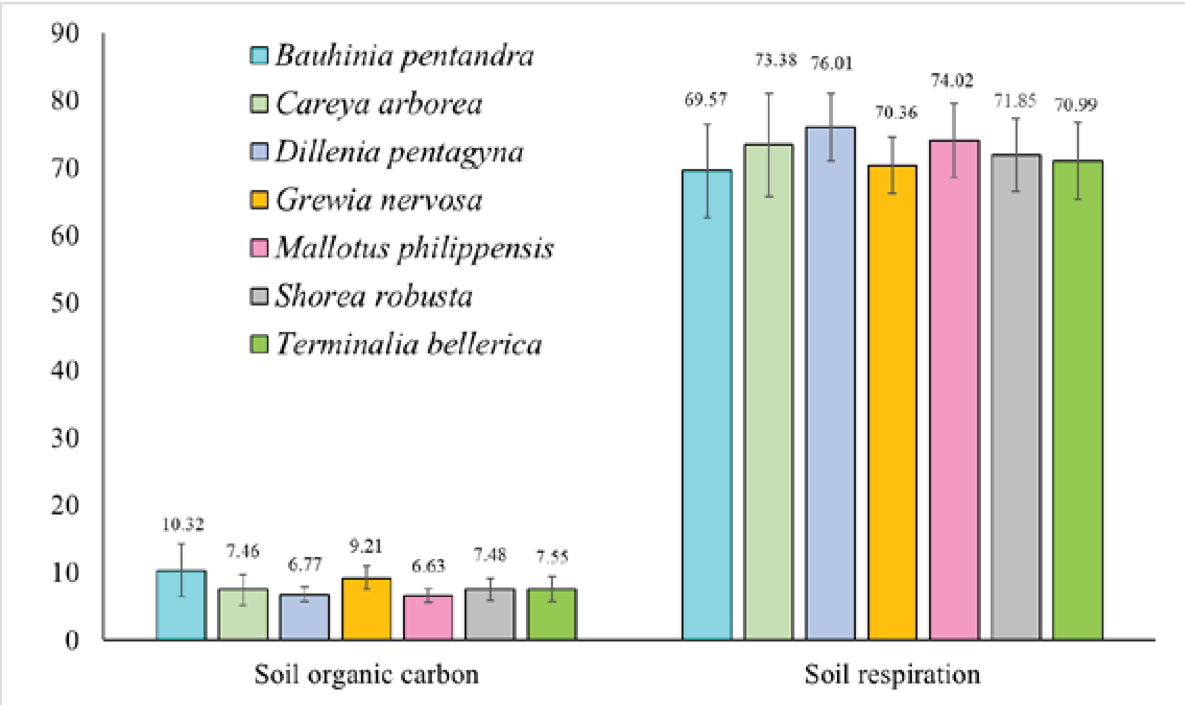

Figure 18. Overall soil organic carbon (t/ha) and soil respiration (mg CO_2/g soil) of rhizosphere soils of selected plant species in Bhawal and Madhupur National Parks.

