

Reframing Mangroves as Socio-Ecological Coastal Infrastructure: Development and Application of a Six-Pillar Socio-Ecological Infrastructure Framework

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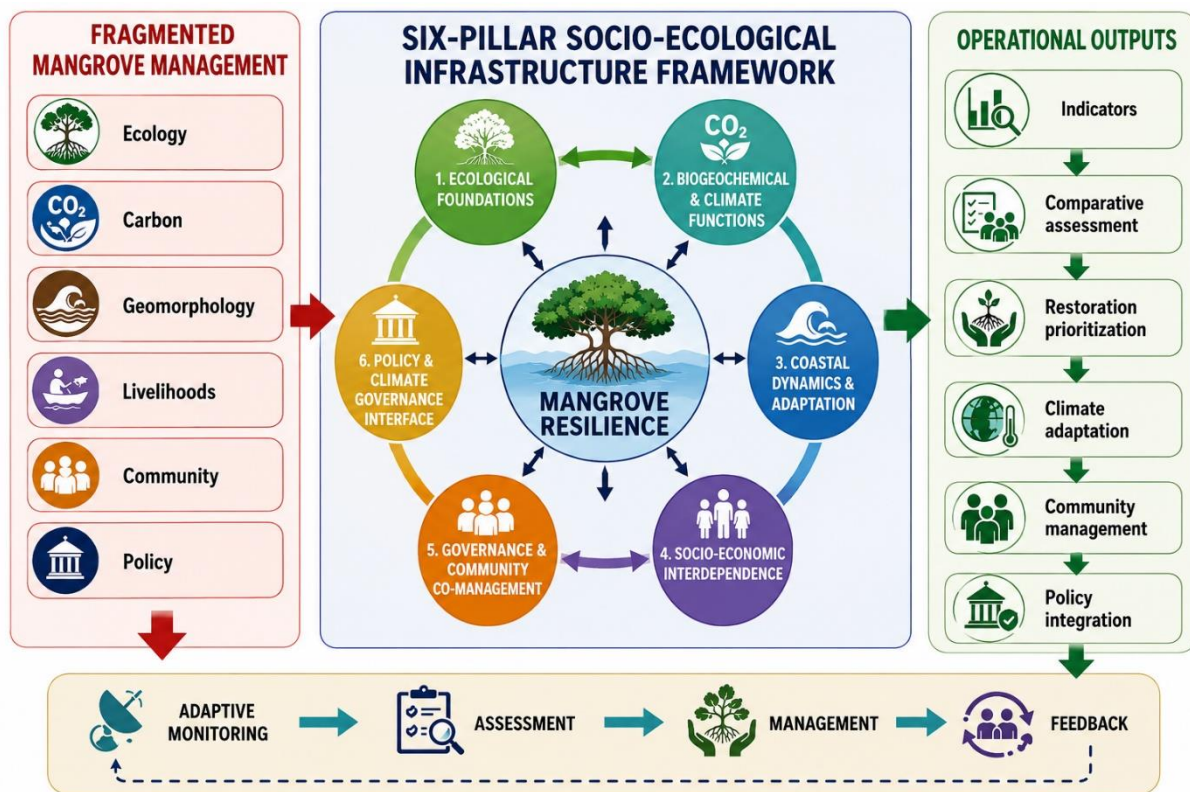
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Graphical Abstract Figure. Graphical Framework of Mangrove Ecosystem Functions and Conceptual Models.

Structured Abstract

Background:

Mangrove conservation research has historically evolved across multiple disciplinary domains, including ecology, geomorphology, biogeochemistry, environmental and pollution science, and coastal governance. Although each field has generated significant knowledge, these perspectives have often remained fragmented, resulting in conservation strategies that address isolated aspects of mangrove systems rather than their integrated functioning.

Objective:

This study proposes an integrated socio-ecological framework for mangrove protection that synthesizes ecological knowledge, coastal geomorphology, climate regulation functions, and community governance. Drawing upon Indian mangrove research – including ecological

observations (Jagtap, 1985), physico-chemical assessments of arid mangrove ecosystems (Sawale, 2012), biodiversity and pollution studies (Sumra, 2025), blue carbon and ecosystem service analyses (Malasatar, 2024), and coastal vulnerability research (Vaidya, 2025) – the study develops a comprehensive framework applicable to mangrove management in India and comparable tropical coastlines.

Results:

The resulting Six-Pillar Socio-Ecological Infrastructure Framework organizes mangrove resilience into six interacting dimensions: ecological foundations; biogeochemical and climate functions; coastal dynamics and adaptation; socio-economic interdependence; community co-management; and policy–climate governance. Each pillar is linked to representative indicators and potential management responses. Illustrative applications to the Sundarbans and Kachchh demonstrate how the same framework can organize contrasting ecological, geomorphological, socio-economic, and governance contexts and identify context-specific management priorities. The framework is presented as an analytical and decision-support structure rather than as a quantitatively validated predictive model.

Conclusion:

Effective mangrove protection requires reframing these ecosystems as socio-ecological infrastructure systems whose resilience depends on interactions among ecological processes, sediment dynamics, climate functions, community participation, and governance. The proposed framework provides an integrated structure for organizing these dimensions, translating them into context-dependent indicators, and supporting adaptive management. Its empirical performance, relative pillar importance, and predictive utility remain to be tested through comparative and longitudinal studies.

Key Message	Importance
Mangroves should be managed as socio-ecological infrastructure rather than isolated ecosystems.	Integrates ecology and governance.
Six interacting pillars determine long-term resilience.	Provides the conceptual basis of the study.
Conservation depends on maintaining hydrology, sediment dynamics, biodiversity, and community participation simultaneously.	Supports integrated management.
Adaptive governance and continuous monitoring are essential under climate change.	Connects science with practice.

Standard Abstract (≤150 words)

Mangrove ecosystems are critical components of coastal socio-ecological systems, providing shoreline protection, biodiversity support, carbon sequestration, and livelihood opportunities for coastal communities. However, increasing pressures from climate change, coastal development, and environmental degradation threaten their resilience and long-term sustainability. This study proposes a Six-Pillar Socio-Ecological Infrastructure Framework that integrates ecological processes, climate regulation functions, coastal geomorphological dynamics, socio-economic interdependence, community co-management, and policy–climate governance. By synthesizing these interconnected dimensions, the framework provides a holistic analytical approach for understanding how mangrove ecosystems contribute to coastal resilience. Empirical insights from regions such as the Sundarbans and coastal areas of Gujarat illustrate the practical relevance of the framework for ecosystem-based adaptation and sustainable coastal governance. The manuscript also highlights policy implications, research gaps, and pathways for strengthening mangrove conservation within broader climate adaptation and coastal management strategies.

Keywords: Mangrove ecosystems; Coastal socio-ecological resilience; Ecosystem-based adaptation; Blue carbon; Coastal governance; Climate change adaptation; Sustainable coastal management.

The manuscript conveys one clear message:

Problem

Mangrove knowledge is multidisciplinary but fragmented.



Gap

Existing approaches provide valuable perspectives, including mangrove–SDG, NbS, EbA and SES approaches, but the manuscript argues that a more explicit operational integration is useful.



Method

Multidisciplinary evidence synthesis → recurring resilience determinants
→ domain consolidation → six pillars



Contribution

Six-Pillar Socio-Ecological Infrastructure Framework



Operationalization

Pillar → indicator → interpretation → management response



Application

Sundarbans vs Kachchh



Insight

The same six dimensions apply, but their relative management relevance differs with ecological and institutional context



Validation pathway

Expert assessment → pilot sites → multi-site comparison → longitudinal monitoring →
quantitative testing



Impact

Restoration + climate adaptation + community governance + policy integration

1. Introduction

Mangrove ecosystems occupy a narrow transitional zone between terrestrial and marine environments, yet their ecological influence extends far beyond the immediate intertidal region. Across tropical and subtropical coastlines, mangroves function as natural coastal defenses, biodiversity reservoirs, carbon sinks, and livelihood support systems for millions of coastal inhabitants (Worthington et al., 2020). Recent research increasingly recognizes mangrove ecosystems as critical nature-based solutions for strengthening coastal resilience and climate adaptation in tropical and subtropical regions. Global assessments highlight that mangroves reduce coastal vulnerability by attenuating wave energy, stabilizing sediments, and protecting coastal infrastructure from storm surges and extreme weather events (Alongi, 2020; Analuddin et al., 2023). Growing attention has also been directed toward the role of mangroves within integrated coastal socio-ecological systems, where ecological processes, sediment dynamics, and human governance structures interact to shape long-term coastal stability (Friess et al., 2020; Goldberg et al., 2020). The global biophysical diversity of mangroves, including differences in tidal regimes, salinity gradients, and sedimentary contexts, further influences ecosystem structure, productivity, and vulnerability to deforestation and degradation (Worthington et al., 2020).

Recent studies additionally emphasize the importance of mangroves as globally significant blue carbon ecosystems. Blue carbon ecosystems (BCEs), such as mangrove forests, seagrass meadows, and tidal marshes, play a vital role in long-term carbon sequestration while delivering a range of ecosystem services. In addition to storing significant amounts of carbon, these coastal habitats contribute to shoreline stabilization, reduce the impacts of coastal hazards, and support

fisheries by providing essential breeding and nursery grounds for marine species. These forests store substantial quantities of organic carbon within both biomass and waterlogged sediments, where anaerobic conditions slow decomposition and allow carbon to remain sequestered for extended periods (Alongi, 2020; Macreadie et al., 2021). Consequently, mangrove conservation and restoration have become increasingly integrated into international climate mitigation strategies and ecosystem-based adaptation initiatives (UNEP, 2021; Macreadie et al., 2021). At the same time, contemporary research highlights intensifying multi-scale pressures from coastal development, industrial expansion, pollution, and climate-driven sea-level rise. These pressures interact across ecological and socio-economic dimensions, influencing sediment dynamics, hydrological connectivity, and biodiversity structure within coastal landscapes (Goldberg et al., 2020; Friess et al., 2020). As a result, recent scholarship increasingly calls for integrated socio-ecological approaches to mangrove management that combine ecological science, geomorphological understanding, climate policy, and community participation within unified governance frameworks (UNEP, 2021; Macreadie et al., 2021).

Mangrove ecosystems have therefore attracted growing global research attention because of their ecological and socio-economic significance. Studies across Southeast Asia, Africa, and Latin America highlight the role of mangroves in coastal protection, fisheries productivity, and carbon sequestration (Barbier, 2016; Duke et al., 2007; Lovelock et al., 2015). Restoration initiatives in tropical regions further demonstrate the importance of hydrological connectivity and species-specific ecological conditions for successful mangrove rehabilitation (Primavera & Esteban, 2008). These global studies reinforce the need for integrated socio-ecological approaches that recognize mangrove ecosystems as dynamic coastal systems shaped by interacting ecological, geomorphological, and governance processes. Despite extensive ecological research, mangrove conservation strategies often remain fragmented across disciplinary domains, including ecology, pollution monitoring, geomorphology, and climate policy. Such fragmentation limits the development of integrated coastal management approaches capable of addressing the complex socio-ecological dynamics of mangrove systems.

In India, where extensive coastal populations depend on marine resources and shoreline stability, mangrove ecosystems represent a critical component of coastal resilience. Despite their recognized importance, conservation strategies have frequently been implemented in fragmented ways. Management interventions have often focused independently on plantation programs, biodiversity inventories, pollution monitoring, or carbon-stock assessments. While

these approaches have generated valuable scientific knowledge, they rarely address the interconnected ecological and socio-economic processes that determine long-term mangrove resilience. This fragmentation across ecological, biogeochemical, geomorphological, socio-economic, and governance domains is illustrated in Figure 1, highlighting the need for an integrated framework capable of connecting these dimensions within a common analytical structure.

This paper proposes and advances a comprehensive framework that integrates ecological science, geomorphological processes, climate regulation functions, pollution dynamics, and community governance within a single analytical perspective. The framework builds upon several decades of Indian mangrove research, including ecological observations of species zonation and ecosystem functioning (Jagtap, 1985), studies of structural characteristics and physico-chemical drivers in arid mangrove environments (Sawale, 2012), investigations of biodiversity patterns and heavy-metal accumulation (Sumra, 2025), analyses of sediment carbon storage and ecosystem services (Malasatar, 2024), and coastal geomorphological assessments of shoreline change and vulnerability (Vaidya, 2025). Recognizing mangroves as socio-ecological infrastructure expands the scope of conservation beyond habitat protection. It emphasizes the role of mangrove ecosystems in supporting coastal stability, climate mitigation, fisheries productivity, and community livelihoods. Such an integrative understanding is particularly important in the context of accelerating environmental change, including sea-level rise, coastal urbanization, and industrial development along many Indian shorelines.

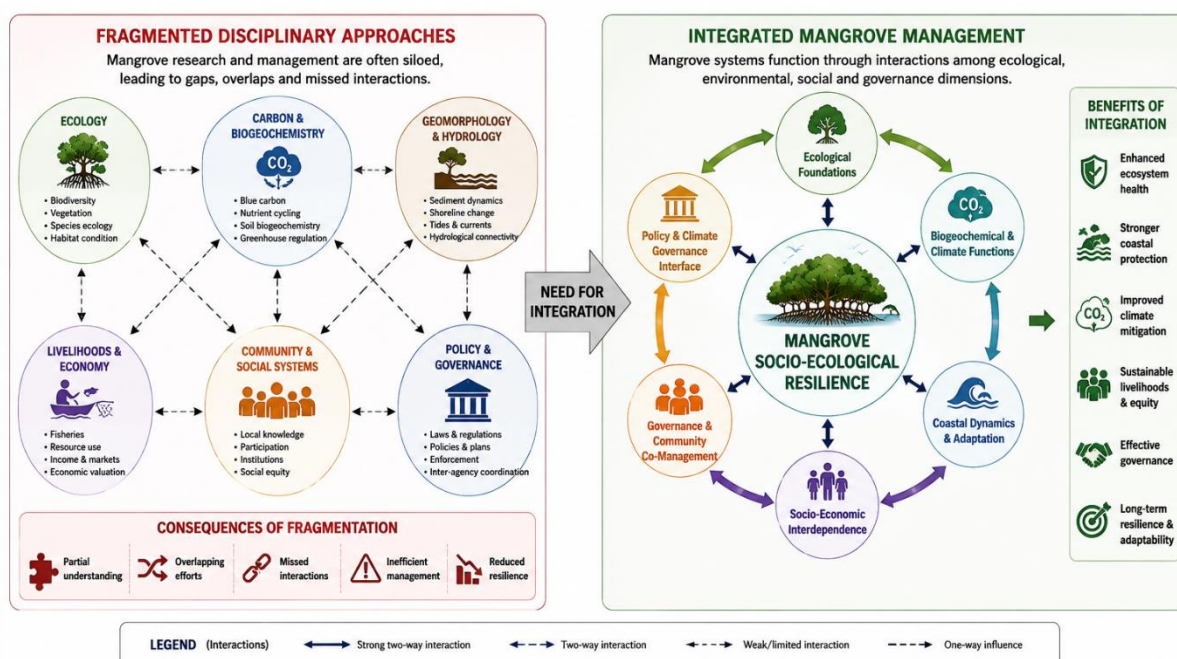


Figure 1. Fragmented disciplinary approaches to mangrove management.

