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Review

Climate-Induced Environmental Change and Human Well-Being in the Transboundary Sundarbans: A Systematic Review

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ABSTRACT: The world's largest contiguous mangrove forest and among the most climate-vulnerable social-ecological systems, the transboundary Sundarbans is shared by Bangladesh and India. Overdependence on its ecosystem resources, along with accelerating sea-level rise, salinity intrusion from seawater, tropical cyclones, riverbank erosion, and mangrove degradation, increasingly threatens the integrity of its ecosystem and livelihoods for millions. In this systematic review, we synthesise the latest evidence on climate-related environmental change and its impact on human welfare across the transboundary Sundarbans. A systematic search of the literature from January 2010 to July 2026 was conducted using the Scopus, Web of Science, and PubMed databases, and grey literature sources were selected following the PRISMA 2020 guidelines. Of the 535 previous articles references identified in the search, 23 studies met our pre-established inclusion criteria and were analyzed using a narrative thematic synthesis. Results highlight salinity intrusion, sea-level rise, repetitive hits of tropical cyclones, shoreline erosion, and mangrove degradation as key climate-change-related drivers of the region. The new stressors compromise agricultural productivity, fisheries production, and ecosystem services, while concomitantly raising drinking-water salinity and the incidence of food insecurity. Climate-related diseases (e.g., gender inequalities, livelihood dependence, and poor adaptive capacity) lead to higher vulnerability to climate change impacts for women, children, and forest- and fishery-dependent households. The review also points to ongoing gaps in transboundary governance, alignment of environmental monitoring, climate finance, and integrated adaptation planning between Bangladesh and India. You need to strengthen ecosystem-based adaptation, climate-resilient livelihoods, public health interventions, gender-responsive policies, and bilateral governance mechanisms to increase robustness against the long-term effects of disease outbreaks. This review also offers an inclusive evidence base to assist policymakers, researchers, and development practitioners in designing climate adaptation and integrated climate-smart management strategies specific to the transboundary Sundarbans, as well as similar at-risk UES, using the delineated key themes.

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Keywords: Climate change; Sundarbans; Human well-being; Salinity intrusion; Climate-induced migration; Mangrove degradation; Ecosystem-based adaptation; Transboundary governance

1. Introduction

The Sundarbans, the world's largest contiguous mangrove forest, covers about 10,000 km^2 of the lower Ganges–Brahmaputra–Meghna (GBM) Delta and is one of the most biologically productive coastal ecosystems on Earth. The forest covers about 62% in Bangladesh and 38% in India, making it one of the world's largest transboundary forests [1,2]. The Sundarbans is known as a UNESCO World Heritage Site in both countries and supports globally significant biodiversity, including the Royal Bengal tiger (*Panthera tigris tigris*), Ganges river dolphin (*Platanista gangetica*), Irrawaddy dolphin (*Orcaella brevirostris*), estuarine crocodile, and more than 450 species of wildlife, while delivering critical ecosystem services such as shoreline stabilization, blue carbon storage, fisheries production, nutrient cycling, and storm-surge protection [3–6]. Simultaneously, the delta directly supports millions of livelihoods dependent on agriculture, fisheries, aquaculture, honey harvesting, forest-derived products, and ecotourism, making it one of the climate-change-most-vulnerable coupled human-natural systems worldwide [7,8].

In contrast, climate change has become a key driver affecting the physical integrity and social well-being of this region. The relative sea-level rise has been faster owing to global ocean warming and local land subsidence, saltwater in rivers, groundwater, and agricultural soils [8,9]. At the same time, an increase in either the occurrence or intensity of severe tropical cyclones, especially Sidr (2007), Aila (2009), Amphan (2020), Yaas (2021), Remal (2024), and other extreme weather events, has increased coastal flooding, embankment failure rates, habitat destruction, and possibly involuntary displacement of vulnerable populations. Together with the anthropogenic pressures, including upstream freshwater withdrawal, unplanned expansion of shrimp aquaculture, pollution, and land use changes, as well as overexploitation of natural resources, these climate-driven pressures create cumulative risks that challenge the adaptive capacity of many local communities [10,11]. Adaptation that necessitates coordinated transboundary governance of hydrological, ecological, and socio-economic processes that transgress national boundaries is mainly fragmented between Bangladesh and India [12] due to institutional structures, financing mechanisms, and conservation policies.

Human well-being is a state in which people are able to satisfy their basic material needs, live long and healthy lives, feel secure, have good social relations, and have the freedom to choose and pursue their goals. Drawing on the Millennium Ecosystem Assessment, it defines human well-being as consisting of five interrelated elements: basic material for a good life, health, good social relations, security, and freedom of choice and action. These dimensions are fundamentally related to the benefits that people receive from ecosystems and ecosystem services [13,14]. In the Sundarbans context, human well-being was defined as the ability of people and communities to access secure livelihoods, enjoy good health, have secure food and water, sustain social and cultural relationships, and have the freedom to adapt and make choices about their future. The provision of ecosystem services by the Sundarbans mangrove ecosystem, including fisheries, forest products, coastal protection, freshwater regulation and cultural values, is closely linked to human well-being. Human well-being is measured on the basis of the framework provided by the Millennium Ecosystem Assessment (MEA) in terms of five interrelated dimensions: basic material for a good life, health, security, good social relations, and freedom of choice and action. Climate and non-climate changes in the Sundarbans ecosystem influence these dimensions of well-being, both directly and indirectly [15,16].