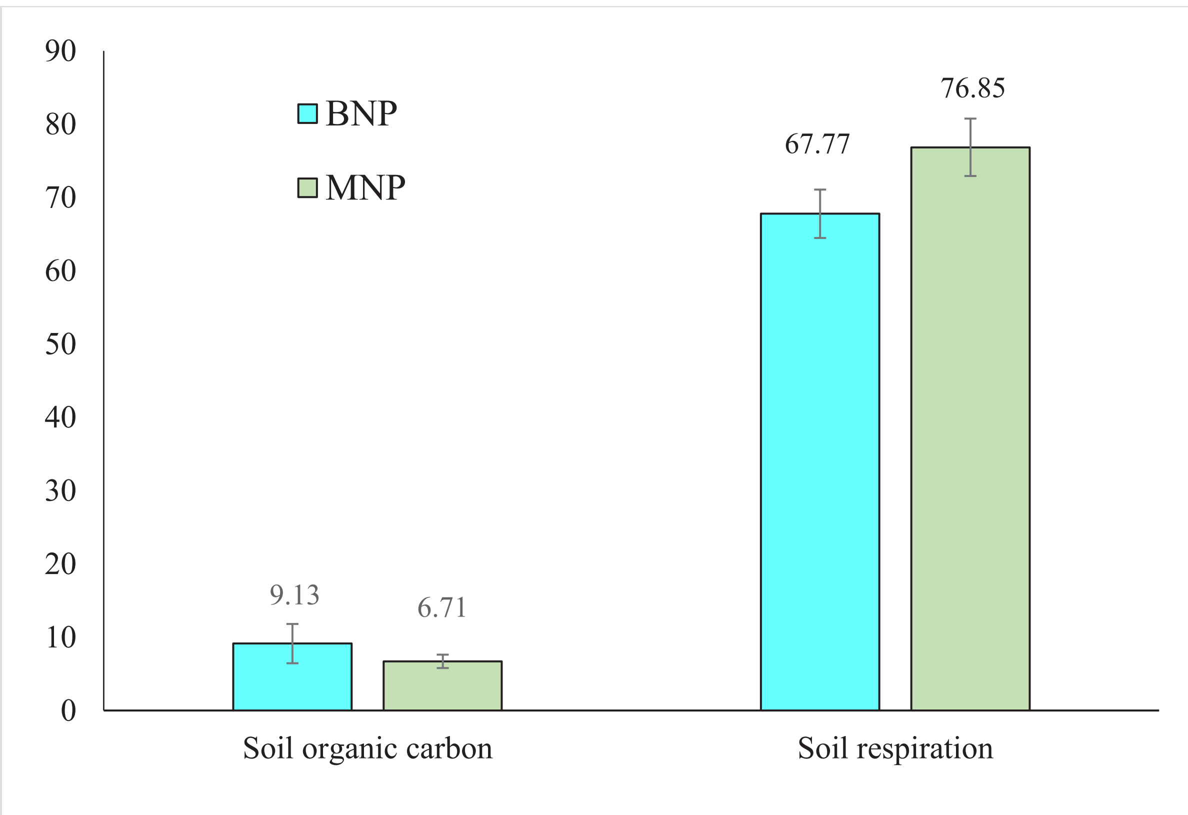

Figure 19. Soil organic carbon (t/ha) and soil respiration (mg CO_2/g soil) of rhizosphere soil of Bhawal (BNP) and Madhupur National Parks (MNP)