Schematic representation of the principal disciplinary domains that have commonly been considered separately in mangrove assessment, including ecology, biogeochemistry and carbon, geomorphology and coastal dynamics, livelihoods, community participation, and governance and policy. The figure illustrates the conceptual fragmentation that motivates development of an integrated socio-ecological infrastructure framework.

1.1 Positioning the Socio-Ecological Infrastructure Framework within Existing Coastal Management Approaches

Mangrove conservation has increasingly been addressed through several conceptual frameworks within environmental science and coastal governance. Among the most widely applied are ecosystem-based adaptation (EbA), nature-based solutions (NbS), and broader socio-ecological systems (SES) approaches. These frameworks have significantly advanced understanding of how natural ecosystems contribute to climate resilience and sustainable development. However, each approach tends to emphasize particular dimensions of ecosystem management rather than the integrated functioning of coastal systems. Ecosystem-based adaptation primarily focuses on the use of biodiversity and ecosystem services to reduce vulnerability to climate change. Nature-based solutions highlight the capacity of natural ecosystems to address societal challenges such as coastal protection, water management, and disaster risk reduction. Socio-ecological systems theory, in contrast, emphasizes the complex interactions between human institutions and ecological processes within coupled human–environment systems.

While these frameworks provide important insights, mangrove ecosystems often require a more explicitly integrated perspective that simultaneously accounts for ecological processes, sediment dynamics, climate regulation, pollution buffering, and governance structures. The Socio-Ecological Infrastructure Framework proposed in this study extends these approaches by conceptualizing mangroves as multi-functional coastal infrastructure systems.

Within this perspective, mangrove forests operate not only as ecological habitats but also as dynamic coastal infrastructure that stabilizes sediments, regulates carbon cycles, filters pollutants, and supports human livelihoods. This framing emphasizes that mangrove resilience depends on the interdependence of ecological processes, geomorphological dynamics, socio-economic dependence, and governance institutions. By integrating these dimensions within a unified analytical structure, the framework provides a more comprehensive basis for

understanding how mangrove ecosystems contribute to long-term coastal stability and climate adaptation.

At the foundation of the framework lies the biophysical system, which includes mangrove ecology, sediment dynamics, hydrological processes, and coastal geomorphology. These components shape the structural and functional characteristics of mangrove habitats and determine ecosystem productivity, stability, and spatial distribution. These ecological processes support key ecosystem functions, including carbon sequestration, nutrient cycling, habitat provision, shoreline stabilization, and pollution buffering. Together, these functions sustain the ecological integrity of mangrove landscapes while regulating important coastal biogeochemical processes. Through these ecological functions, mangrove ecosystems generate substantial socio-economic benefits for coastal societies. These benefits include coastal protection from storms and erosion, fisheries productivity, climate regulation through carbon storage, and disaster risk reduction for vulnerable coastal communities. The final component of the framework involves governance and policy mechanisms, which shape conservation outcomes and long-term ecosystem management. These mechanisms include mangrove restoration programs, community-based co-management systems, coastal zoning policies, and climate adaptation strategies. A feedback loop connects governance interventions back to the biophysical system, illustrating adaptive governance processes. Through restoration initiatives, regulatory policies, and community stewardship, management decisions influence ecological stability, habitat recovery, and long-term resilience of mangrove ecosystems.

1.2 From Roots to Actions: Analytical Structure of this Manuscript

To guide the discussion, the manuscript adopts an analytical progression that links ecological foundations with conservation practice. While the paper presents an integrated socio-ecological framework, ecological grounding remains essential before addressing governance and policy dimensions. Accordingly, the discussion follows a four-stage analytical progression that connects ecological processes with conservation strategies:

Roots – Ecological Mechanisms

This section examines the fundamental ecological characteristics of mangrove ecosystems, including species adaptations, sediment dynamics, hydrological processes, and biodiversity interactions that structure mangrove habitats.

Risks – Destabilizing Pressures

This section analyses anthropogenic and environmental pressures affecting mangrove ecosystems, including coastal development, pollution, habitat conversion, and climate-driven shoreline change.

Resilience – Socio-Ecological Value

This section evaluates the ecosystem services provided by mangroves, including coastal protection, fisheries support, carbon sequestration, and climate regulation, highlighting their importance for coastal sustainability.

Actions – Operational Strategies

The final section translates ecological knowledge into practical strategies for restoration, community governance, and policy implementation that support long-term coastal management and resilience.

1.3 Framework Validation and Applicability

The Six-Pillar Socio-Ecological Infrastructure Framework was developed through a structured conceptual synthesis of published research on Indian mangrove ecosystems, encompassing ecological, geomorphological, biogeochemical, socio-economic, and governance perspectives. Rather than being derived from a single empirical dataset, the framework consolidates evidence from ecological studies, biodiversity assessments, blue-carbon research, sediment dynamics, pollution monitoring, and coastal governance literature into a unified analytical structure. The six pillars were retained because they represent distinct but interacting dimensions repeatedly identified across these evidence domains as relevant to mangrove resilience and long-term sustainability.

The framework is proposed as a conceptual and analytical decision-support framework rather than a predictive ecological model. Its purpose is to organize multidisciplinary evidence into a coherent structure that facilitates interdisciplinary research, restoration planning, adaptive coastal management, and policy development. By integrating ecological processes, coastal geomorphology, biogeochemical functions, socio-economic dependence, community co-management, and policy governance, the framework extends existing Nature-Based Solutions, Ecosystem-Based Adaptation, and Socio-Ecological Systems perspectives by explicitly positioning mangroves as multifunctional socio-ecological coastal infrastructure. Although developed primarily from evidence concerning Indian mangrove systems, the framework is

designed to remain adaptable to other tropical and subtropical coastal contexts, subject to local ecological, institutional, and socio-economic conditions.

As a conceptual synthesis, the framework provides an analytical foundation for future research rather than a definitive predictive model. Further refinement should involve expert evaluation, comparative regional applications, empirical case studies, and long-term ecological monitoring to assess the relative contributions and interactions of the six pillars under different environmental and governance conditions. Such studies will strengthen the framework's applicability as a decision-support tool for evidence-based mangrove conservation and sustainable coastal management.

The ecological and environmental gradients underlying mangrove zonation are illustrated in Figure 2, which integrates tidal inundation, elevation, salinity, sediment characteristics, dominant mangrove species, and associated ecological functions across the landward–seaward gradient. These spatial patterns highlight the role of hydrological and sedimentary processes in shaping mangrove distribution, establishment, persistence, and functioning, providing a direct ecological foundation for the Coastal Dynamics and Adaptation pillar of the proposed framework.

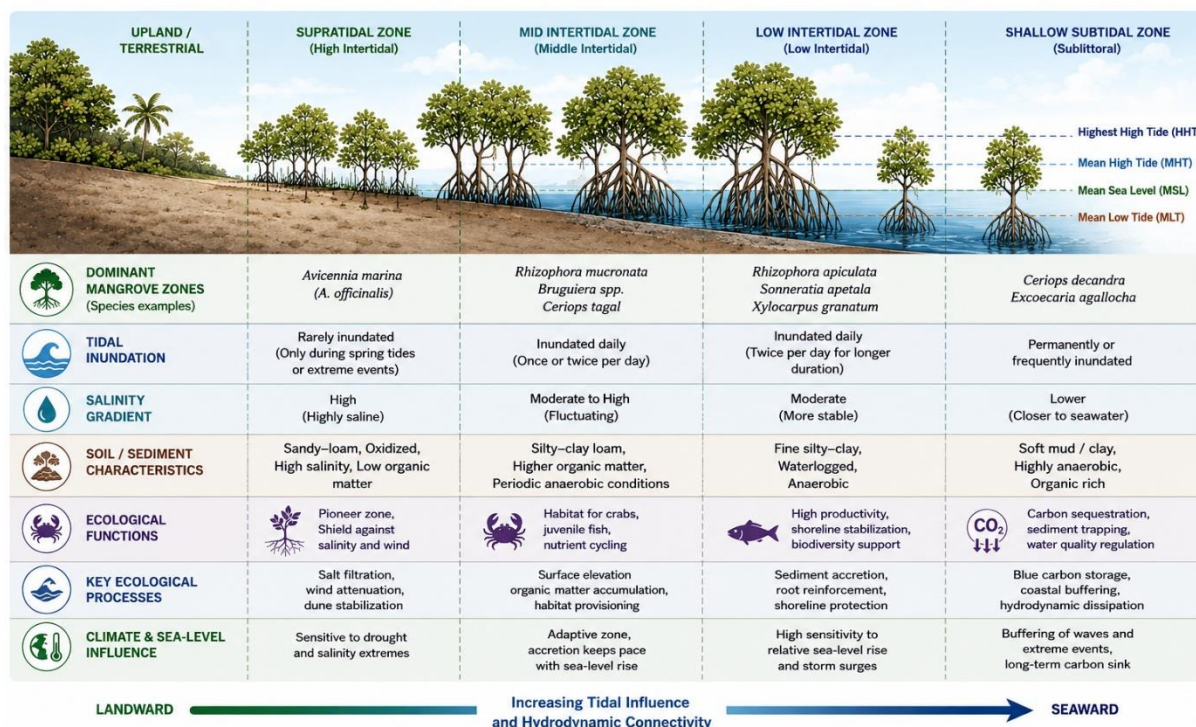


Figure 2. Mangrove zonation across the tidal and environmental gradient.

Schematic representation of mangrove distribution from upland/terrestrial areas to shallow subtidal zones, showing changes in tidal inundation, salinity, soil and sediment characteristics, dominant mangrove species, and associated ecological functions. The gradient illustrates how hydrological and sedimentary conditions influence mangrove establishment, distribution, and ecosystem functioning.

Coastal dynamics constitute an important determinant of mangrove persistence because vegetation distribution and ecosystem stability are influenced by tidal exchange, sediment transport, shoreline erosion and accretion, wave exposure, and changes in coastal morphology. These processes interact with vegetation establishment and sediment retention, creating feedbacks between mangrove structure and coastal stability. Accordingly, the Coastal Dynamics and Adaptation pillar incorporates indicators that capture hydrological connectivity, shoreline change, sediment dynamics, and exposure to coastal hazards.

Mangrove forests store substantial quantities of organic carbon within both biomass and waterlogged sediments (Macreadie et al., 2021). And, the processes responsible for carbon sequestration in mangrove ecosystems involve the continuous transformation, transport, and storage of organic matter within soils and sediments. These interconnected pathways underpin the exceptional blue-carbon capacity of mangrove forests and contribute significantly to long-term climate regulation. The principal pathways of organic carbon cycling in mangrove ecosystems are illustrated in Figure 3.

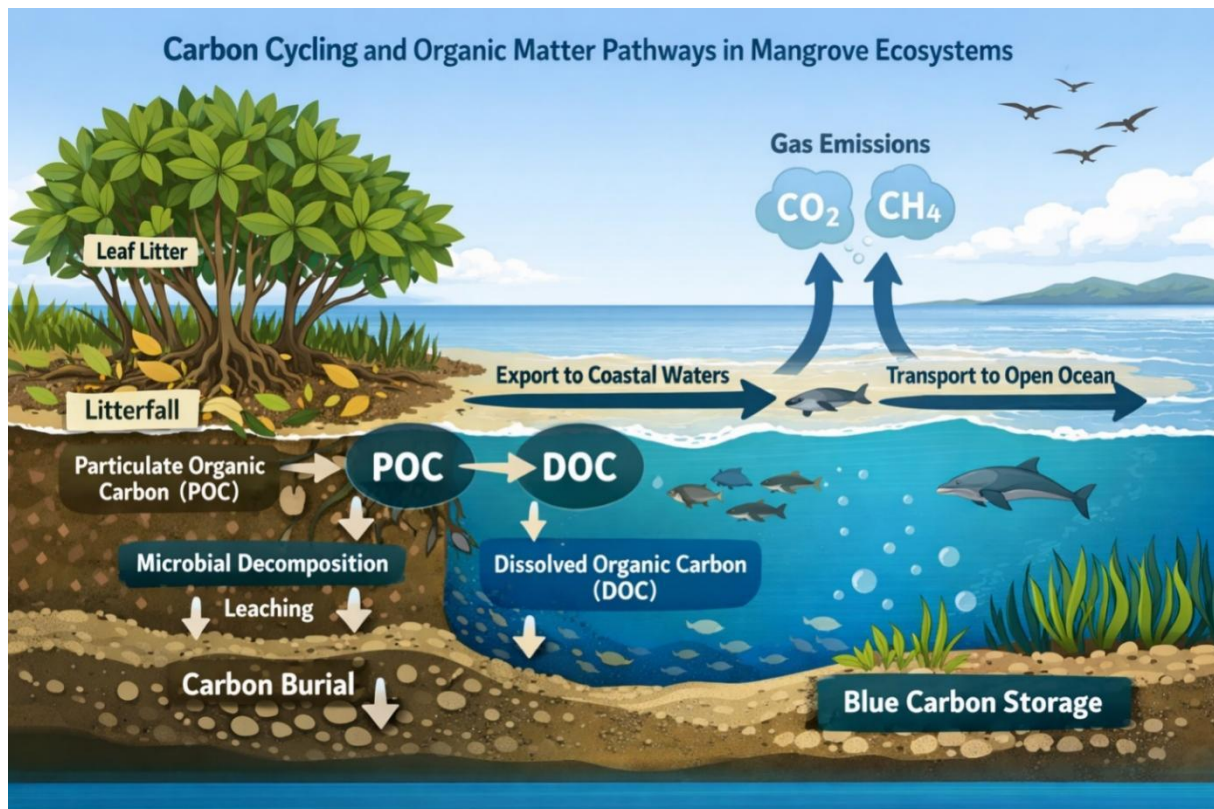


Figure 3. Carbon Cycling and Organic Matter Pathways in Mangrove Ecosystems. Conceptual diagram illustrating organic carbon dynamics in mangrove soils. Leaf litter and root inputs contribute to particulate and dissolved organic carbon pools through microbial decomposition and physical transport, with portions stored in sediments and others exported to adjacent coastal waters.

