A SUSTAINABLE SETTLEMENT PROTOTYPE FOR DEVELOPING MANGROVE ECO- TOURISM IN SUNDARBANS: DESIGN PRINCIPLES AND CONCEPTS FOR DISASTERADAPTABILITY THROUGH CLIMATE RESPONSIVE ARCHITECTURE

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ABSTRACT

Mangrove ecosystems are facing severe degradation due to sea-level rise, coastal erosion, cyclones and climatic change, which are further intensified by unplanned tourism and human intervention that affect soil profiles and sediment properties. Traditional vernacular construction methods are unable to resist these environmental stresses. This paper proposes a climate-responsive and disaster-resilient prototype for tropical mangrove settlements, featuring adaptive architectural strategies without compromising ecosystem integrity. Various literature studies and field surveys, combined with results from the analysis phase, help to identify architectural factors that need to be addressed during the design phase. The proposed “Settlement Prototype” emphasizes the use of local materials and construction techniques, high-pitched roofs as a response to hot-humid climatic conditions, structural systems capable of withstanding high wind velocities and elevated floor levels as a response to tidal fluctuations. In addition to mitigating climatic and environmental challenges, the prototype promotes community participation, environmental consciousness, and sustainable livelihoods opportunities. The research aims to support the long-term ecological stability of the Sundarbans by aligning architectural design with local environmental conditions and risk factors, thereby encouraging responsible tourism. This study seeks to establish a model for future eco-sensitive developments in fragile coastal and deltaic mangrove regions

Keywords: *Mangrove settlement, disaster resilience, climate adaptability, construction technique, eco-tourism.*

1. INTRODUCTION

The largest contiguous mangrove forest in the world and UNESCO World Heritage, the Sundarbans, covers an area of approximately 10,000 km and lies in both Bangladesh and India. This exclusive tidal ecosystem includes vital protective coastal measures, preservation of biodiversity, and carbon storage (Giri et al., 2011) and has livelihoods and eco-tourism possibilities. The area is also exposed to more frequent threats of climate change, such as cyclones, Sidr (2007), Aila (2009), and Amphan (2020) as well as salinity, floods and erosion. The hazards destroy not only the natural systems but also settlements and the majority of tourism infrastructure is not designed to be resilient to disasters. The recovery process after the disaster in many cases is focused on the rapid economic resurgence than focusing on a long-lasting plan. Even though eco-tourism, climate adaptation and community resilience have become debatable concepts, they are not always discussed collectively in Sundarbans context. Until recently, studies in participatory design and architectural prototypes with the incorporation of ecological, social, and disaster-resilient design are rare (Islam & Bhuiyan, 2018; Rahman et al., 2021). The conventional construction is not appropriate due to environmental challenges, including high salinity, tides, and humidity, as well as pneumatophores. Vernacular construction, which previously adapted itself to such conditions, is finding it difficult to cope with escalated dangers underscoring the lack of creative, climate-conscious ideas. The proposed research will look into the development of a prototype sustainable settlement design for mangrove-based eco-tourism, with the aim of a climate-responsive settlement stilt structure as a form of eco-tourism settlement that: (1) includes vernacular elements in dealing with hostile environments, (2) has minimal ecology imprinting through sensitive site integration and (3) is one where the structure can be used in residential, commercial, and tourism functions. The focus is to come up with a duplicate model that ensures enhanced resilience to against disasters and alleviated the environmental conservation and local economic development in the Sundarbans. The main objective of this research is to develop a replicable, climate-responsive, and disaster-resilient eco-tourism settlement prototype for mangrove environments, integrating vernacular architectural principles and ecological sensitivity within the context of the Sundarbans.