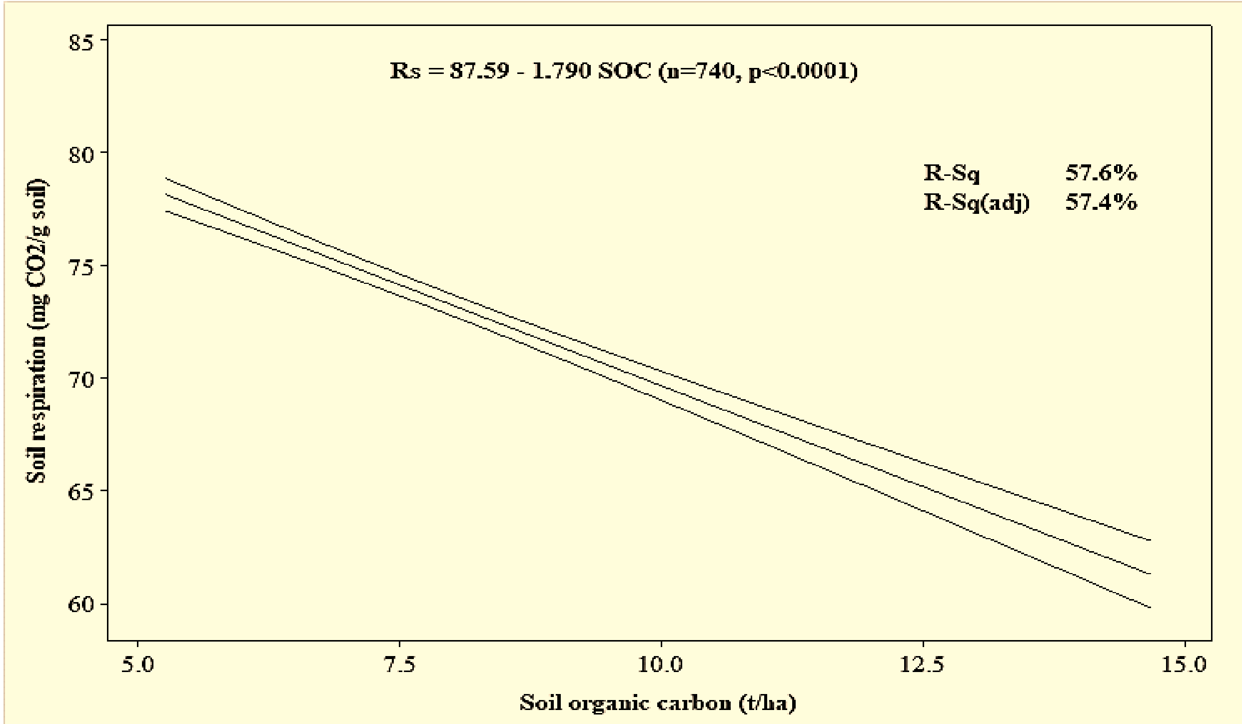

Figure 20. Regression analysis between soil respiration and soil organic carbon (overall data).

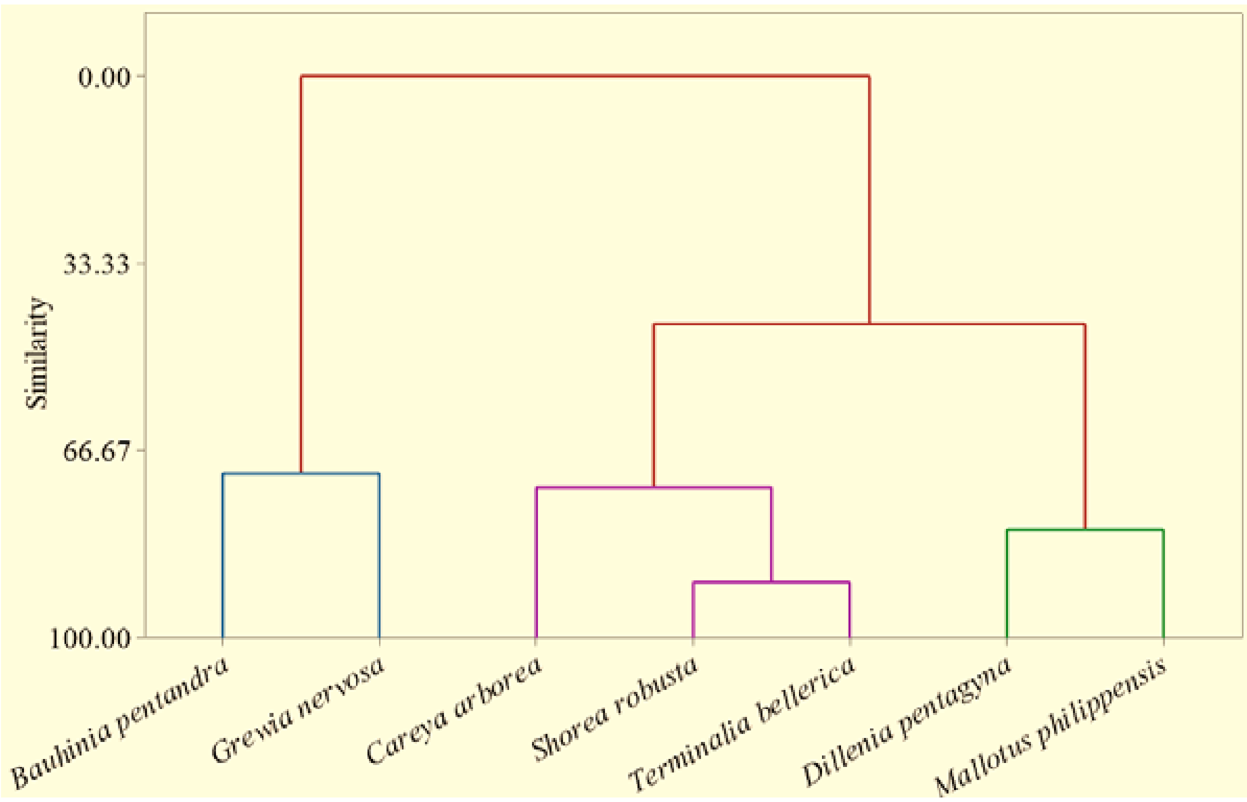

Figure 21. Cluster analysis of plant species on the basis rhizosphere soil bulk density, organic carbon, soil organic carbon and soil respiration. (overall data).