Figure 3 illustrates the dynamic pathways through which mangrove ecosystems capture, transform, and retain organic carbon. Aboveground litterfall and belowground root production supply organic matter that is processed through microbial decomposition and physical transport, generating particulate and dissolved organic carbon pools. While a proportion of this material is exported to adjacent estuarine and coastal waters, a substantial fraction is buried within waterlogged sediments where decomposition is slowed, enabling long-term carbon storage. These processes explain the importance of mangrove soils as globally significant blue-carbon reservoirs and reinforce the role of carbon cycling as one of the core ecological functions underpinning the proposed Six-Pillar Socio-Ecological Infrastructure Framework.

To support practical application, the framework incorporates context-dependent indicators that can be assessed through ecological, environmental, socio-economic, institutional, and policy-based approaches, allowing resilience conditions and management priorities to be evaluated across different mangrove settings. Figure 4 summarizes the overall development pathway from

multidisciplinary evidence and resilience determinants to indicator selection and management decision support, while Figure 5 presents the resulting six-pillar framework.

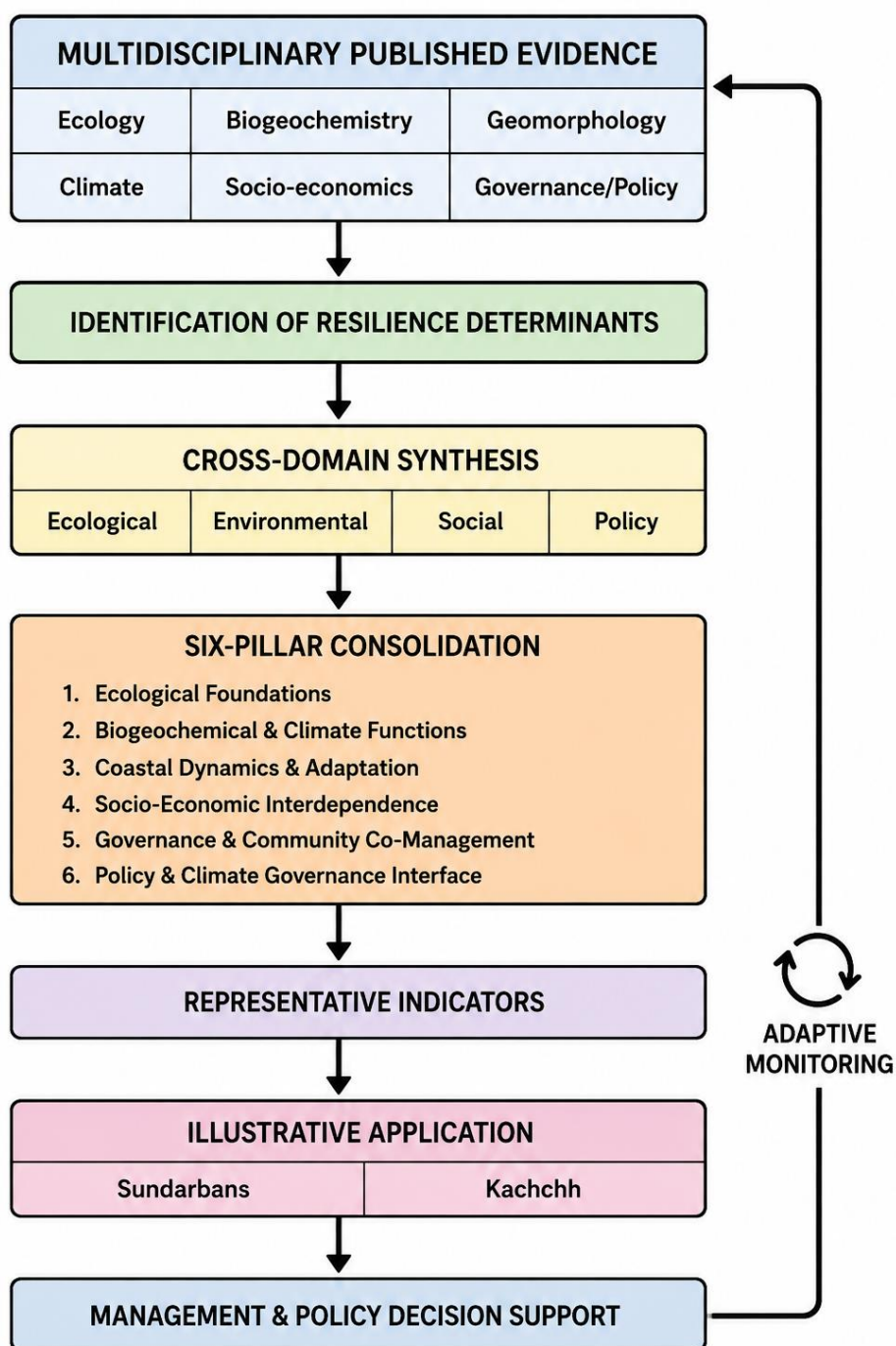


Figure 4. Framework development pathway from multidisciplinary evidence to the Six-Pillar Socio-Ecological Infrastructure Framework. *Published evidence spanning ecological, biogeochemical, geomorphological, climatic, socio-economic, and governance domains was synthesized to identify recurring determinants of mangrove resilience. These determinants were*

consolidated into six interacting pillars, translated into representative indicators, and applied illustratively to contrasting mangrove systems to support management and policy decision-making. This is intended to operate as an adaptive, structured framework in which monitoring and subsequent empirical evidence can refine indicator selection and framework application.

The proposed Six-Pillar Socio-Ecological Infrastructure Framework is presented in Figure 5, illustrating how the six interacting dimensions jointly shape mangrove socio-ecological resilience.

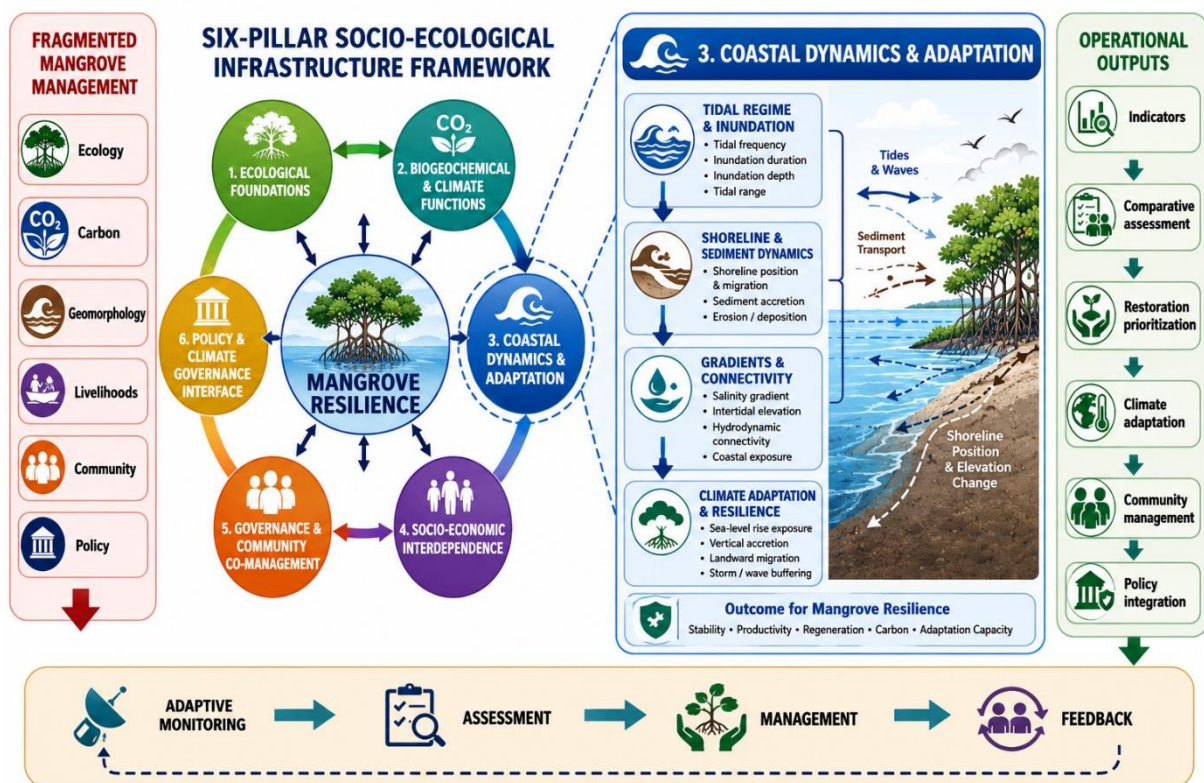


Figure 5. Six-Pillar Socio-Ecological Infrastructure Framework for Mangrove Resilience.

The framework conceptualizes mangrove socio-ecological resilience as an emergent property of six interacting pillars: ecological foundations; biogeochemical and climate functions; coastal dynamics and adaptation; socio-economic interdependence; governance and community co-management; and the policy–climate governance interface. Bidirectional interactions among the pillars emphasize that ecological condition, physical coastal processes, human dependence, community capacity, and institutional action jointly influence resilience and management outcomes. (cf. External pressures viz. industrial expansion, hydrological aberration, heavy metal contamination, infrastructure barriers, rising sea-levels, etc.)

As shown in Figure 5, none of the six pillars operates independently. Rather, ecosystem resilience emerges from their continuous interaction, reinforcing the need for integrated conservation and adaptive management approaches.

1.4 Relationship to Existing Coastal Governance and Sustainability Frameworks

Mangrove conservation has increasingly been addressed through several conceptual approaches within coastal and environmental governance. Prominent among these are Nature-Based Solutions (NbS), Ecosystem-Based Adaptation (EbA), and broader Socio-Ecological Systems (SES) frameworks. These perspectives have significantly advanced understanding of the role of natural ecosystems in climate resilience and sustainable development (Cohen-Shacham et al., 2016; Folke et al., 2005; Seddon et al., 2020).

Nature-Based Solutions emphasize the capacity of ecosystems to address societal challenges such as climate adaptation, coastal protection, and water management through the conservation, restoration, and sustainable management of natural systems (Cohen-Shacham et al., 2016; Seddon et al., 2020). Ecosystem-Based Adaptation focuses specifically on the use of biodiversity and ecosystem services to help communities adapt to climate change impacts, particularly in vulnerable coastal regions (Munang et al., 2013).

Socio-Ecological Systems theory, in contrast, highlights the interconnected relationships between ecological processes and human governance structures within coupled human–environment systems. This perspective emphasizes feedbacks between ecosystem dynamics and institutional responses, recognizing that environmental sustainability depends on adaptive governance and community participation (Folke et al., 2005; Ostrom, 2009). While these approaches provide valuable conceptual foundations, mangrove ecosystems often require a more explicitly integrated analytical framework that simultaneously considers ecological processes, geomorphological dynamics, carbon cycling, pollution buffering, and governance structures. Many existing frameworks emphasize either ecosystem services or governance dynamics but do not fully capture the role of mangroves as multi-functional coastal infrastructure systems capable of stabilizing sediments, attenuating storm impacts, and regulating coastal biogeochemical cycles (Barbier et al., 2011; Alongi, 2020).

The Socio-Ecological Infrastructure Framework proposed in this study extends these approaches by conceptualizing mangroves not merely as ecological habitats but as dynamic coastal infrastructure systems that regulate sediment transport, store carbon, buffer pollution, and sustain coastal livelihoods. Within this perspective, mangrove resilience emerges from the

interaction of ecological processes, sediment dynamics, socio-economic dependence, and institutional governance mechanisms. By integrating these dimensions within a unified analytical structure, the framework provides a more comprehensive basis for understanding how mangrove ecosystems contribute to long-term coastal stability, climate adaptation, and sustainable coastal development.

The novelty of the present framework lies in three complementary contributions. First, it reframes mangroves as socio-ecological coastal infrastructure rather than as isolated ecological systems, thereby explicitly recognizing their coupled roles in ecological functioning, climate regulation, coastal protection, livelihoods, community stewardship and governance. Second, it integrates these previously distributed dimensions within a single Six-Pillar Socio-Ecological Infrastructure Framework, providing a common analytical structure for examining interactions and trade-offs among ecological, biogeochemical and climate, coastal dynamics and adaptation, socio-economic, community co-management, and policy–climate governance dimensions. Third, it operationalizes this integrated structure by linking each pillar to representative indicators, context-specific assessment, management priorities and decision-making, thereby providing a pathway from multidisciplinary evidence to practical conservation, restoration and coastal-resilience planning. The framework is therefore proposed not as a replacement for existing mangrove, sustainability, socio-ecological, or nature-based adaptation approaches, but as an integrative and operational extension that connects their complementary perspectives within a common resilience-oriented structure.

To our knowledge, existing mangrove sustainability and socio-ecological frameworks have not commonly brought these six dimensions together within a single operational structure explicitly designed to connect ecological functioning, coastal dynamics, community dependence, co-management, and policy–climate governance.