2. LITERATURE REVIEW

Resilience design of the Sundarbans mangrove habitat should employ a multidisciplinary approach that combines the input of climate responsive design, structural ingenuity, alternative materials, and disaster resistant design. The region is frequently exposed to natural hazards that impose extreme wind loads, flood inundation, and debris impact on built structures. Poor choice of site and lack of stiff characteristics, such as high plinths, streamlined roofs, and a flexible foundation, can often cause dire structural damage (Rahman et al., 2011). Both inadequately constructed buildings and heavy construction machinery crush mangrove soils, which hinders the aeration of roots, and cyclonic winds of over 150km/h and storm surges of 3 - 6 m wash away poorly designed buildings (DasGupta & Shaw, 2017; Chatterjee et al., 2020). Tourist accommodations are hardly disaster-resistant these days; ground-level villas have been swept away by cyclones, but stilt-based residential dwellings within the communities have had better resilience (Chowdhury & Haque, 2015; Mukhopadhyay et al., 2021). Yet, resilience may be compromised as post-disaster reconstruction tends to focus more on sources of revenue like tourism (Sarker et al., 2022). Salty soil, air, and water cause the increased rate of steel and concrete corrosion, and the regular lifespan of the unprotected infrastructure is about 5 or 10 years (Ghosh et al., 2016; Islam & Tabassum, 2020). When concrete is exposed to chloride in the salt areas, it decays twice to thrice the rate of buildings constructed inland (Kabir & Hossain, 2012). Use of materials and coatings that can withstand salinity is important in ensuring long life. The analyzed literature reveals that Sundarbans settlements are highly vulnerable due to exposure to cyclones, salinity-induced material degradation, and inadequate construction standards that compromise structural performance and ecological balance. In response, the proposed prototype uses treated bamboo and timber in a modular and replaceable construction system, allowing damaged elements to be repaired or replaced over its lifespan, thereby extending the overall service life of the building while preserving the surrounding ecology.

3. METHODOLOGY

In this research, a qualitative and design-based methodology was used, combining literature review, field observation, and design synthesis. Available studies and reports were consulted to identify the major environmental issues facing the Sundarbans such as cyclones, tidal waves, soil salinity and material degradation. Observation of local settlements, tourist facilities as well as informal constructions with locals and craftsmen provided insights into the practices of vernacular construction and its flaws. These insights were systematically analyzed and mapped against formal disaster-resilient and climate-adaptive design principles, guiding the development of design strategies that both respect local practices and enhance structural and ecological resilience. Based on this analysis, a settlement prototype was developed. The proposed design incorporates elevated flooring, aerodynamic shapes of roofs, use of non-salinity materials and environmental-friendly underpinnings, which seeks to disrupt the fewest elements in the environment as possible besides bolstering resilience and effective sustainability of eco-tourism in the mangrove zones.

4. CONTEXTUAL ANALYSIS

4.1 Biophysical Environment & Climate

Humidity, temperature, rainfall, hydrology, salinity, and wind flow can be collectively addressed as climatic and environmental parameters forming the biophysical environment & mangrove ecosystem. The Sundarbans is located south of the tropic of cancer and at the northern limits of the Bay of Bengal and may therefore be classified as Tropical Moist Forests. Climatically, the area of the forest falls within the tropical wet humid zone of the monsoon region, which has a massive amount of rainfall, high humidity and warm climate. The coolest temperatures occur during December-January and the warmest, towards the close of the dry season in May-June.

However, The forest area is exposed to cyclones, tidal surges and floods caused by storms because of its coastal location. It is situated at the apex of the Bay of Bengal, lies directly in the path of cyclonic storms that either form over the sea or descend from the Himalayas. These storms often bring with them intense winds, floods, and tidal surges, which converge along this coastal stretch and trigger sudden and frequent natural disasters. For centuries, major cyclones have caused immense loss of human life and widespread destruction of vegetation across the Sundarbans.

4.2 Local Architecture & Settlement Pattern

The Sundarbans settlement patterns rely heavily on both the environmental and climatic state. The design of local communities is a representation of the availability of resources as well as the need to manage frequent natural hazards. Customary housing is generally made out of locally available building materials including mud, bamboo, thatch, golpata (Nypa palm) and wood. Vernacular houses remain structurally fragile under extreme wind loads due to poor roof-to-wall anchorage, erosion of earthen plinths, and decay of untreated bamboo or thatch in high-salinity and humidity environments (The human toll of chronic waterlogging in coastal Bangladesh, 2016; Jeger, 2024).