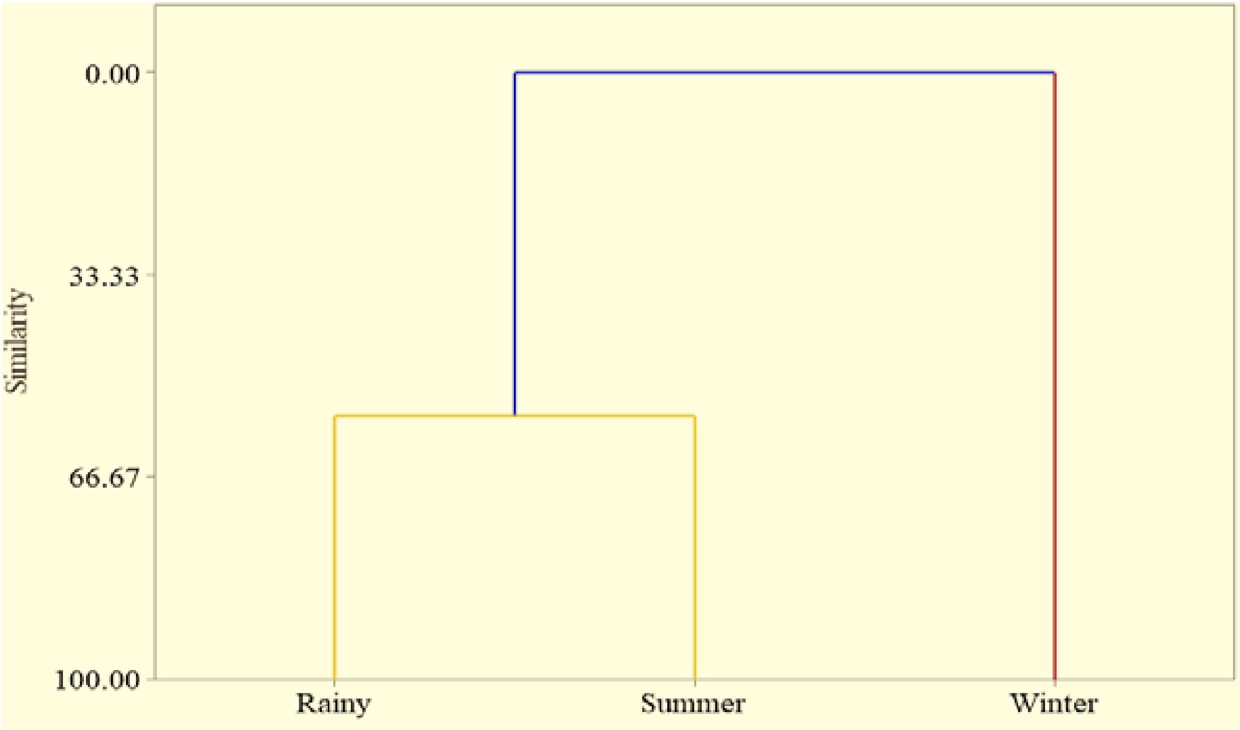

Figure 22. Cluster analysis of seasons on the basis rhizosphere soil bulk density, organic carbon, soil organic carbon and soil respiration (overall data).