1.5 Objectives and Scope of the Study

This study aims to synthesize current knowledge on Indian mangrove ecosystems within an integrated socio-ecological perspective that connects ecological functioning, coastal geomorphology, blue carbon dynamics, pollution processes, governance, and community participation. Building upon evidence from ecological and environmental studies, the authors develop a Six-Pillar Socio-Ecological Infrastructure Framework to illustrate how these interacting components collectively determine mangrove resilience and long-term sustainability. In addition to reviewing current scientific understanding, the work explores

representative case studies, discusses policy and management implications, identifies implementation challenges, and highlights emerging research directions. By positioning mangroves as living coastal infrastructure, the study seeks to provide a practical conceptual framework that supports interdisciplinary research, evidence-based conservation planning, and adaptive coastal governance in India and comparable tropical coastal regions

Mangrove sustainability has increasingly been examined through integrated conceptual approaches that connect ecosystem functions with broader sustainable development objectives. For example, a systematic review in *Environmental Development* developed a conceptual framework linking mangrove ecosystems with the Sustainable Development Goals, demonstrating the value of integrating ecological and socio-economic dimensions within a common sustainability perspective (Eyzaguirre et al., 2023). Such work provides an important foundation for moving beyond discipline-specific assessments of mangrove ecosystems. However, the dimensions governing mangrove resilience are often addressed separately, particularly ecological integrity, biogeochemical and climate functions, coastal geomorphological dynamics, livelihood dependence, community participation, and institutional and policy capacity.

The present study builds on this conceptual-framework literature but addresses a different analytical need: the explicit integration of these interacting dimensions into a unified structure for assessing mangrove resilience as a socio-ecological infrastructure framework. Rather than treating mangroves primarily as providers of ecosystem services or as components of sustainable-development goals, the proposed framework connects the ecological and physical processes that maintain mangrove systems with the social and institutional processes that determine their protection, use, and long-term resilience. The novelty of the framework therefore lies not in identifying individual mangrove functions, which are well established, but in integrating previously fragmented ecological, biogeochemical, coastal-dynamic, socio-economic, community-governance, and policy–climate dimensions into a single systems-oriented structure that can be translated into indicators for comparative assessment and adaptive coastal management.

Accordingly, this study aims to: (i) develop a Six-Pillar Socio-Ecological Infrastructure Framework for integrating the ecological, biogeochemical, coastal, socio-economic, community-governance, and policy dimensions of mangrove resilience; (ii) operationalize the framework through representative, context-dependent indicators and an application procedure; and (iii) demonstrate its analytical utility through an illustrative comparison of the Sundarbans

and Kachchh mangrove systems. The study does not seek to provide quantitative validation or predictive modelling of the framework; rather, it establishes an analytical architecture and a basis for subsequent empirical testing.

2. Framework Development Methodology

2.1 Multidisciplinary Evidence Synthesis

The Six-Pillar Socio-Ecological Infrastructure Framework was developed through a structured conceptual synthesis of published research spanning mangrove ecology, biogeochemistry, blue carbon, coastal geomorphology, climate adaptation, socio-economic dependence, community-based management, and environmental governance. The purpose of the synthesis was not to perform a systematic review or quantitative meta-analysis, but to identify recurring determinants of mangrove resilience across disciplinary domains and organize them into an integrated analytical structure. The six pillars are organized around mangrove socio-ecological resilience and represented as interacting components rather than independent categories (Figure 5).

Particular attention was given to evidence describing the biological foundations of mangrove ecosystems, carbon and nutrient processes, contaminant interactions, sediment and shoreline dynamics, coastal protection, livelihood dependence, community participation, institutional arrangements, and policy implementation. Indian mangrove systems provided the principal geographical context because the manuscript subsequently applies the framework to contrasting Indian systems, while the resulting domains are intended to provide a transferable framework for comparable tropical and subtropical coastal environments.

2.2 Identification and Consolidation of Framework Domains

The framework was developed through four analytical steps. First, recurring determinants of mangrove resilience were identified across the multidisciplinary evidence base. Second, related determinants were grouped into broader functional domains according to their primary ecological, environmental, social, or institutional role. Third, relationships among these domains were examined to identify dimensions that should be represented as interacting rather than independent components. Fourth, the resulting domains were consolidated into six complementary pillars and linked to representative indicators and potential management applications. The six pillars were retained because each represents a distinct dimension of

mangrove resilience while remaining functionally connected to the other pillars. The six-pillar structure should therefore be understood as an analytical consolidation derived from recurring evidence domains rather than as a statistically optimized classification or an empirically validated causal model.

This process produced the following analytical sequence:

Published evidence → recurring resilience determinants → domain consolidation → six interacting pillars → representative indicators → framework application → management and policy decisions.

The resulting framework is therefore intended as a systems-oriented analytical structure rather than a predictive ecological model. Its purpose is to organize multidisciplinary evidence, identify interactions and management gaps, and provide a basis for subsequent empirical testing.

2.3 Translation of Framework Domains into Indicators

To facilitate practical application, each pillar was linked to representative indicators that can be measured or assessed using field observations, remote sensing, environmental monitoring, socio-economic surveys, institutional records, or policy analysis. Indicator selection is intended to remain context-dependent rather than prescriptive because mangrove systems differ in ecological conditions, hydrological regimes, geomorphology, socio-economic dependence, and governance capacity.

The indicators therefore serve two purposes: first, to provide measurable representations of the six framework dimensions; and second, to support identification of management priorities and interactions among ecological, social, and institutional conditions. The framework does not prescribe a universal weighting scheme for the six pillars. Instead, it provides an adaptable structure through which appropriate indicators and assessment methods can be selected according to local management objectives. The overall development pathway linking multidisciplinary evidence, resilience determinants, pillar consolidation, indicator selection, illustrative application, and management decision support is summarized in Figure 4.

Literature was considered relevant when it addressed at least one of the six emerging domains or provided evidence linking mangrove condition with ecological functioning, coastal processes, human dependence, community management, or institutional governance. Because

this study was designed as a conceptual synthesis rather than a systematic review, no formal PRISMA-based screening or quantitative study-quality scoring was performed.

3. Mangrove Ecosystems and Socio-Ecological Importance

3.1 Life Between Land and Sea

Mangrove ecosystems occupy the intertidal zone where environmental conditions fluctuate continuously between marine and terrestrial influences. These forests are shaped by tidal inundation, salinity gradients, sediment deposition, and freshwater inflows, producing spatial vegetation patterns adapted to environmental gradients. Field studies from the Kachchh region of western India illustrate this pattern clearly. In high-salinity upper intertidal zones, the mangrove species *Avicennia marina* frequently dominates due to its exceptional tolerance to saline conditions and environmental stress (Sawale, 2012; Sumra, 2025). Lower intertidal zones, which experience more frequent tidal inundation and retain higher sediment moisture, typically support taller and denser mangrove vegetation.

Mangrove plants possess specialized structural and physiological adaptations that enable survival in saline, waterlogged, and oxygen-deficient soils. These adaptations include mechanisms for salt regulation, specialized root systems that facilitate gas exchange, and reproductive strategies suited to unstable coastal substrates (Tomlinson, 1986; Kathiresan, 2002; ICFRE, 2020). Early ecological studies demonstrated that mangrove vegetation typically develops distinct zonation patterns, with each species occupying ecological niches determined by tidal frequency, salinity levels, and soil conditions (Jagtap, 1985). Restoration initiatives that fail to account for these natural zonation patterns frequently experience low survival rates.

3.2 Distribution of Mangroves in India

Mangrove ecosystems in India occur across several distinct geomorphological settings.

Deltaic mangroves on the eastern coast develop in major river deltas such as the Sundarbans within the Ganges–Brahmaputra delta. These systems receive substantial freshwater input and sediment deposition, creating highly productive and species-rich habitats. In contrast, non-deltaic mangroves along the western coast, particularly in Gujarat and Maharashtra, occur in arid or semi-arid environments characterized by limited freshwater inflow and elevated salinity conditions. Island mangroves in the Andaman and Nicobar Islands display comparatively high

species diversity due to favorable climatic conditions and complex coastal geomorphology (Kathiresan, 2018; ICFRE, 2020).

3.3 Soil, Sediment, and Ecological Foundations

Mangrove ecosystems are strongly influenced by sediment characteristics. Mangrove soils are typically waterlogged and oxygen-deficient, conditions that slow microbial decomposition and allow large quantities of organic matter to accumulate (Malasatar, 2024). Leaf litter plays a central ecological role in mangrove food webs. Decomposing plant material supports diverse organisms including crabs, molluscs, bacteria, fungi, and other benthic organisms, forming detritus-based food webs fundamental to mangrove ecosystem productivity (Jagtap, 1985).

Key sediment parameters influencing mangrove health include:

- Salinity levels
- Nutrient availability (nitrogen and phosphorus)
- Dissolved oxygen conditions
- Sediment texture and organic matter content

Fine-grained, dark, and moisture-rich sediments typically indicate strong ecological functioning.

3.4 Biodiversity and Ecological Interactions

Mangrove ecosystems support diverse biological communities that contribute to nutrient cycling and sediment stabilization. Macrofaunal organisms such as gastropods, bivalves, polychaetes, and crustaceans recycle organic matter and aerate sediments through burrowing activity (Sawale, 2012). Phytosociological studies show that patterns of species dominance often reflect environmental stress conditions (Sumra, 2025). Ecosystems with higher species diversity generally display greater resilience to environmental disturbances.

3.5 Blue Carbon and Climate Regulation

Mangrove ecosystems are recognized as globally significant blue carbon ecosystems because they store large quantities of carbon in both vegetation biomass and waterlogged sediments. Slow decomposition under anaerobic conditions allows carbon to remain stored for long periods (Malasatar, 2024; Alongi, 2020). Disturbance of mangrove soils through drainage,

deforestation, or coastal development can release stored carbon into the atmosphere. Consequently, mangrove conservation contributes directly to climate mitigation.

4. External Pressures on Coastal Systems

4.1 Anthropogenic Pressures

Increasing population density along coastlines has intensified resource extraction, land conversion, and industrial development in mangrove areas. Activities such as grazing, aquaculture expansion, dredging, port development, and wastewater discharge alter sediment dynamics and hydrological connectivity. Ecological research has long warned about the consequences of excessive resource exploitation in mangrove ecosystems (Jagtap, 1985). Contemporary studies confirm that cumulative anthropogenic pressures remain major drivers of mangrove decline (Sawale, 2012; Malasatar, 2024; Vaidya, 2025).

4.2 Coastal Dynamics and Shoreline Change

Mangrove ecosystems are closely linked to coastal geomorphological processes. Their distribution is influenced by sediment transport, tidal currents, and shoreline morphology. Research on western Indian coastlines indicates that shoreline change depends on sediment supply, tidal current patterns, riverine inputs, and coastal infrastructure development (Vaidya, 2025). Engineering structures such as seawalls and breakwaters may disrupt sediment flows, leading to erosion or excessive deposition that affects mangrove habitats.

4.3 Pollution and Heavy-Metal Contamination

Mangrove ecosystems function as natural biofilters that trap suspended sediments and associated contaminants within their complex root networks and anoxic soils (Sumra, 2025; MacFarlane et al., 2016). Fine-grained sediments deposited in mangrove forests have strong adsorption capacity for heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), copper (Cu), zinc (Zn), and arsenic (As), commonly introduced through industrial discharge, port activity, shipping traffic, and urban runoff. By retaining these contaminants, mangrove sediments act as long-term pollutant sinks while simultaneously protecting adjacent coastal waters from immediate contamination. However, environmental disturbances may remobilize stored pollutants, posing risks to estuarine food webs.

4.3.1 Heavy Metals in Indian Mangrove Systems

Recent studies across Indian mangrove ecosystems indicate increasing heavy-metal contamination, particularly in rapidly industrializing coastal regions. Sediment analyses in the Sundarbans have documented elevated concentrations of Cd, Pb, Ni, Cu, and Zn, with cadmium identified as a significant ecological risk (Majumdar et al., 2023; Banerjee et al., 2012; Islam et al., 2023). Similarly, studies from the Saurashtra coast of Gujarat report accumulation of Pb, Cu, Zn, Fe, Mn, and Cd associated with port development and industrial expansion (Karangiya et al., 2024).

4.3.2 Sediment–Carbon–Heavy Metal Nexus

Heavy-metal dynamics in mangrove ecosystems are closely linked to sediment carbon processes. Mangrove soils store large quantities of organic carbon, and anaerobic sediment conditions facilitate the formation of metal-binding compounds such as sulfides and organometallic complexes (Alongi, 2020). These geochemical conditions that stabilize carbon storage also immobilize heavy metals, creating a sedimentary buffer that reduces pollutant mobility.

4.4 Climate Change and Sea-Level Rise

Climate change introduces additional challenges for mangrove ecosystems, including rising sea levels, intensified storms, and altered sediment transport patterns. Mangroves can adapt through vertical sediment accretion and landward migration. However, infrastructure barriers such as embankments and coastal development often restrict this natural adjustment process, creating conditions described as coastal squeeze (Vaidya, 2025).

4.5 Emerging Technologies for Mangrove Monitoring

Advances in digital technologies can transform the monitoring and management of mangrove ecosystems by enabling more timely, accurate, and spatially comprehensive assessments. Satellite-based remote sensing now provides continuous observations of mangrove extent, shoreline dynamics, vegetation health, and land-use change, allowing managers to detect degradation and evaluate restoration outcomes over large coastal regions. When integrated with Geographic Information Systems (GIS), these datasets support spatial analyses that identify vulnerable areas, prioritize conservation efforts, and inform evidence-based coastal planning.

Unmanned Aerial Vehicles (UAVs), commonly known as drones, further enhance monitoring by providing high-resolution imagery for assessing canopy condition, regeneration success, erosion patterns, and storm damage. Artificial intelligence (AI)-based image classification can

rapidly process satellite and drone imagery to distinguish mangrove species, detect vegetation stress, identify illegal encroachment, and monitor changes in ecosystem condition with greater efficiency than conventional field surveys.

Digital Twin like emerging simulation concepts offer additional opportunities by integrating ecological observations, environmental data, and spatial information into dynamic virtual representations of mangrove ecosystems. Although still at an early stage of application, such simulations have the potential to support scenario analysis, restoration planning, and adaptive management under changing environmental conditions.