Some, however, other households take a semi-permanent or permanent building approach, like use of mud plinths strengthened with concrete overlays, or corrugated metal roofs, or all-brick-and-concrete. Though they are more storm resistant, they are less affordable to low-income groups, and have a prolonged lifetime because of degraded materials caused by salinity and moisture. Therefore, there is a rising realization of the necessity of disaster responsive architectural planning, which makes use of the vernacular durability and incorporates modern disaster resistance elements to make them sustainable in this brittle mangrove habitat.

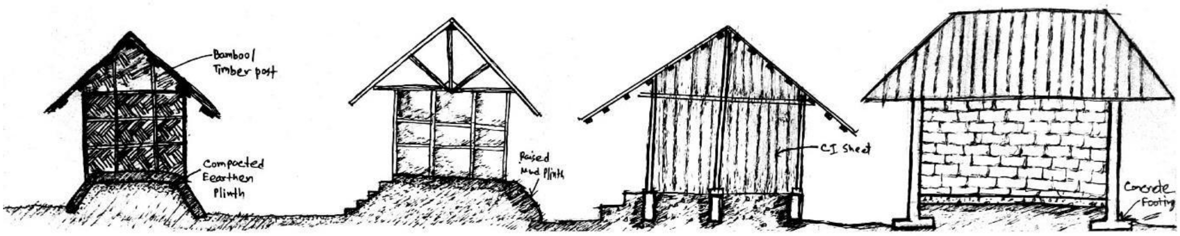


Figure 1: Different types of structures available in the region. a) Katcha (non-durable), b) Katcha (durable), c) Semi Pacca, d) Pacca.

Table 1: Analysis of local archetype and construction materials

	Katcha (Non-durable)	Katcha (Durable)	Semi-Pacca	Pacca
Foundation	-Earthen Plinth	-Earthen Plinth	-Earthen Plinth -Brick perimeter wall with earthen fill -Brick and concrete	-Brick -Concrete
Wall Structure	-Bamboo/Timber Post	-Bamboo/Timber Post	-Bamboo/Timber Post	-Brick -Concrete
Wall Enclosure	-Organic Material (jute, sticks, straw, bamboo mats, split-bamboo/ Earthen Plaster)	-Wood -CI Sheet	-Organic materials -Earthen walls -Brick particles -CI Sheets	-Brick plaster -Mortar
Roof Structure	-Split bamboo -Reed stalk frame	-Bamboo/Timber frame	-Bamboo/Timber frame	-Refined concrte
Roof Shading	-Thatch (Catkin Grass/Golpata) -CI Sheet	-CI Sheet	-CI Sheet	-CI Sheet

The comparative typological analysis of Katcha, Semi-Pacca, and Pacca structures reveals distinct structural and environmental vulnerabilities that directly inform the proposed design responses.

Table 2: Typological Weaknesses and Corresponding Design Responses

Existing Typology	Identified Weakness	Design Response in Prototype
Katcha	Roof uplift and plinth erosion during cyclones	Hip roof with ridge beam, diagonal bracing, elevated stilt platform
Katcha	Rapid decay of untreated bamboo and thatch	Treated timber and bamboo with modular replacement system
Semi-Pacca	Material incompatibility and corrosion	Unified lightweight structural system with non-saline-sensitive

		materials
Pacca	High ecological footprint and soil compaction	Low-impact stilt foundation minimizing ground contact
Pacca	Accelerated deterioration in saline environments	Avoidance of reinforced concrete; use of renewable, repairable materials

5. DESIGN PRINCIPLES & CONCEPTS DERIVED FROM CONTEXTUAL ANALYSIS

Vernacular architecture analysis by climatic and environmental factors gives essential instructions towards spatial and internal needs in delicate ecosystems. The built form should be in reaction to an ecological condition, and any considerations within the design are drawn to architectural parameters with an aim of low impact on the environment while maintaining effective resilience.