Natural disasters, wrought by climate-induced environmental change, threaten human well-being through multiple pathways that are direct and indirect and highly intertwined. Rising salinity of potable water, in addition to hypertensive disorders of pregnancy like gestational hypertension or pre-eclampsia,

CKD, dermatoses, and gastrointestinal ailments. Salinization, hydrological alteration, and changing hydrologic regimes reduce crop yields, lower fishery catch per unit effort, and increase dependence on climate-sensitive livelihoods, negatively affecting food security [17,18]. Rückle et al. [19] mentioned, "Riverbank erosion, loss of land, and recurrent cyclones lead to displacement and forced migration, also impacting the livelihoods with an uneven burden on women, children, indigenous peoples, and small-scale fishing potential". Further to this, emerging evidence indicates that repeated climate shocks can lead to anxiety, depression, trauma, eco-anxiety, and deterioration in subjective well-being, with climate change being situated as an environmental hazard and public health threat [20]. Mangrove degradation diminishes natural coastal protection, compromises blue carbon storage and biodiversity, whilst also threatening vital ecosystem services that local communities rely on [21,22]. Table 1 explores the research findings on climate drivers and human well-being related to the transboundary Sundarbans.

Table 1. Major climate-induced environmental changes and their implications for human well-being in the transboundary Sundarbans.

Climate Driver	Environmental Impacts	Human Well-Being Impacts	References
Sea-level rise	Coastal inundation, land loss	Displacement, livelihood loss	[8,17]
Salinity intrusion	Soil and groundwater salinization	Hypertension, reduced crop yield, food insecurity	[23,24]
Tropical cyclones	Mangrove damage, embankment breaches	Mortality, trauma, migration, poverty	[7,20]
Riverbank erosion	Loss of settlements and farmland	Climate displacement, economic insecurity	[19]
Mangrove degradation	Biodiversity decline, reduced blue carbon	Reduced ecosystem services and coastal protection	[5]
Fisheries decline:	Reduced fish abundance	Income loss, nutritional insecurity	[18,25]

Despite an expansion of research in the Sundarbans region over the last decade, existing evidence is still widely dispersed across disciplinary boundaries (ecology and environmental science, public health, economics and migration studies, disaster management, and psychology) and conducted largely in national rather than transboundary contexts. Thus, only a few studies have thoroughly investigated how climate-driven environmental changes affect multiple aspects of human well-being jointly across the entire Bangladesh-India Sundarbans social-ecological system [26]. Moreover, there has been relatively little synthesis as to the effectiveness of adaptation strategies, ecosystem-based approaches (EBAs), governance, and cross-border institutional arrangements. Bridging these knowledge gaps is critical for implementing the Sustainable Development Goals (SDGs), individual commitments under the Paris Agreement, the Kunming–Montreal Global Biodiversity Framework, and integrated climate adaptation planning on deltas.

This systematic review therefore synthesizes evidence from both peer-reviewed and grey literature to assess the interconnectedness of climate-driven environmental change for human well-being across the transboundary Sundarbans. The review consists of three research questions: (i) What have been the documented climate-induced environmental changes across the transboundary Sundarbans? (ii) By which ecological, socio-economic, and health pathways do these changes exert their impacts on human well-being? (iii) What are the adaptation strategies, governance mechanisms, and transboundary policy responses in place, and what important gaps still exist?

This review synthesizes available evidence from both Bangladesh and India to generate a holistic understanding of climate–ecosystem–human interactions to inform policy recommendations that enhance ecosystem resilience, strengthen human well-being, and enable coordinated transboundary climate governance.

The review also fits the journal's ecological-civilization perspective because the Sundarbans demonstrates the inseparability of ecological integrity and human well-being; mangrove conservation, fisheries sustainability, freshwater security, disaster-risk reduction, livelihood resilience, and community agency are interdependent objectives. An ecological-civilization approach therefore calls for adaptation

strategies that protect ecosystem functions while enabling coastal communities to maintain secure livelihoods and participate meaningfully in decisions affecting natural resources.

2. Materials and Methods

This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [27]. Because the eligible evidence is heterogeneous in design, outcome measurement, and disciplinary focus, quantitative meta-analysis was not appropriate; instead, we used a narrative thematic synthesis. The review process comprised database searching, grey-literature searching, deduplication, title/abstract screening, full-text eligibility assessment, data extraction, quality appraisal, and thematic synthesis. The protocol was not prospectively registered; this limitation is reported explicitly.