Community participation remains equally important within this technological landscape. Mobile-based reporting platforms and citizen science applications can enable local communities to document pollution events, shoreline erosion, illegal clearing, and changes in mangrove health, complementing scientific monitoring with real-time local observations. Combined with satellite observations and environmental forecasting, these approaches can contribute to early warning systems for coastal hazards, ecosystem degradation, and climate-related disturbances. Together, these technologies and community-based approaches (Figure 6) provide enabling infrastructure for continuous monitoring, assessment, and adaptive management of mangrove systems.

5. Six-Pillar Socio-Ecological Infrastructure Framework

5.1 The Six Pillars

This study proposes a Six-Pillar Socio-Ecological Infrastructure Framework that conceptualizes mangrove ecosystems as integrated coastal systems shaped by interacting ecological, geomorphological, climatic, and governance processes.

The Six-Pillar Socio-Ecological Infrastructure Framework represents the principal conceptual contribution of this study. The framework was derived by consolidating recurring determinants of mangrove resilience identified across ecological, biogeochemical, geomorphological, socio-economic, and governance literature. Rather than treating these dimensions as independent ecosystem services, the framework conceptualizes them as interacting components of a coupled coastal system in which ecological condition, physical processes, human dependence, community capacity, and institutional action jointly influence long-term resilience.

The six pillars represent interconnected domains:

1. Ecological Foundations

Species adaptations, root structures, sediment interactions, and ecological zonation patterns that structure mangrove ecosystems.

2. Biogeochemical and Climate Functions

Processes such as carbon sequestration, nutrient cycling, and metal immobilization that regulate climate and pollutant dynamics.

3. Coastal Dynamics and Adaptation

Geomorphological processes including sediment transport, shoreline change, and tidal exchange that shape mangrove distribution.

4. Socio-Economic Interdependence

Dependence of coastal communities on mangroves for fisheries, coastal protection, and livelihood resources.

5. Governance and Community Co-Management

Participatory management systems involving local communities, researchers, and government institutions.

6. Policy and Climate Governance Interface

National environmental regulations, coastal management policies, and climate strategies that translate ecological knowledge into institutional action.

Together, these pillars form an integrated framework for understanding mangroves as adaptive socio-ecological infrastructure systems supporting coastal resilience.

5.2 Rationale for the Six-Pillar Framework

The six-pillar structure was selected because each pillar represents a distinct but interdependent determinant of mangrove resilience. Ecological foundations describe the biological and structural basis of ecosystem functioning; biogeochemical and climate functions capture carbon storage, nutrient cycling, and contaminant regulation; coastal dynamics and adaptation describe sediment transport, shoreline stability, tidal exchange, and physical responses to environmental change; socio-economic interdependence captures human dependence on mangrove resources and coastal protection; governance and community co-management represent participatory and

institutional capacity at the local level; and the policy–climate governance interface connects ecological knowledge with formal environmental, coastal, and climate policies.

The six pillars should therefore not be interpreted as independent categories. Their value lies in their interactions. For example, ecological degradation may alter sediment stability and carbon storage, which can affect coastal protection and livelihood security; conversely, effective community participation and policy implementation may improve conservation outcomes and reinforce ecological resilience. The framework consequently emphasizes relationships among domains rather than isolated assessment of individual ecosystem functions. Table 1 translates the six conceptual pillars into representative processes, measurable indicators, potential data sources, and management applications, thereby providing an operational bridge between the conceptual framework and practical environmental assessment.

Table 1. Operational structure of the Six-Pillar Socio-Ecological Infrastructure Framework.

Pillar	Core function	Key processes/dimensions	Representative indicators	Potential data sources	Management relevance
1. Ecological foundations	Ecosystem biological functioning	Species composition, and regeneration, zonation, root structure, vegetation condition	Species richness, regeneration rate, canopy condition, vegetation extent	Field surveys, ecological inventories, remote sensing	Restoration and biodiversity management
2. Biogeochemical functions	Climate regulation and environmental buffering	Carbon storage, nutrient cycling, processes, contaminant retention	Soil organic carbon, soil nutrient concentrations, sediment contaminant levels	Soil and water sampling, laboratory analysis	Climate mitigation and pollution management

Pillar	Core function	Key processes/dimensions	Representative indicators	Potential data sources	Management relevance
3. Coastal dynamics and adaptation	Physical stability and coastal protection	Sediment deposition, erosion, accretion, tidal exchange, shoreline change	Shoreline change rate, sediment accretion, tidal connectivity, erosion rate	GIS, satellite imagery, UAVs, sediment monitoring	Coastal protection and adaptation planning
4. Socio-economic interdependence	Human well-being and livelihood support	Fisheries, resource dependence, coastal protection, livelihood exposure	Fisheries dependence, household income dependence, resource-use intensity	Household surveys, livelihood assessment, economic data	Livelihood planning and social resilience
5. Governance and community co-management	Participatory management capacity	Participation, institutions, compliance, community monitoring	Participation local rate, compliance, monitoring activity, institutional coordination	Interviews, surveys, institutional records	Adaptive and community-based management
6. Policy and climate governance interface	Institutional integration and implementation	Environmental regulation, climate policy, restoration programmes, financing	Policy implementation, restoration investment, enforcement capacity, climate-plan integration	Policy analysis, government records, programme assessments	Policy alignment and implementation

Indicator domain	Recommended indicators
Tidal dynamics	Tidal inundation frequency/duration
Coastal geomorphology	Shoreline change rate
Sediment dynamics	Sediment accretion/erosion rate
Elevation	Relative surface elevation
Salinity	Porewater/surface-water salinity
Hydrodynamics	Tidal connectivity / inundation extent
Climate adaptation	Relative sea-level-rise exposure
Vegetation response	Zonation, density, recruitment and regeneration

5.3 Comparison with Existing Frameworks

The positioning of the Six-Pillar Framework relative to established Nature-Based Solutions, Ecosystem-Based Adaptation, Socio-Ecological Systems, and mangrove–Sustainable Development Goal approaches is summarized in Table 2.

Table 2. Comparison of the Six-Pillar Framework with Existing Integrated Mangrove and Coastal Sustainability Approaches.

Approach/framework	Primary emphasis	Ecological processes	Climate adaptation	Coastal dynamics	Socio-economic dimensions	Community participation	Policy/governance	Contribution of present framework
Mangrove–SDG conceptual framework	Linking mangroves with Sustainable	✓	✓	±	✓	±	✓	Provides a sustainability/SDG-oriented

Approach/framework	Primary emphasis	Ecological processes	Climate adaptation	Coastal dynamics	Socio-economic dimensions	Community participation	Policy/governance	Contribution of present framework
(Eyzaguirre et al., 2023)	Development Goals							foundation; does not specifically structure the physical, ecological, social, community, and policy dimensions as six interacting resilience pillars
Nature-Based Solutions	Ecosystem-based solutions to societal challenges	✓	✓	✓	✓	±	±	Strong solution-oriented approach but broader than mangrove resilience and not organized around six specific interacting dimensions

Approach/framework	Primary emphasis	Ecological processes	Climate adaptation	Coastal dynamics	Socio-economic dimensions	Community participation	Policy/governance	Contribution of present framework
Ecosystem-Based Adaptation	Climate adaptation through ecosystem management	✓	✓	✓	✓	±	✓	Strong climate-adaptation orientation but less explicit integration of community co-management and policy interfaces within one mangrove-specific structure
Socio-Ecological Systems approaches	Coupled human–environment relationships	✓	±	±	✓	✓	✓	Provides systems perspective but is generally broader and not specifically structured around

Approach/framework	Primary emphasis	Ecological processes	Climate adaptation	Coastal dynamics	Socio-economic dimensions	Community participation	Policy/governance	Contribution of present framework
								mangrove coastal resilience
								Integrates six interacting dimensions and translates them into indicators and management applications
Six-Pillar Framework	Integrated mangrove socio-ecological resilience	✓	✓	✓	✓	✓	✓	

Existing approaches therefore provide complementary conceptual foundations rather than competing frameworks. The present framework builds on these perspectives by emphasizing the explicit interaction of six dimensions that jointly determine mangrove resilience and by providing an indicator-oriented structure through which these dimensions can be assessed and linked to management decisions. The framework is consequently positioned as an integrative extension of existing sustainability, nature-based adaptation, socio-ecological, and mangrove–SDG perspectives rather than as a replacement for them.

5.4 Framework Application Procedure

The framework is intended to function as a systems-oriented assessment structure rather than as a sequential management prescription. Application begins with definition of the mangrove system, spatial boundary, and management objective. The six pillars are then assessed using

locally appropriate indicators. The resulting evidence is examined not only within individual pillars but also across interactions and potential trade-offs among pillars. Areas of vulnerability or underperformance are identified, management priorities are established, and interventions are subsequently monitored to determine whether changes in one pillar influence other dimensions of system resilience.

The proposed application sequence is therefore:

(1) define the system and management objective; (2) assess the six pillars; (3) select context-specific indicators; (4) identify interactions and trade-offs; (5) identify priority vulnerabilities; (6) select management interventions; and (7) monitor outcomes and revise management actions through adaptive governance.

This procedure allows the framework to be adapted to different ecological, socio-economic, and institutional contexts while maintaining its integrated systems perspective. The relationship between representative indicators, their interpretation, and potential management responses is summarized in Table 3.

Table 3. Indicator-to-Decision Structure for Applying the Six-Pillar Socio-Ecological Infrastructure Framework.

Pillar	Example indicator	What measures	it Potential interpretation	Example management response
Ecological foundations	Species diversity / Ecosystem regeneration	integrity	Declining values may indicate ecological degradation	Restoration and species-management interventions
Biogeochemical and climate functions	Soil organic carbon	Carbon-storage integrity	Reduced stocks may indicate disturbance or degradation	Protection, restoration, and carbon monitoring
Coastal dynamics	Shoreline change / sediment accretion	Physical stability	Increasing erosion may indicate coastal vulnerability	Hydrological and sediment-

Pillar	Example indicator	What measures	it Potential interpretation	Example management response
				management intervention
Socio-economic interdependence	Household livelihood dependence	Human dependence and exposure	High dependence may increase vulnerability ecosystem degradation	Livelihood social diversification and to resource-management measures
Governance and community co-management	Participation / compliance	Local management capacity	Low participation may weaken conservation implementation	Strengthen participatory institutions and community monitoring
Policy and climate governance	Policy implementation / restoration investment	Institutional capacity	Weak implementation may limit conservation effectiveness	Improve coordination, financing, enforcement, and policy integration

Table 3 demonstrates how the framework can move from conceptual diagnosis to management decision-making. Importantly, the indicators are illustrative rather than prescriptive; their selection, measurement frequency, and interpretation should be adapted to local ecological conditions, management objectives, data availability, and institutional capacity.

The Six-Pillar Socio-Ecological Infrastructure Framework illustrates mangrove ecosystems as a central intertidal system sustained by six interacting dimensions: ecological foundations, biogeochemical and climate functions, coastal dynamics, socio-economic interdependence, governance and community co-management, and policy–climate governance integration. The framework synthesizes ecological insights on mangrove zonation and ecosystem functioning

(Jagtap, 1985), structural and physico-chemical determinants of mangrove growth (Sawale, 2012), biodiversity patterns and pollution interactions (Sumra, 2025), sediment-carbon storage and ecosystem service functions (Malasatar, 2024), and coastal geomorphological dynamics shaping shoreline stability (Vaidya, 2025). By integrating these domains within a unified socio-ecological structure, the framework conceptualizes mangroves not merely as coastal forests but as adaptive ecological infrastructure systems that support climate resilience, community livelihoods, and coastal protection in India.

Mangrove ecosystems are closely linked to coastal geomorphological processes, where shoreline evolution is continuously influenced by tidal dynamics, sediment deposition, erosion, and sea-level change. Understanding these processes is essential for evaluating ecosystem resilience and planning effective restoration strategies. Coastal geomorphological processes, including sediment transport, tidal exchange, shoreline erosion and accretion, and wave action, are therefore treated as core components of the Coastal Dynamics and Adaptation pillar. Mangrove resilience is shaped by interacting tidal, geomorphological, sedimentary, salinity, and coastal processes that vary along the land–sea gradient. These processes influence mangrove establishment, persistence, regeneration, shoreline stability, and capacity to adapt to environmental change, and are therefore incorporated within the ecological and coastal-dynamics dimensions of the framework.

The Six-Pillar Socio-Ecological Infrastructure Framework is intended to be applied as a systems-oriented assessment tool rather than a sequential management process. Individual pillars should not be interpreted independently because ecological resilience emerges from their interactions. The framework may be used to evaluate restoration projects, compare mangrove ecosystems, identify management priorities, or guide interdisciplinary research by considering ecological, environmental, socio-economic, and governance dimensions simultaneously. In practice, managers may adapt the framework according to local ecological conditions, institutional capacity, and conservation objectives while maintaining its integrated systems perspective.

From Fragmented Protection to Integrated Resilience

Mangrove conservation in India is increasingly challenged by interacting pressures from coastal development, pollution, and climate change. Addressing these challenges requires moving beyond fragmented management approaches toward integrated socio-ecological frameworks

that link ecological processes, coastal dynamics, community livelihoods, and governance mechanisms.

6. Illustrative Applications of the Six-Pillar Framework

The Six-Pillar Socio-Ecological Infrastructure Framework provides a conceptual structure for examining how ecological processes, sediment dynamics, socio-economic dependence, and governance systems interact to shape mangrove resilience. To demonstrate its analytical utility, the framework is applied illustratively to two contrasting Indian mangrove systems: the Sundarbans deltaic ecosystem and the arid mangroves of Kachchh in Gujarat. These applications were selected because the two systems differ substantially in ecological, geomorphological, climatic, socio-economic, and governance contexts. The purpose is not to empirically validate the framework, but to demonstrate how the same six dimensions can be interpreted across contrasting settings, identify context-specific resilience constraints and management priorities, and illustrate the framework's potential for comparative assessment and decision support.

6.1 Applying the Six-Pillar Framework to Indian Mangrove Systems

To illustrate the practical relevance of the Six-Pillar Socio-Ecological Infrastructure Framework, selected mangrove systems in India are examined through the lens of the six interacting pillars of resilience. These case studies demonstrate how ecological processes, sediment dynamics, socio-economic dependence, and governance structures interact to shape mangrove sustainability across contrasting coastal environments.