5.1 Climatic Factors & Design Considerations

The unique climatic conditions of the Sundarbans such as, high humidity, heavy monsoon rainfall, including frequent cyclones and saline water intrusion enforce in adopting climate responsive architectural design strategies. These climatic parameters serve as direct inspiration in design features like high stilted floors or vents to block flood threats, open ventilation systems to block thermal discomfort, and locally sourced moisture-proof materials to overcome corrosion and saltwater intrusion. Through these climate considerations in the design process, it is possible to create a base to these settlements that are not only environmentally sensitive but also those that can sustain both functionality and comfort in conditions of extreme weather.

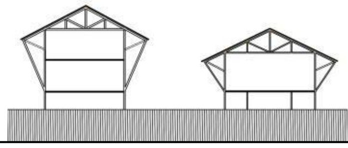
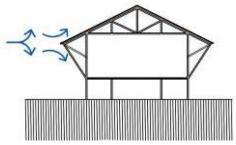
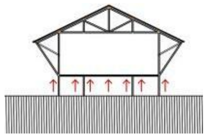
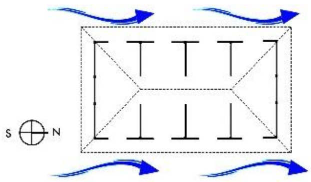
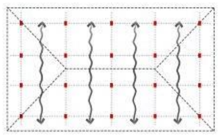
Table 3: Design considerations derived from climatic factors

Climatic Factors	Architectural Strategy	Design Description
High Humidity	Open Floor Plan	Pavilion like structures with large opening for cross-ventilation and raised floor to capture air circulation
Tidal Flow	Stilt Platform	Elevated Structures constructed on stilt platform/foundation remain safe from tidal inundation
High Wind Velocity	Hip Roof	Four-sided Sloping roof ensures runoff and resist uplift during cyclones
Driving Rain	Extended overhangs & Deep Eaves	Deep Eaves and Verandahs to shield walls and openings from rain impact
Salinity	Natural Materials	Using salt-resistant, renewable resources (treated timber, thatched roof, bamboo) following local construction technique

5.2 Architectural Factors

Climate-informed design considerations translate into specific architectural factors to determine the physical measures of the following structure, to enhance adaptability and optimum resilience. The physical measures described here are used to establish the design parameters of scale, form, and proportions of the structures as derived from disaster resilience and ecological needs. The architecture should be of a low-rise building with aerodynamic form and roof geometries to secure durability and stability against high cyclone winds. Additionally, careful placement of settlement and structural orientation is optimized to maximize natural ventilation and follow the direction of regular tidal flow.

Table 4: Design parameters of architectural factors

Architectural Factors	**Design Parameters**	**Graphical Illustrations**
Building Height	-Floor level should vary between 1-2 floors for compact proportion & safety against wind flow	
Building Shape & Geometry	-Compact geometries (rectangular, square footprints) to minimize wind drag and structural complexity. - Aerodynamic Roof Form reduce wind pressure and uplift during cyclones.	
Building Structure	- Buildings should be raised on stilts 4-5 ft above ground level. - Protects from tidal flow, floods, and waterlogging.	
Building Orientation	- Buildings must be oriented in the North-South elongated position - ensure stability with minimum wind pressure	
Structural Orientation	- Building rows should allow tidal waves to pass through. - Higher spacing maintained toward the water flow direction.	

6. DESIGN DEVELOPMENT

The final built form of the research is a representation of a climate responsive resilient design complementing the local architecture and climate context. The traditional timber structure of this region has been selected as to upgrade it with more climate responsive features identified in the study and analysis phase to achieve better resilience and sustainability. Inspiration for the design was drawn from the local building construction technique using locally available material to ensure sustainability and adaptability of the design. Moreover, consideration for severe climatic condition of mangrove area like cyclone, driving rain, high speed wind, high salinity also reshape the total built form and helped to generate more site-specific architecture.