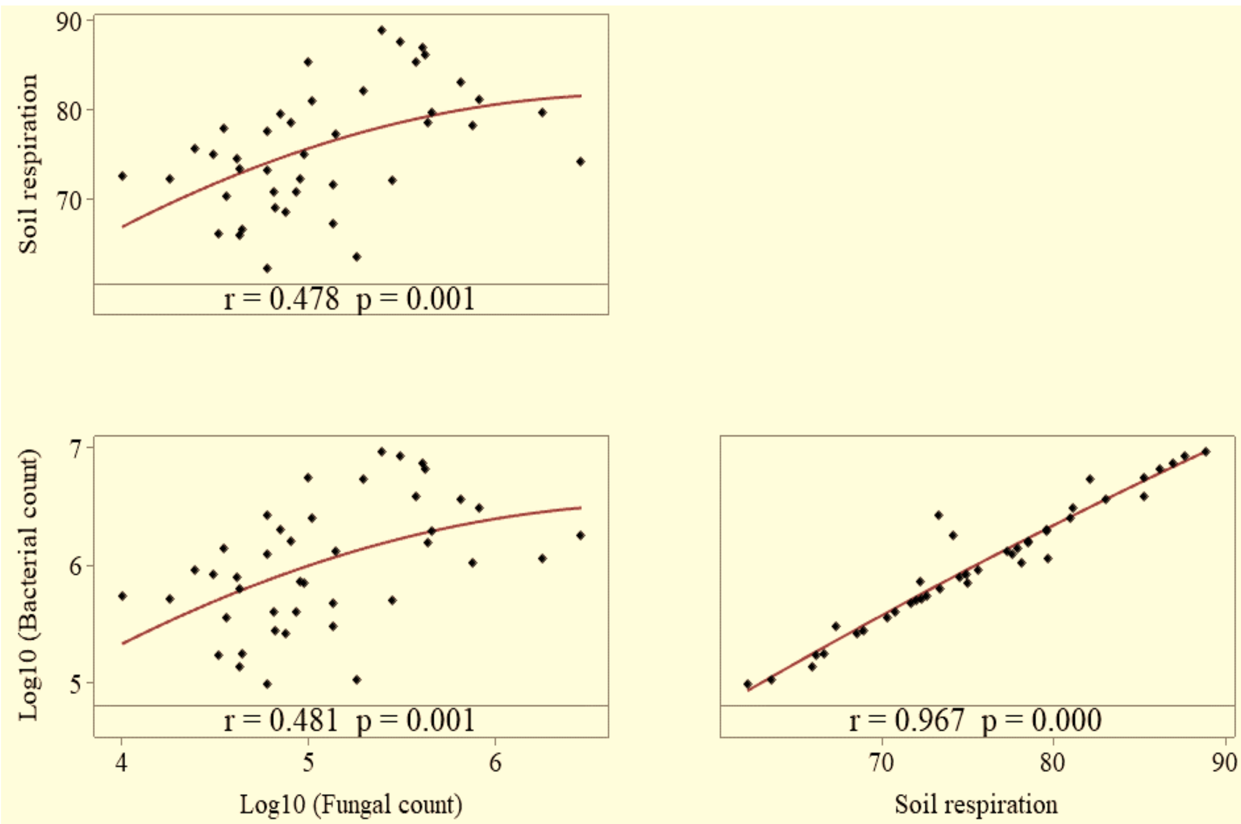

Figure 23. Correlation among soil respiration, bacterial count (log-transformed) and fungal count (log-transformed)(overall data).