6.2 Case Studies

6.2.1 Case Study 1: Sundarbans Mangrove System

Ecological Foundations:

The Sundarbans constitute the largest contiguous mangrove forest in the world and support high species diversity. The deltaic environment formed by the Ganges–Brahmaputra River System supplies nutrient-rich sediments that sustain highly productive mangrove ecosystems.

Coastal Dynamics:

The region is strongly influenced by tidal processes and continuous sediment deposition from major river systems. At the same time, the Sundarbans are highly exposed to cyclones and storm surges, which periodically reshape shoreline morphology and influence ecosystem dynamics.

Biogeochemical Functions:

Mangrove soils in the Sundarbans store substantial quantities of organic carbon and function as globally significant blue-carbon reservoirs. Sediment studies also reveal the accumulation of heavy metals such as cadmium, lead, and zinc, often associated with upstream industrial activities.

Socio-Economic Interdependence:

Millions of coastal residents depend on the Sundarbans for fisheries, fuelwood, and other ecosystem resources, demonstrating the strong linkage between ecosystem health and community livelihoods.

Governance and Policy Context:

Management of the Sundarbans involves protected area regulations, transboundary cooperation between India and Bangladesh, and community-based resource management initiatives that aim to balance conservation objectives with local livelihood needs.

6.2.2 Case Study 2: Arid Mangroves of Kachchh (Gujarat)

Ecological Foundations:

Mangrove ecosystems in the Kachchh region develop under arid environmental conditions characterized by high salinity and limited freshwater inflow. The species *Avicennia marina* dominates these habitats due to its high tolerance to saline and water-stressed environments.

Coastal Dynamics:

These mangroves are shaped primarily by tidal exchange and sediment transport within shallow coastal environments. Limited river discharge means that sediment supply and tidal hydrology play particularly important roles in maintaining ecosystem stability.

Biogeochemical Functions:

Mangrove soils in the region contribute to carbon storage and pollutant retention, particularly in areas affected by industrial development along the Gujarat coastline.

Socio-Economic Interdependence:

Local communities rely on mangrove ecosystems for fisheries resources, shoreline stabilization, and protection from coastal erosion and storm impacts.

Governance and Restoration Efforts:

Mangrove restoration initiatives in Gujarat increasingly emphasize hydrology-based restoration approaches, community participation, and improved monitoring of ecological recovery.

6.3 Comparative Insights from the Case Studies

The Sundarbans and Kachchh case studies demonstrate that, despite contrasting environmental settings, mangrove resilience is consistently governed by the interaction of ecological, geomorphological, socio-economic, and institutional processes. The Sundarbans represent a humid, deltaic ecosystem characterized by high biodiversity, abundant sediment supply, and strong riverine influence, whereas the mangroves of Kachchh occur in an arid coastal environment dominated by high salinity, limited freshwater inflow, and tidal hydrodynamics. These differences highlight the ecological diversity of Indian mangrove systems while emphasizing that the fundamental drivers of resilience remain interconnected (Jagtap, 1985; Sawale, 2012).

Across both regions, ecological functioning depends on maintaining natural hydrological connectivity, sediment dynamics, and ecosystem integrity, while long-term sustainability is reinforced through community participation and supportive governance. Similarly, both systems provide critical ecosystem services, including shoreline stabilization, fisheries support, carbon sequestration, and protection against climate-related coastal hazards, although the relative importance of individual processes varies according to local environmental conditions (Alongi, 2020; Friess et al., 2019). These comparisons demonstrate that effective mangrove conservation cannot rely on ecological restoration alone but must integrate environmental, social, and governance dimensions within a unified management approach.

The Six-Pillar Socio-Ecological Infrastructure Framework provides this integrative perspective by accommodating regional ecological variation while maintaining a consistent systems-based structure for assessing mangrove resilience. Consequently, the framework offers a transferable conceptual basis for comparative assessment, adaptive management, and evidence-based conservation planning across diverse mangrove ecosystems in India and other tropical coastal

regions. The contrasting application of the six pillars to the Sundarbans and Kachchh is summarized in Table 4, highlighting context-specific resilience constraints and corresponding management implications.

Table 4. Comparative application of the Six-Pillar Framework to the Sundarbans and Kachchh.

Pillar	Sundarbans	Kachchh	Framework-based management implication
Ecological foundations	Deltaic mangrove system with high ecological complexity and biodiversity	Arid mangrove system adapted to high environmental stress	Restoration and conservation strategies must be locally adapted
Biogeochemical and climate functions	Important carbon-storage function with documented contaminant concerns	Carbon and environmental functions shaped by arid conditions and local pressures	Carbon and contaminant monitoring should be context-specific
Coastal dynamics and adaptation	Strong tidal and sedimentary dynamics with cyclone and storm-surge exposure	Strong influence of aridity, tidal conditions and shoreline processes	Hydrology and sediment dynamics should be incorporated into coastal planning
Socio-economic interdependence	Strong dependence on fisheries and other mangrove resources	Local communities depend on coastal and mangrove-associated resources	Conservation should account for livelihood dependence
Governance and community management	Protected-area co-management, participation	Local conservation and institutional coordination across coastal areas	Participatory governance should reflect local institutional conditions

Pillar	Sundarbans	Kachchh	Framework-based management implication
	transboundary considerations		
Policy and governance	Requires integration of climate conservation, adaptation and multi-level governance	Requires alignment of mangrove protection and coastal climate planning	Policy implementation and institutional coordination are central to resilience

Table 4 demonstrates how the same six pillars can identify different resilience constraints and management priorities across contrasting mangrove environments. The comparison also illustrates the transferability of the framework while retaining flexibility in indicator selection and interpretation. Because these applications are based on the existing literature synthesized in this manuscript, they should not be interpreted as new field measurements or empirical validation of the framework.

7. Empirical Evaluation Pathway and Testable Propositions

7.1 Pathway for Empirical Evaluation

The present framework is intentionally positioned at the conceptual and analytical stage of framework development. Its next stage requires empirical evaluation across multiple mangrove systems. A systematic evaluation pathway could proceed through expert assessment of pillar definitions and indicators, pilot application to individual sites, multi-site comparative assessment, longitudinal monitoring, quantitative examination of relationships among indicators, and subsequent refinement of the framework. Such evaluation should examine whether the proposed indicators are sensitive to changes in mangrove condition, whether interactions among pillars can be empirically detected, whether the relative importance of individual pillars varies across ecological and governance contexts, and whether framework-based assessments improve management prioritization compared with isolated assessment of individual ecosystem functions. The present study therefore establishes the conceptual and analytical architecture and identifies a pathway through which future empirical research can

assess indicator sensitivity, relative pillar importance, interaction strength, transferability, and decision-support performance.

7.2 Testable propositions emerging from the framework

The framework generates several propositions that can be evaluated through future empirical research:

P1. Mangrove resilience is positively associated with the integrity of ecological foundations and maintenance of hydrological connectivity.

P2. Coastal protection is jointly influenced by vegetation condition and sediment dynamics rather than by vegetation extent alone.

P3. The climate-regulation function of mangroves depends on the persistence and integrity of sediment-associated carbon stocks.

P4. Greater socio-economic dependence on mangrove resources increases the social consequences of ecological degradation.

P5. Community participation and co-management capacity influence the implementation and durability of conservation interventions.

P6. Policy and institutional capacity mediate the translation of ecological knowledge into effective coastal-resilience outcomes.

These propositions define the empirical research agenda generated by the framework and should be interpreted as testable hypotheses rather than findings established by the present conceptual synthesis.

To complement the conceptual framework and facilitate its practical application, a series of tables is presented throughout this manuscript. As one can see, the Tables 1, 2, 3, and 4 above summarize the principal characteristics of the six pillars, the analytical structure of the Six-Pillar Socio-Ecological Infrastructure Framework, indicator-to-decision structure for applying the Six-Pillar Socio-Ecological Infrastructure Framework, and the comparative application of the Six-Pillar Framework to the Sundarbans and Kachchh, respectively. Table 5 outlines a community monitoring toolkit that highlights practical approaches for participatory environmental monitoring and adaptive management, while Table 6 summarizes the roles and responsibilities of key stakeholders, emphasizing the collaborative governance required for effective mangrove conservation and long-term coastal resilience.

Table 5. Community Monitoring Toolkit.

Monitoring activity	Indicator	Frequency
Shoreline photographs	Erosion	Annual
Seedling survival	Restoration success	Annual
Species diversity	Biodiversity	Annual
Leaf condition	Vegetation health	Quarterly
Illegal cutting	Human disturbance	Immediate reporting

Table 6. Various Stakeholders and their Responsibilities.

Stakeholder	Primary responsibility
Scientists	Monitoring
Communities	Stewardship
NGOs	Capacity building
Coastal authorities	Enforcement
Government	Policy

8. Implications for Environmental Management

The framework has practical implications because it connects ecological condition with the physical, social, and institutional processes that influence mangrove resilience. Its principal management value is not to prescribe a universal intervention, but to provide a structured basis for identifying context-specific constraints and aligning monitoring, restoration, community participation, and governance responses.

8.1 Policy and management implications for coastal governance

The case studies discussed above demonstrate that mangrove resilience emerges from the interaction of ecological processes, coastal geomorphology, and socio-economic systems. These examples highlight the importance of management approaches that address mangroves not only as ecological habitats but also as components of broader coastal socio-ecological systems. Translating these insights into effective coastal governance requires policy frameworks that integrate ecological science, community participation, and long-term climate adaptation strategies. Recognizing mangroves as natural coastal infrastructure provides a foundation for developing management approaches that simultaneously support ecosystem conservation, disaster risk reduction, and sustainable livelihoods.

Mangrove ecosystems play a crucial role in strengthening coastal socio-ecological resilience by providing ecosystem services that support biodiversity conservation, climate regulation, fisheries productivity, and coastal livelihoods. Effective coastal governance should therefore adopt ecosystem-based management approaches that recognize mangroves as natural infrastructure capable of reducing climate risks and enhancing long-term coastal stability. Integrating mangrove conservation into coastal development planning is essential for minimizing disaster risks associated with storm surges, coastal erosion, and sea-level rise. Policy frameworks should prioritize the maintenance of tidal connectivity, sediment supply pathways, and natural hydrological processes, which are fundamental to sustaining mangrove ecological functioning. Preventing industrial pollution and regulating coastal infrastructure development are equally important to avoid disruptions to these processes.

Community participation represents another key component of sustainable mangrove governance. Local communities possess extensive ecological knowledge of mangrove landscapes and often serve as the primary stewards of coastal resources. Participatory monitoring programs, community-based restoration initiatives, and collaborative management frameworks can therefore improve conservation outcomes while strengthening social acceptance of environmental policies.

In addition, the growing recognition of blue carbon ecosystems offers new opportunities to integrate mangrove conservation into national climate mitigation and adaptation strategies. Incorporating mangrove carbon stocks into greenhouse gas inventories, climate adaptation planning, and voluntary carbon markets may create new financial incentives for conservation while supporting international climate commitments. Taken together, these approaches

highlight the importance of integrated governance systems that align ecological science, community engagement, and policy instruments to support sustainable coastal management. Recognizing mangroves as living coastal infrastructure provides a practical framework for linking ecosystem conservation with climate resilience, disaster risk reduction, and sustainable development.

8.2 Restoration planning

The framework suggests that mangrove restoration should not be evaluated solely through changes in vegetation cover or survival rates. Restoration planning should simultaneously consider ecological integrity, hydrological and sedimentary conditions, carbon and biogeochemical functions, livelihood dependence, community participation, and institutional capacity. This approach can help distinguish between restoration sites where ecological intervention is the primary requirement and those where governance, hydrology, sediment supply, or community participation represent the principal constraints.

8.3 Climate adaptation

Mangrove conservation can contribute simultaneously to climate adaptation and mitigation by maintaining coastal protection functions and sediment-associated carbon stocks. The framework encourages these functions to be assessed together rather than through separate conservation and climate-policy processes.

8.4 Community-based management

The socio-economic and community-governance pillars emphasize that long-term conservation depends on relationships between ecosystem condition and local institutions. Participatory monitoring, local ecological knowledge, livelihood considerations, and shared decision-making can therefore complement scientific monitoring and strengthen management legitimacy.

8.5 Policy integration

The policy–climate governance interface provides a mechanism for connecting ecological evidence with coastal-zone planning, restoration programmes, climate adaptation strategies, conservation regulation, and financing mechanisms. The framework can therefore support cross-sectoral coordination where mangrove management responsibilities are distributed among multiple institutions.

8.6 Transferability

Although the framework is primarily informed by Indian mangrove systems, its six dimensions represent broadly applicable components of mangrove socio-ecological resilience. Application beyond India should nevertheless retain flexibility in indicator selection and interpretation because hydrological regimes, geomorphology, species composition, livelihood structures, institutional arrangements, and policy environments vary substantially among regions.

8.7 Practical Management Recommendations

The Six-Pillar Socio-Ecological Infrastructure Framework provides a practical basis for translating scientific understanding into effective conservation and management actions. While specific interventions should be adapted to local ecological and socio-economic conditions, several overarching recommendations emerge from the integrated framework. These recommendations emphasize the importance of maintaining ecological integrity, strengthening community participation, and embedding mangrove conservation within broader coastal governance and climate adaptation strategies.

1. **Restore natural hydrological connectivity before planting initiatives:** Restoration programmes should first re-establish natural tidal exchange, sediment transport pathways, and freshwater flows, as successful mangrove regeneration depends primarily on appropriate hydrological conditions rather than planting alone.
2. **Prioritize native species according to natural ecological zonation:** Species selection should reflect local tidal elevation, salinity gradients, and sediment characteristics to maximize survival, maintain biodiversity, and preserve ecosystem functioning.
3. **Integrate mangrove conservation into district and regional climate adaptation plans:** Recognizing mangroves as natural coastal infrastructure can strengthen disaster risk reduction, shoreline stabilization, and climate resilience within coastal development policies.
4. **Establish long-term ecological monitoring programmes:** Continuous monitoring of vegetation dynamics, shoreline change, sediment accretion, biodiversity, water quality, and blue carbon stocks is essential for evaluating restoration success and informing adaptive management.
5. **Strengthen community-based co-management and stakeholder participation:** Active involvement of local communities, government agencies, researchers, and non-governmental organizations enhances stewardship, improves compliance with

conservation measures, and incorporates valuable local ecological knowledge into management decisions.