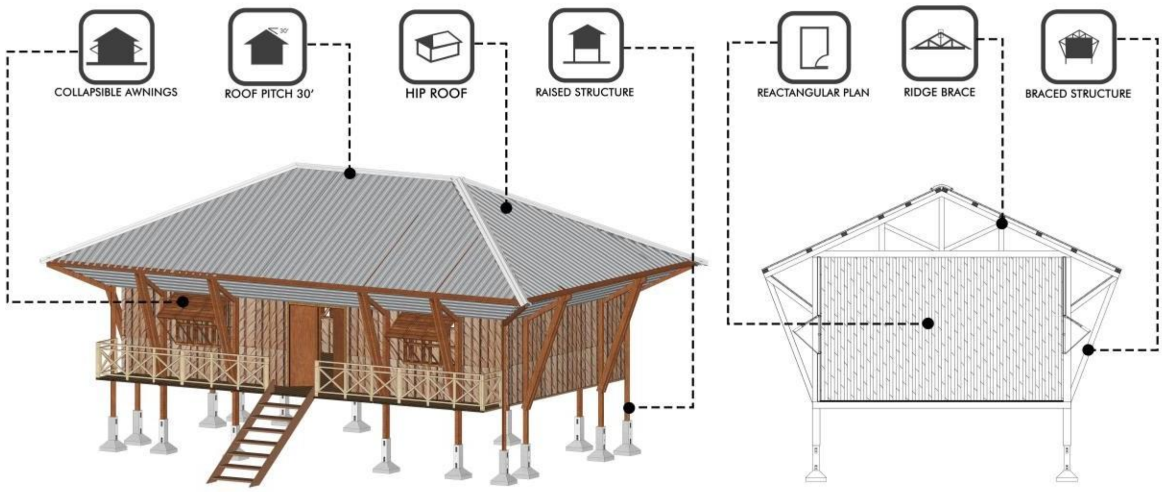


Figure 2: Climate-responsive architectural and structural features of the proposed mangrove settlement prototype

Building Mass and Form: The design has been generated on a single rectangular plan for compactness and durability. The compact rectangular design employs reinforced Nypa Palm walls, offering a lightweight, low-maintenance, and thermally comfortable enclosure in warm-humid conditions.

Building Orientation: The study of wind analysis gives a clear indication of orientation decisions, yet it requires site-specific justification for determining the alignment of the structure. Although wind direction varies seasonally, the prevailing winds in the region generally originate from the south-east to south-west. During the pre-monsoon and monsoon periods, particularly from March to April, strong winds predominantly blow from the south to south-west, while in the winter season the dominant wind direction shifts to the north-west. In addition, cyclonic storms occur frequently during the mid-year period, driven by strong coastal wind systems along the northern coastline (Forest Department, Ministry of Environment and Forests [FD], 2010). Therefore, considering north and south as the dominant direction of wind flow, North-South elongated orientation (longer side at East-West direction) is proposed for less wind pressure and better stability.

Roof Design: A four-pitched hip roof with an angle of 30' has been selected for better wind resistance. The top roof sheet is protected through providing enclosed small overhang around the bottom of the roof. This will minimize the chance of roof catching wind and lifting while providing shade and rain cover to the façade.

Structural Considerations: To ensure strength against high-speed wind flow, the roof truss was improvised by using "Ridge Beam" and "Eave Beam" which would provide more structural integrity. Diagonal Bracings are designed to support roof overhang and to prevent roof turn over during high wind condition. Cyclone resistant design features are included with supporting references and load reasoning in the paper.

- Hip roofs: Heap roofs provide better protection for the roof from lifting during cyclone wind. Roof pitch with an angle of 30 degree also minimizes impact of cyclone wind
- Ridge beams: Wooden truss is designed with ridge beams that will brace the roof-truss member and provide continuity and load transfer along the roof apex, improving overall structural stability under fluctuating wind loads.
- Diagonal bracing: Diagonal bracing provides roof anchorage and prevents roof turnover. It also enhances lateral stiffness during high wind velocities and cyclic loading during storms.

- Roof overhangs: Extended overhanging with diagonal bracing is used to protect facade material from extreme weather effects when properly proportioned and securely anchored.