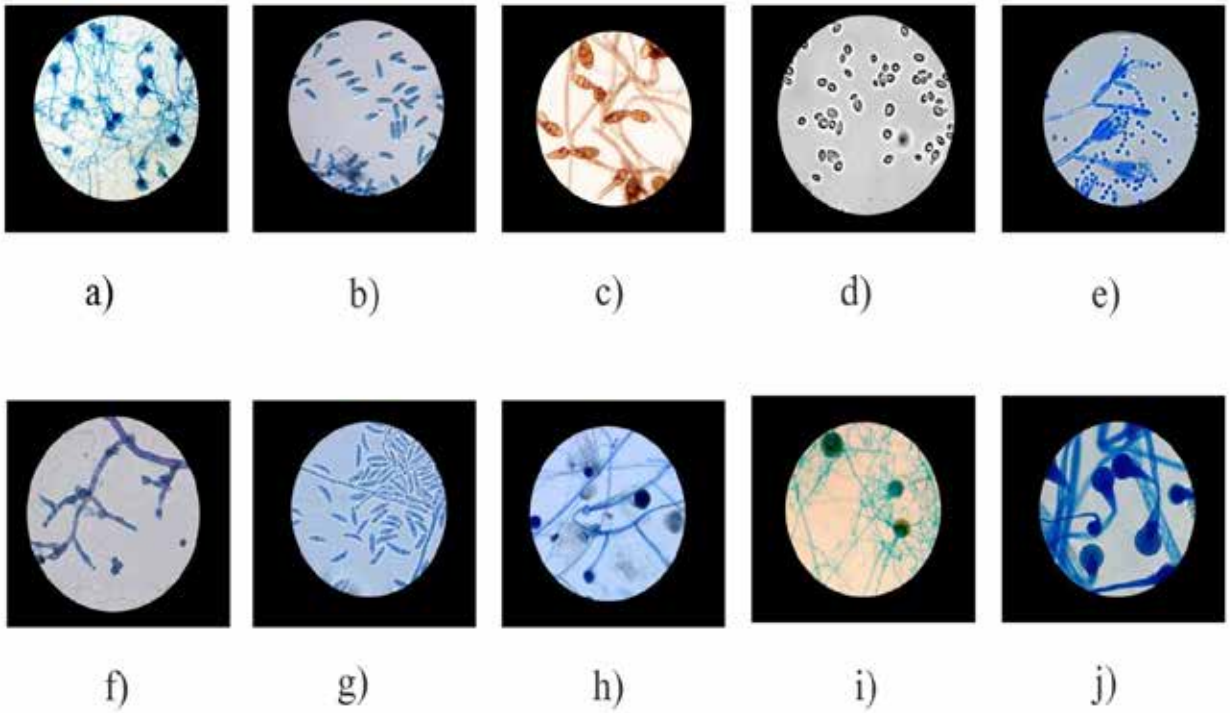

Figure 24. Microscopic photos of some fungi found in soil samples; a) *Aspergillus* sp. b) *Colletotrichum* sp. c) *Alternaria* sp. d) Yeast e) *Penicillium* sp. f) *Trichoderma* sp. g) *Fusarium* sp. h) *Mucor* sp. i) *Rhizopus* sp. j) *Absidia* sp.

CHAPTER V

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study provides comprehensive insights into the interactions between forest site, seasonality, plant species, and soil properties in a deciduous Sal forest ecosystem. The findings reveal that BNP exhibits higher SOC accumulation, whereas MNP has greater Rs, likely due to variations in microbial activity and organic matter decomposition. Seasonal variations significantly influence SOC, OC, BD, and Rs, with monsoon conditions enhancing organic carbon inputs and microbial proliferation. Among plant species, *B. pentandra* contributes most to SOC storage, while *D. pentagyna* drives higher Rs, indicating species-specific roles in soil carbon cycling. Hierarchical cluster analysis demonstrates that plant species exert differential effects on soil attributes, emphasizing the potential for targeted species selection in afforestation and reforestation efforts.

The regression analysis highlights an inverse relationship between SOC and Rs, suggesting that higher SOC levels may stabilize soil carbon by reducing microbial respiration. Moreover, microbial abundance strongly correlates with Rs, indicating that bacterial and fungal communities play a pivotal role in soil carbon fluxes. These results underscore the need to integrate microbial dynamics into forest management strategies to enhance carbon sequestration and ecosystem stability. Future research should explore the mechanistic pathways through which plant-microbe interactions influence carbon cycling, particularly under changing climatic conditions. Understanding these ecological processes will be critical for devising effective conservation and restoration strategies aimed at improving soil health and mitigating carbon emissions in forested landscapes.

5.2 Recommendations

5.2.1 Forest Management and Carbon Sequestration Strategies for Sal Forests

5.2.1.1 Selection of Species for Soil Carbon Sequestration

- *Bauhinia pentandra* and *Grewia nervosa* exhibited the highest SOC levels, making them ideal candidates for enhancing soil carbon storage.
- *Mallotus philippensis* had the lowest SOC, indicating its lesser contribution to carbon sequestration. However, its role in microbial abundance suggests that it may improve soil fertility through microbial-driven processes.
- *Shorea robusta, Careya arborea* and *Terminalia bellerica* demonstrated moderate SOC levels, making them suitable for maintaining soil stability while supporting carbon storage.

i. ***Recommendation:*** Prioritize *B. pentandra* and *G. nervosa* for afforestation and reforestation efforts aimed at increasing soil carbon sequestration, while incorporating *S. robusta, C. arborea* and *T. bellerica* to maintain ecosystem stability.