6. **Incorporate blue carbon into national and regional climate policy:** Quantifying and protecting mangrove carbon stocks can support greenhouse gas mitigation strategies, climate adaptation planning, and emerging blue carbon financing mechanisms.
7. **Regulate coastal development that disrupts sediment transport and tidal connectivity:** Infrastructure projects such as ports, embankments, seawalls, and land reclamation should be planned to minimize impacts on sediment dynamics and natural hydrological processes that sustain mangrove ecosystems.
8. **Adopt adaptive management informed by scientific monitoring:** Conservation strategies should be periodically evaluated using ecological indicators and monitoring data, allowing management interventions to be modified in response to changing environmental conditions, climate impacts, and socio-economic pressures.

Collectively, these recommendations demonstrate how the Six-Pillar Socio-Ecological Infrastructure Framework can guide evidence-based decision-making by linking ecological science, community participation, and policy implementation. Applying these principles can enhance the long-term resilience of mangrove ecosystems while supporting sustainable coastal development, biodiversity conservation, and climate adaptation.

9. Future Research Directions

The Six-Pillar Socio-Ecological Infrastructure Framework provides a foundation for identifying future research priorities that integrate ecological understanding, technological innovation, and adaptive governance. As coastal environments become increasingly vulnerable to climate change, sea-level rise, industrial development, and other anthropogenic pressures, interdisciplinary research will be essential for advancing evidence-based mangrove conservation and sustainable coastal management.

9.1 Digital and Community-Enabled Monitoring for Framework Implementation

Digital and community-based technologies can provide enabling infrastructure for implementing and monitoring the Six-Pillar Framework. Satellite remote sensing, GIS, UAV observations, environmental sensors, artificial intelligence-assisted image analysis, and

community reporting can provide complementary information on vegetation condition, shoreline change, sediment dynamics, pollution, restoration outcomes, and human pressures. These tools can improve the spatial and temporal resolution of framework assessment and support adaptive management. Digital technologies are therefore treated as enabling infrastructure for monitoring, assessment, and decision support rather than as independent dimensions or additional pillars of mangrove resilience.

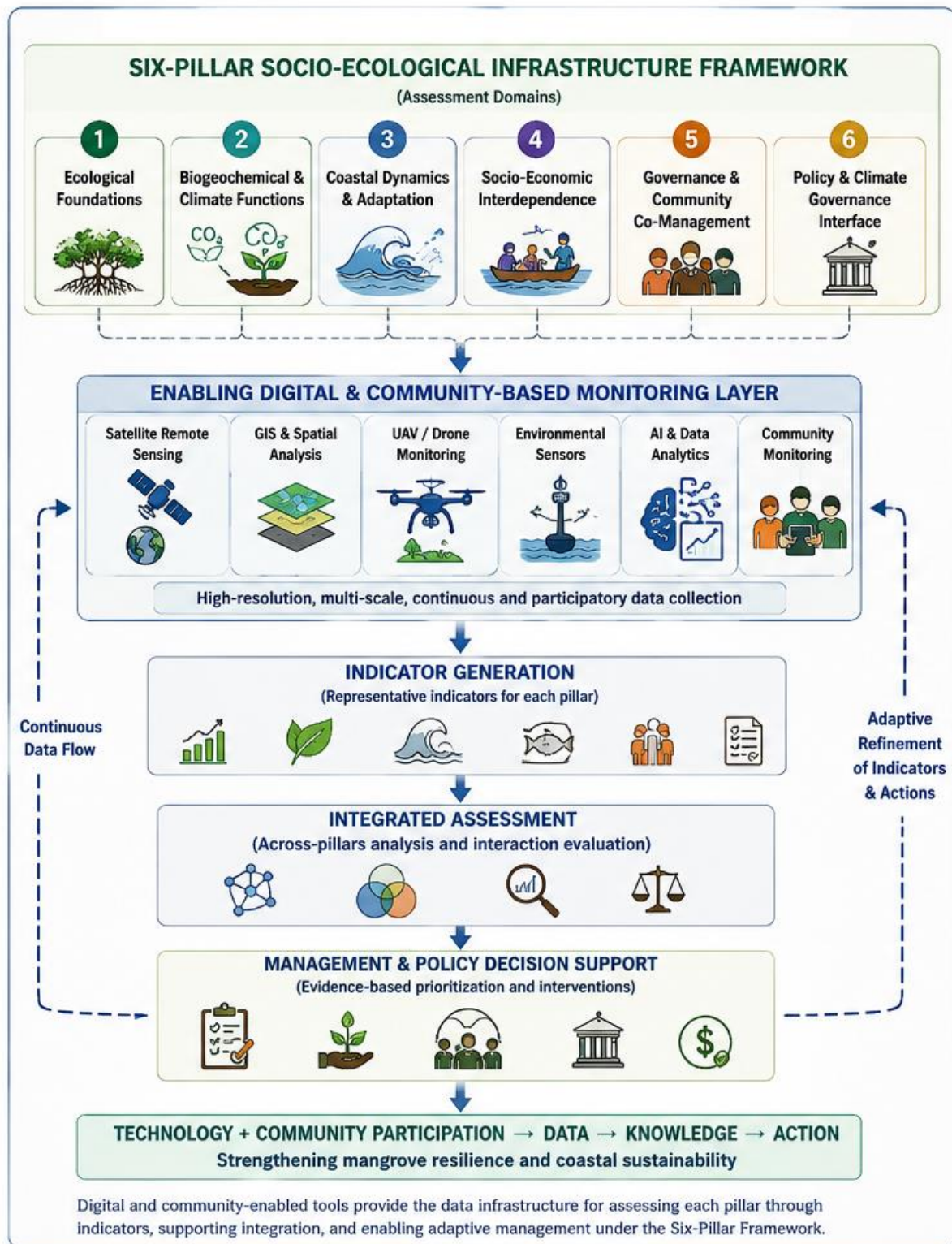


Figure 6. Digital and Community-Enabled Monitoring for Framework Implementation. Conceptual representation of how satellite remote sensing, GIS, UAV observations, environmental sensors, AI-assisted analysis, and community reporting can provide complementary data for monitoring the six framework dimensions, supporting assessment,

management decisions, and adaptive governance. Digital technologies are represented as enabling infrastructure rather than as an additional framework pillar.

As illustrated in Figure 6, satellite observations, UAVs, GIS, artificial intelligence, environmental sensors, and community reporting provide complementary capabilities for adaptive ecosystem monitoring and decision support.

The increasing complexity of coastal environmental challenges highlights the need for research that combines ecological science with emerging digital technologies. Future studies should prioritize the development of artificial intelligence (AI)-assisted monitoring systems capable of integrating satellite imagery, UAV (drone) observations, field measurements, and environmental sensor data to detect changes in mangrove extent, vegetation health, shoreline dynamics, and ecosystem degradation in near real time. Such approaches have the potential to improve the efficiency, spatial coverage, and accuracy of environmental monitoring while supporting more rapid and informed management responses.

Advances in artificial intelligence, machine learning, and environmental simulation provide additional opportunities for predictive mangrove research. Digital Twin like approaches could integrate remote sensing, hydrological observations, ecological monitoring, and climate projections into dynamic representations of mangrove systems, supporting scenario analysis, restoration planning, and adaptive management under changing environmental conditions. When integrated with Geographic Information Systems (GIS), UAV-based surveys, cloud-based environmental monitoring platforms, and high-resolution remote sensing, such approaches could provide spatially explicit information for conservation planning, ecosystem assessment, and long-term monitoring of coastal change.

9.1.1 Toward Predictive Mangrove Science

Emerging advances in AI, Earth observation, and integrated environmental modelling offer new opportunities to move mangrove research from descriptive assessments toward predictive and adaptive management. AI-assisted analysis of satellite imagery, drone observations, and environmental monitoring data can improve the detection of ecological change and support timely conservation interventions. Similarly, Digital Twin technologies have the potential to integrate ecological, hydrological, and climatic information into dynamic decision-support platforms capable of evaluating restoration scenarios and anticipating future environmental change. When combined with Geographic Information Systems (GIS), remote sensing, and

long-term ecological monitoring, these emerging approaches can strengthen evidence-based planning and enhance the capacity of researchers and coastal managers to implement resilient, adaptive, and scientifically informed mangrove conservation strategies.

9.2 Blue Carbon, Pollution, and Ecosystem Services

Future investigations should also strengthen blue carbon accounting by improving estimates of carbon sequestration, long-term storage, and greenhouse gas dynamics under different restoration and management strategies. More accurate quantification of sediment carbon accumulation, methane emissions, and carbon stability under disturbance conditions would enhance the integration of mangrove ecosystems into national climate mitigation and adaptation policies. Similarly, predictive models for heavy-metal transport, accumulation, and remobilization could improve pollution risk assessment and support more effective environmental management in industrialized and urban coastal regions. Integrating geochemical modelling with ecological indicators and remote sensing data may provide early warning systems for contaminant stress in vulnerable mangrove ecosystems. Expanding research on ecosystem service valuation will further improve understanding of the ecological, economic, and social benefits provided by mangroves, including coastal protection, fisheries support, water purification, carbon sequestration, and disaster risk reduction. Such research can strengthen evidence-based conservation policies and support sustainable investment and financing mechanisms for mangrove restoration.

9.3 Climate Adaptation and Participatory Governance

Climate adaptation research should increasingly incorporate integrated modelling of sea-level rise, coastal erosion, storm-surge impacts, extreme weather events, and changing hydrological conditions to improve the resilience of restoration programmes and coastal infrastructure planning. Particular attention should be given to understanding thresholds beyond which mangrove ecosystems may lose their capacity to maintain vertical accretion or migrate landward under accelerating sea-level rise. Equally important is the expansion of citizen science and community-based monitoring programmes. Smartphone applications, cloud-based reporting platforms, and participatory monitoring networks can enable local stakeholders to contribute observations on shoreline erosion, pollution events, vegetation stress, illegal clearing, and restoration outcomes. Combining community-generated observations with satellite monitoring and environmental forecasting can enhance adaptive governance while strengthening local stewardship and environmental awareness. Finally, longitudinal studies

spanning multiple decades are needed to evaluate restoration success, ecosystem recovery trajectories, biodiversity dynamics, carbon sequestration persistence, and the long-term effectiveness of governance interventions across diverse mangrove settings. Collectively, these research priorities will support the continued refinement and empirical evaluation of the Six-Pillar Socio-Ecological Infrastructure Framework while strengthening the integration of ecological science, digital innovation, and participatory governance. Advancing these research areas will improve evidence-based decision-making and enhance the resilience of mangrove ecosystems under accelerating environmental and climatic change, thereby supporting sustainable coastal management in India and other tropical coastal regions.

10. Limitations

The Six-Pillar Socio-Ecological Infrastructure Framework is intentionally presented as a conceptual and analytical framework rather than a validated predictive model. Its principal contribution is the integration and operational structuring of previously fragmented dimensions of mangrove resilience. Quantitative validation of relationships among the six pillars, determination of relative pillar importance, and assessment of indicator sensitivity remain subsequent research tasks. Accordingly, the comparative applications presented in this study should be interpreted as illustrative demonstrations of framework use rather than as independent empirical tests of framework performance.

The framework is primarily informed by research conducted on Indian mangrove ecosystems, which encompass diverse ecological settings, climatic conditions, governance structures, and socio-economic contexts. Although the six pillars represent broadly applicable dimensions of mangrove resilience, their relative importance and interactions may vary across regions owing to differences in environmental conditions, biodiversity, hydrological regimes, coastal geomorphology, land-use practices, and institutional arrangements. Consequently, application of the framework outside India should consider local ecological and governance contexts and, where appropriate, be adapted to regional conditions.

The present synthesis is qualitative and does not assign quantitative weights to the six pillars or explicitly model their interactions. Future research should therefore focus on empirical evaluation through comparative case studies, long-term ecological monitoring, expert elicitation, and interdisciplinary modelling to examine the relative contributions of individual framework components under different environmental and governance settings. Such

investigations would provide opportunities to refine the framework and assess its applicability across a wider range of mangrove ecosystems.

In addition, the effectiveness of mangrove conservation ultimately depends not only on ecological processes but also on governance capacity, institutional coordination, stakeholder participation, and the availability of long-term financial and technical resources. Variability in these factors across regions may influence the successful implementation of restoration and management strategies, highlighting the importance of adaptive governance and continuous environmental monitoring.

Despite these limitations, the Six-Pillar Socio-Ecological Infrastructure Framework provides a comprehensive conceptual foundation for integrating ecological science, coastal geomorphology, climate adaptation, community participation, and policy governance within a unified analytical structure. By synthesizing diverse strands of mangrove research into an integrated socio-ecological perspective, the framework offers a practical foundation for future empirical research, adaptive coastal management, and evidence-based conservation planning in India and other tropical coastal regions. The cumulative interactions among ecological processes, ecosystem functions, community participation, governance, and climate adaptation are synthesized in Figure 7, which presents the integrated socio-ecological feedback pathway proposed by this framework.