Support and Foundation: The built form is raised upon 4-5 feet high stilt supports in case of regular tidal surges and flood events. Specially designed concrete footing will give protection from frequent tidal surges and high salinity by protecting the timber of the foundation. Mean tide heights in the Sundarbans have been documented at approximately 1.5-2m during monsoon and dry periods at coastal points, reflecting typical tidal dynamics (Aziz & Paul, 2015). During cyclones, most extreme surges have been recorded from 3m up to 6m in the coastal edge (DasGupta & Shaw, 2017), and in extreme historical events possibly even higher. However, surge levels can differ greatly across the Sundarbans due to distance from the coast and presence of mangrove buffers. For precise design, local hydraulic modeling is ideal for determining stilt height. For a settlement prototype in the Sundarbans area, this research follows existing guidelines for disaster-prone rural housing in Bangladesh recommend elevating homestead by at least 5 ft (appx. 1.5 m) above surrounding levels where possible, with greater heights advised in areas exposed to higher storm surge levels (Housing and Building Research Institute [HBRI], 2018).

Air Circulation and openings: Enough ventilation & thermal comfort for interior space is ensured by providing enough window openings with collapsible awnings, that can be closed during cyclone events and provide protection against rain.

Building Materials: For roofing, galvanized trapezoidal sheet was selected for the best balance of cost, availability, durability, and ease of installation for eco-tourism infrastructure. While trapezoidal profile adds structural strength and promotes quick drainage, the paint coating helps resist salt spray and humidity. On the other hand, timber from locally available rain tree is used for the structural frame-trusses, purlins & flooring with proper seasoning and treatment to achieve durability against humidity & salinity. While saline air and tidal moisture accelerate the deterioration of bamboo and timber in coastal environments, the proposed prototype ensures long-term durability through a modular and demountable structural system rather than material permanence. Treated bamboo and timber are used to reduce environmental impact, and any damaged components can be selectively removed and replaced without compromising the overall structural integrity. This strategy extends the effective service life of the settlement, minimizes material waste, and supports sustainable maintenance under harsh mangrove conditions.

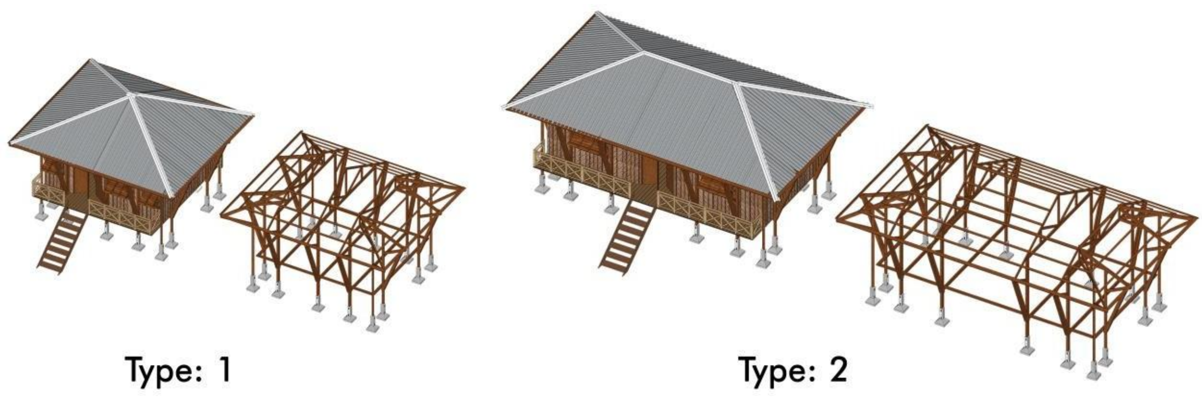


Figure 3: Modularity of the proposed settlement prototype, illustrating a repeatable structural module that can be combined, extended or reconfigured to support residential, commercial and eco-tourism functions

Modularity: The proposed built form is designed with modular components and by following similar structural configurations, the basic prototype can be reconfigured to create various spaces and types of buildings to support different eco-tourism and residential functions.