5.2.1.2 Improving Soil Health through Bulk Density Management

- *Bauhinia pentandra* exhibited the highest bulk density, which may negatively impact root penetration and soil aeration.
- *Mallotus philippensis* had the lowest bulk density, making it beneficial for improving soil porosity and aeration.

ii. ***Recommendation:*** To reduce compaction, mix species with lower bulk density (e.g., *M. philippensis*) alongside those with higher bulk density (e.g., *B. pentandra*) in plantation planning to improve soil structure.

5.2.1.3 Enhancing Soil Respiration and Microbial Activity

- *Dillenia pentagyna* exhibited the highest soil respiration (Rs), which may indicate a high decomposition rate and active microbial processes.
- *Careya arborea* and *M. philippensis* also showed relatively high Rs values contributing to carbon flux dynamics.
- *Bauhinia pentandra* had the lowest Rs, suggesting stable carbon retention rather than rapid turnover.

iii. ***Recommendation:*** In conservation planning, *D. pentagyna* and *C. arborea* should be used in areas requiring high nutrient cycling, while *B. pentandra* should be utilized in zones aimed at long-term carbon storage.

5.2.1.4 Maximizing Microbial Contributions to Soil Health

- *Careya arborea*, *B. pentandra*, and *M. philippensis* supported the highest bacterial abundance, enhancing nutrient cycling.
- *Dillenia pentagyna*, *G. nervosa*, and *B. pentandra* showed higher fungal populations, benefiting soil decomposition processes.
- *Shorea robusta* and *Terminalia bellerica* had relatively lower microbial counts, suggesting a slower organic matter turnover.

iv. ***Recommendation:***

- In areas where rapid soil nutrient cycling is needed, promote species like *C. arborea* and *B. pentandra* for bacterial enhancement.
- To improve fungal-driven organic matter decomposition, prioritize *D. pentagyna* and *G. nervosa.*
- In regions where slow decomposition is preferred (e.g., for long-term carbon sequestration), plant *S. robusta* and T. *bellerica.*

5.3 Overall Integrated Strategy

1. For Carbon Sequestration → *B. pentandra, G. nervosa, S. robusta, C. arborea.*
2. For Soil Structure Improvement → *M. philippensis, T. bellerica*.
3. For High Nutrient Cycling and Microbial Activity → *D. pentagyna, C. arborea*.
4. For Long-Term Soil Stability → *S. robusta, T. bellerica*.

5.4 Suggestions

- Apply biofertilizers and microbial inoculants to stimulate beneficial bacteria and fungi, improving soil respiration and organic matter breakdown.
- Promote organic farming and reduced chemical use to maintain healthy microbial populations and enhance nutrient cycling.
- Conduct regular microbial assessments to track changes in bacterial and fungal diversity, ensuring optimal soil conditions for carbon sequestration.
- Investigate the long-term effects of forest management practices on soil organic carbon and microbial communities.
- Assess the impact of climate change on microbial activity, soil respiration, and carbon sequestration in different forest ecosystems.
- Explore the role of mycorrhizal fungi in enhancing carbon sequestration and nutrient cycling, particularly in species with high soil carbon stocks.

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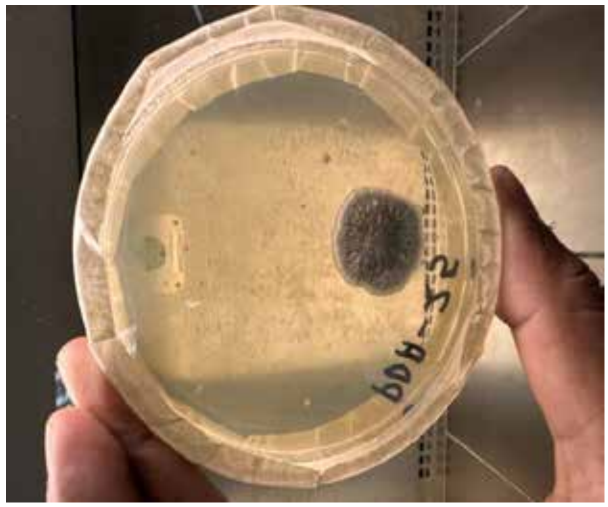
APPENDICES

Annex 1. Field activities to the study areas (Madhupur and Bhawal National Parks)



Annexure

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