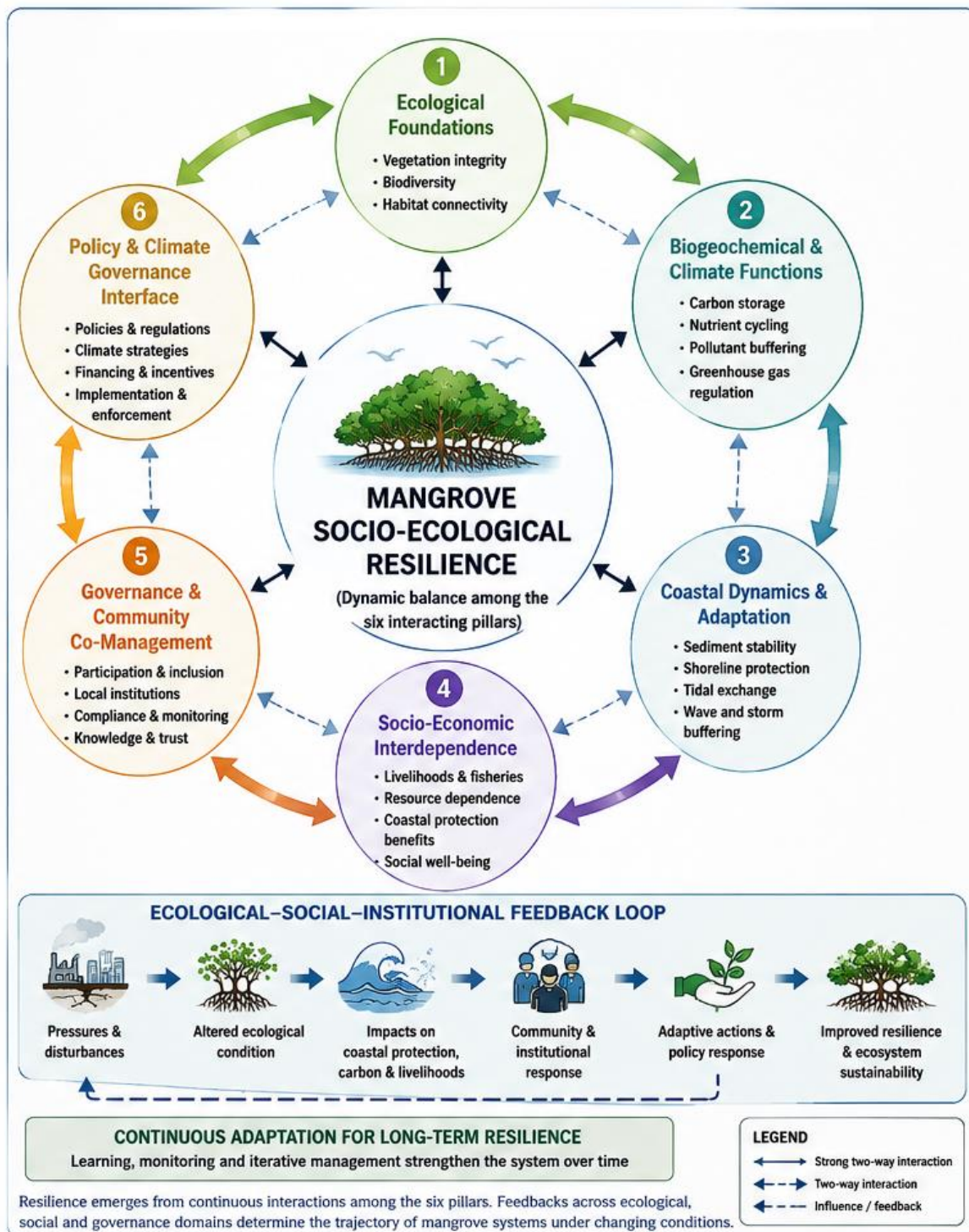


Figure 7. Integrated Socio-Ecological Feedback Pathway. Mangrove ecosystem functioning and human dimensions are interlinked in a cascading pathway that strengthens climate resilience and feeds back to improve mangrove health.

As shown in Figure 7, ecological integrity, sediment stability, carbon storage, biodiversity, sustainable livelihoods, effective governance, and climate resilience can reinforce one another through adaptive management and institutional feedback. This systems perspective reinforces

the central premise of the Six-Pillar Socio-Ecological Infrastructure Framework that long-term mangrove sustainability depends on integration among ecological, environmental, social, and institutional processes rather than isolated management interventions.

11. Conclusion

This study develops a Six-Pillar Socio-Ecological Infrastructure Framework that reframes mangroves as coupled coastal infrastructure rather than isolated ecological systems. The framework integrates ecological foundations, biogeochemical and climate functions, coastal dynamics and adaptation, socio-economic interdependence, community co-management, and policy–climate governance within a common analytical structure for understanding mangrove resilience. The principal contribution is not the identification of new mangrove functions, which are well established, but the integration and operationalization of previously distributed dimensions within a framework that links evidence domains to representative indicators, interpretation, and potential management responses. The illustrative applications to the Sundarbans and Kachchh demonstrate how the framework can organize contrasting ecological and governance contexts and identify context-specific management priorities. The framework is intentionally presented as a conceptual and analytical structure rather than a quantitatively validated predictive model. Its indicators, pillar interactions, relative pillar importance, transferability, and decision-support performance require empirical evaluation through comparative field studies, longitudinal monitoring, and quantitative analysis. The present framework therefore provides both an integrative basis for current mangrove assessment and a testable research architecture for future studies aimed at strengthening evidence-based conservation, restoration, climate adaptation, and coastal governance.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

During the preparation of this manuscript, the authors used OpenAI solely for limited language refinement, specifically to appropriately position adverbial and other grammatical elements to improve transitions between sections and overall readability, without changing the authors' wording, scientific content, interpretation, or intended meaning. Nothing was copied and pasted into the submitted article. No generative AI or AI-assisted technology was used to generate,

fabricate, alter, or interpret research data, figures, experiments, experimental results, or scientific conclusions. Figures were created by the authors using Microsoft Office applications. Free online image-editing tools were used only for minor aesthetic refinement and visual clarity. The authors take full responsibility for the accuracy, originality, integrity, and scientific content of the manuscript and its Supporting Information.

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Supporting Information: Framework Contributions and Supplementary Materials

Reframing Mangroves as Socio-Ecological Coastal Infrastructure: Development and Application of a Six-Pillar Socio-Ecological Infrastructure Framework

The Supporting Information provides additional material documenting the conceptual, structural, and operational contributions of the Six-Pillar Socio-Ecological Infrastructure Framework, together with its illustrative comparison across the Sundarbans and Kachchh mangrove systems.

Highlights

- Reframes mangroves as multifunctional socio-ecological coastal infrastructure.
- Proposes a Six-Pillar Framework for integrated mangrove resilience.
- Links ecology, blue carbon, coastal dynamics, livelihoods and governance.
- Integrates community co-management with adaptive climate governance.
- Provides practical pathways for restoration, monitoring and coastal resilience.
- The novelty lies in reframing mangroves as multifunctional socio-ecological coastal infrastructure through a *Six-Pillar Framework* that integrates ecological processes, biogeochemical and climate functions, coastal dynamics, livelihoods, community co-management, and policy governance into a unified resilience framework.

Authors define the contributions of this study in three distinct parts:

Contribution 1: Conceptual

Mangroves are reframed as socio-ecological coastal infrastructure, rather than being considered only as ecosystems or ecosystem-service providers.

Contribution 2: Structural

Six previously distributed dimensions are organized into a single interacting architecture:

Ecological → Biogeochemical/Climate → Coastal Dynamics → Socio-economic → Community Governance → Policy/Climate Governance

Contribution 3: Operational

The framework does not stop at conceptual categories. It links

pillar → indicator → interpretation → management response.

The contribution is not the identification of new mangrove functions, but the development of an operational architecture that connects those functions across ecological, physical, social and institutional domains and translates them into indicators and management decisions.

Pillar	Sundarbans	Kachchh	Framework interpretation
Ecological	High biodiversity, deltaic system	Stress-tolerant, arid system	Different ecological baselines require different restoration strategies
Coastal dynamics	Riverine sediment and tidal processes	Limited freshwater, tidal dependence	Hydrological/sedimentary interventions must be site-specific
Biogeochemical	Carbon storage + contaminant concerns	Carbon + industrial pollution concerns	Monitoring priorities differ
Socio-economic	High dependence	Local resource resource/coastal protection dependence	Social vulnerability differs
Community governance	Complex protected/transboundary context	Local restoration/co-management	Governance architecture differs

Pillar	Sundarbans	Kachchh	Framework interpretation	
Policy	Multi-level/transboundary	Regional coastal/climate planning	Institutional differs	intervention

The manuscript itself already recognizes that the two systems have contrasting environmental conditions but common interacting resilience dimensions.

FIGURES BELOW

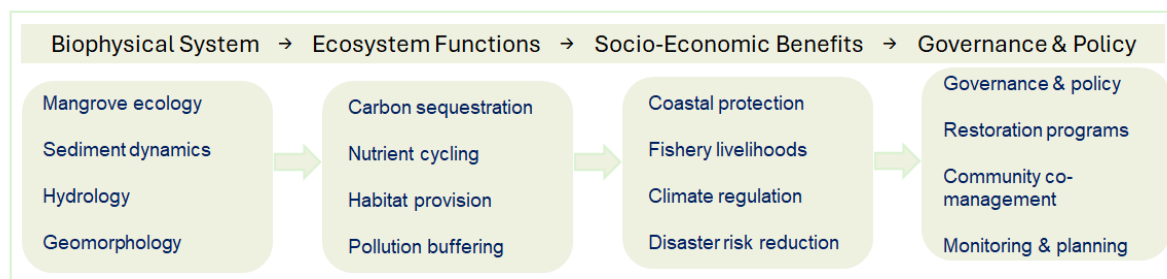


Figure S1. Integrated Socio-Ecological Infrastructure Framework for Mangrove Systems. *Conceptual representation of the framework linking biophysical processes, ecosystem functions, socio-economic benefits, community participation, governance, and policy within an adaptive feedback structure. The figure represents the proposed analytical architecture and does not imply quantified causal relationships among the framework components.*

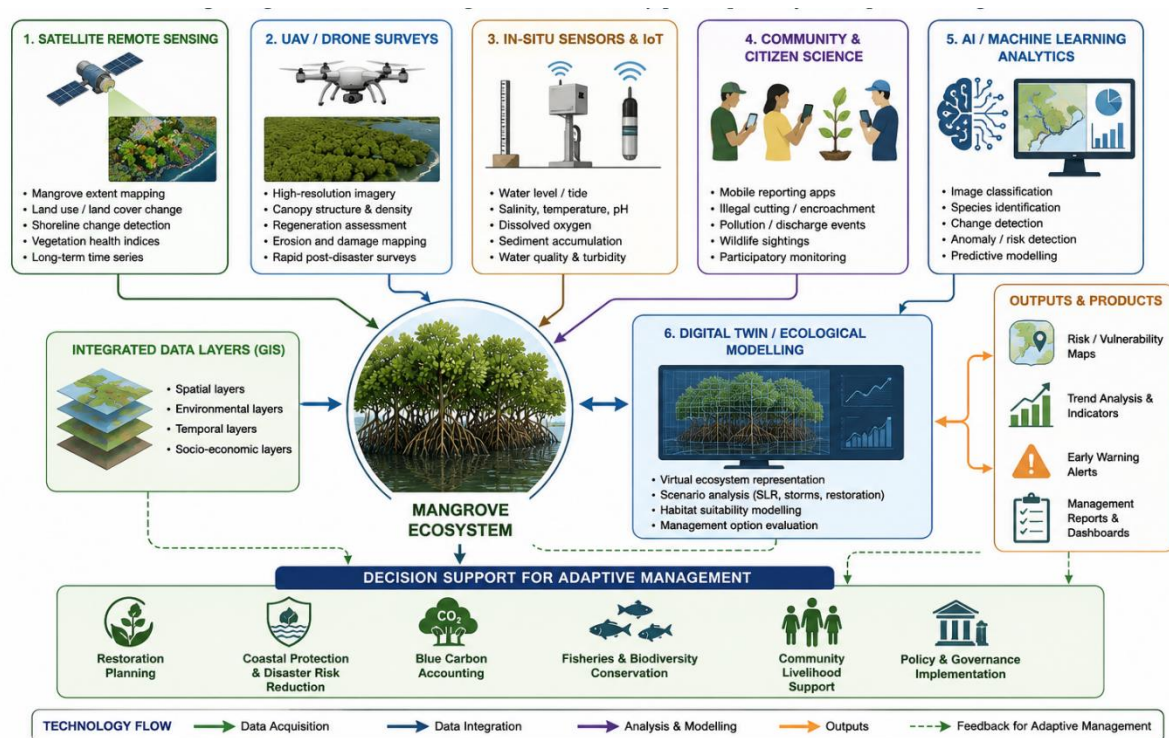


Figure S2. Emerging Technologies for Mangrove Monitoring. *Integrating advanced technologies and community participation for adaptive management.*

As illustrated in **Figure S2**, satellite observations, UAVs, GIS, artificial intelligence, and Digital Twin technologies provide complementary capabilities for adaptive ecosystem monitoring and decision support.

TABLES BELOW

Table S1. Various pillars of the Framework and their scientific focus.

Pillar	Scientific focus	Example indicators
Ecological foundations	Species composition	Species diversity
Climate functions	Carbon storage	Soil organic carbon
Coastal dynamics	Sediment transport	Shoreline change
Socio-economic	Livelihoods	Fisheries productivity
Governance	Community participation	Compliance

Pillar	Scientific focus	Example indicators
Policy	Coastal regulation	Restoration programmes

Table S2. Evidence-to-Pillar Traceability Matrix

Literature domain	Recurring determinant	Six-Pillar assignment	Representative indicator	Management relevance
Mangrove ecology	Species composition, regeneration, zonation	Pillar 1	Species diversity, regeneration rate	Restoration
Blue carbon/biogeochemistry	Carbon storage, nutrient cycling	Pillar 2	Soil organic carbon	Climate mitigation
Geomorphology	Sediment transport, erosion, tidal exchange	Pillar 3	Shoreline change, accretion	Coastal adaptation
Livelihood studies	Resource dependence, fisheries	Pillar 4	Livelihood dependence	Social resilience
Community management	Participation, stewardship	Pillar 5	Participation/co-management	Local governance
Policy/climate governance	Regulation, implementation, financing	Pillar 6	Policy implementation	Institutional coordination

Note: The traceability matrix summarizes how recurring determinants identified across the literature were assigned to the six framework pillars and linked to representative indicators and management relevance. The assignments are analytical categorizations used to construct the framework and should not be interpreted as quantitative estimates of pillar importance.

The authors synthesized recurring determinants from multiple evidence domains, traced them into six domains, and operationalized each domain. The supplementary material is intended to document the construction and illustrative application of the framework. The traceability matrix and comparative tables do not constitute independent empirical validation, quantitative weighting of the six pillars, or a predictive performance assessment. These aspects remain subjects for future empirical research.