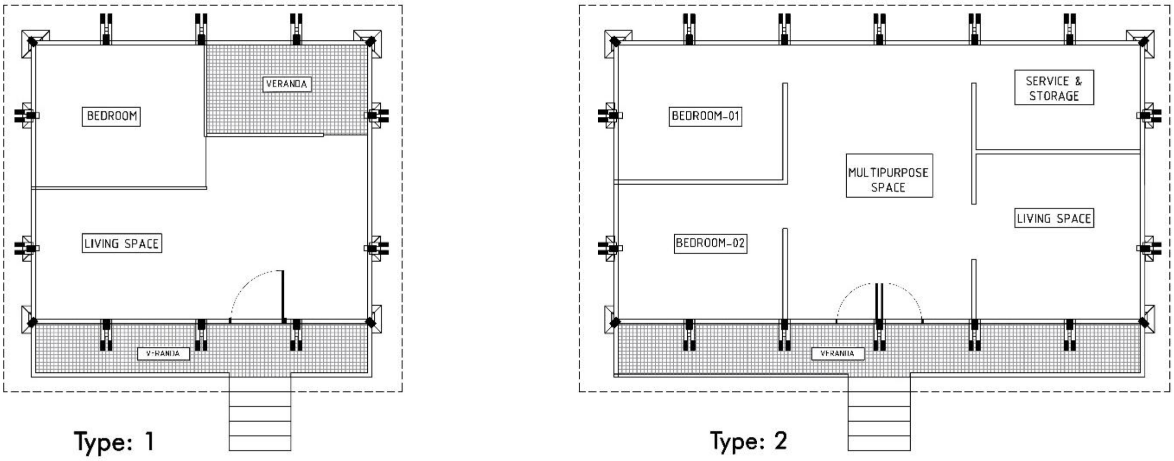


Figure 4: Illustration of modular flexibility showing functional reconfiguration of the prototype for a) Tourist Cottage (left) & b) Homestead (right)

7. RESEARCH OUTCOME AND DISCUSSION

The results demonstrate a climate-responsive, disaster-adaptive, sustainable and resilient settlement prototype. The limitations and drawbacks of current vernacular architecture have been identified and alternative design solutions and materials are suggested to reduce the adverse impacts of climate on traditional forest buildings while protecting mangrove ecology.

Some limitations of the research lie in determining the cost-effective scenario of the proposed design, identifying structural performance under real disaster conditions and assessing feasibility in terms of local craftsmanship and scalability across different settlement clusters. Even though the design is based on local materials and common construction practices, economic analysis, skill mapping of communities, and pilot-scale implementation are needed to determine affordability, replicability and long term sustainability.

Future studies may involve experimental testing of the prototype, exploring its multifunctional applications as a local homestead and investigating how the design can empower communities while preserving ecological integrity.

8. CONCLUSION

The Sundarbans, the world's largest contagious mangrove forest located between Bangladesh and India, has faced serious degradation due to rising sea levels, cyclones, climatic change and coastal erosion. The existing vernacular settlements in this region face difficulties in managing these ecological challenges to sustain long-term habitation. This research aims to develop a climate-sensitive and disaster-resilient settlement prototype that mitigates climate impacts through climate-responsive design strategies. The research is carried out through a comprehensive review of relevant local scholarly publications, technical reports, site surveys and questionnaire-based discussions. The study integrates several design strategies through contextual analysis, including aerodynamic hip roofs to resist cyclone winds, elevated stilt platforms to protect against tidal flooding, open floor plans and large openings to enhance passive ventilation in hot-humid climates. The use of saline-resistant materials and modular design systems further contributes to resilience while minimizing ecological impact.

The proposed prototype not only promotes structural stability but also encourages community involvement, environmental stewardship and sustainable eco-tourism, contributing to both ecological and economic benefits. The findings highlight that site-specific, low-impact, and adaptive design principles must form the foundation for sustaining mangrove-based settlements under increasing climate pressures. The proposed model offers a replicative framework for future eco-sensitive development in coastal and deltaic regions and establishes a precedent for integrating resilience, sustainability, and cultural continuity within fragile ecosystems.

DECLARATION OF USE OF AI

The authors declare that artificial intelligence (AI) tools were used during the manuscript preparation process solely for language editing purposes, including the reduction of grammatical errors, improvement of sentence structure, enhancement of logical flow, and maintenance of overall coherence and clarity of the text. The AI tools were not used in the research design, data collection, analysis, interpretation of results, or generation of original scientific content. All conceptual development, analysis, design decisions, and conclusions remain entirely the responsibility of the authors.

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