2.1. Search Strategy

The academic search covered Scopus, Web of Science, and PubMed. Complementary grey literature was searched through relevant institutional sources, including UNESCO World Heritage Outlook materials, World Bank publications, and CGIAR-related assessments. The search period was January 2010 to July 2026. The core search concept combined the geographic terms ("Sundarbans" OR "Sunderbans") with climate/environment terms ("climate change" OR "sea-level rise" OR salinity OR cyclone* OR erosion OR "mangrove degradation") and human well-being terms (health OR livelihood* OR "food security" OR migration OR displacement OR "mental health" OR well-being OR governance OR adaptation

2.2. Eligibility Criteria

Studies were eligible when they (a) examined the Indian and/or Bangladeshi Sundarbans specifically, (b) assessed a climate-related environmental change, and (c) reported an explicit human well-being outcome or a documented pathway linking environmental change to livelihoods, health, migration, social well-being, or governance. The review studies focused only on biological or ecological outcomes without an explicit human well-being pathway were excluded from the formal evidence synthesis. Reviews, editorials, and commentaries were also excluded from the formal included sample under the stated criteria. Non-climatic pressures such as pollution, aquaculture expansion, land-use change, and upstream water diversion were not treated as climate drivers; where relevant, they are discussed as interacting contextual pressures. Ecological and biodiversity studies excluded from the formal sample may be used separately as contextual evidence when they illuminate ecosystem services, economically or culturally important species, or plausible long-term pathways affecting community resilience. Such contextual evidence is explicitly distinguished from direct evidence of human well-being. Table 2 explores the inclusion and exclusion criteria of the articles during the search strategies.

Table 2. Eligibility Criteria of the Study Selection.

Criterion Category	Inclusion Criteria	Exclusion Criteria
Geographic Scope	Studies conducted in the Indian Sundarbans, Bangladeshi Sundarbans, or the transboundary Sundarbans ecosystem.	Studies conducted outside the Sundarbans region or in mangrove systems without specific reference to the Sundarbans.
Exposure/Driver	Studies assessing climate-related environmental changes, including sea-level rise, salinity intrusion, cyclones, storm surges, flooding, temperature change, rainfall variability, drought, erosion, or other climate-induced environmental changes.	Studies focused exclusively on non-climatic drivers such as pollution, aquaculture expansion, land-use change, industrial development, or upstream water diversion without a climate-related component.

Human Well-Being Outcomes	Studies reporting explicit human well-being outcomes, including impacts on livelihoods, income, food security, health, migration, displacement, social well-being, vulnerability, adaptive capacity, governance, or resilience.	Studies reporting only environmental, ecological, or biological outcomes without demonstrating a pathway to human well-being.
Environment–Human Linkages	Studies documenting a clear causal or conceptual pathway linking climate-related environmental change to human well-being outcomes.	Studies describing environmental change without discussing implications for people, communities, institutions, or livelihoods.
Population of Interest	Human populations, households, communities, resource users, fishers, farmers, women, Indigenous groups, migrants, or governance institutions within the Sundarbans.	Studies focusing solely on flora, fauna, ecological processes, species distributions, or ecosystem functioning without human dimensions.
Study Types	Primary empirical studies, including qualitative, quantitative, mixed-methods, modelling studies with human outcome assessment, and case studies.	Reviews, systematic reviews, meta-analyses, editorials, perspectives, commentaries, opinion pieces, and conceptual papers lacking primary evidence.
Evidence of Climate Impacts	Directly measured, observed, modelled, or perceived impacts of climate change on human well-being.	Studies lacking evidence of climate-related environmental change or lacking human outcome assessment.
Language and Publication Type	Peer-reviewed journal articles and other eligible empirical publications available in the selected review languages.	Non-empirical publications, duplicate records, conference abstracts without sufficient data, and inaccessible full texts.

Human Well-Being Framework

Human well-being is treated as a multidimensional outcome encompassing material and livelihood security, health, food and freshwater security, social relations and participation, and the capacity to cope with and adapt to environmental change. This framing is consistent with the Millennium Ecosystem Assessment and the IPBES approach to relationships among ecosystems, ecosystem services, human well-being, and drivers of environmental change. The six review themes are therefore interpreted as interconnected dimensions rather than independent outcomes.

2.3. Study Selection and Synthesis

Title and abstract screening was followed by full-text assessment against the eligibility criteria. The current manuscript reports 23 sources in the final synthesis, but the reviewer audit identified several entries in Table 3 that may not satisfy the stated criteria, including reviews and studies whose primary exposure is pollution rather than climate change. These records must therefore be re-screened against the original eligibility criteria before final submission. The formal evidence synthesis should contain only studies that satisfy those criteria; excluded ecological, pollution-focused, or review evidence should be moved to a clearly labelled contextual section or removed. The final PRISMA count must be taken directly from the search and screening records rather than reconstructed from the manuscript. The synthesis remains narrative because of heterogeneity in design and outcomes. Evidence is organized around six domains: climate-related environmental drivers; livelihoods and economic well-being; physical health; mental and social well-being; migration and displacement; and governance, adaptation, and community agency.

Table 3. Quality Appraisal and Eligibility status of the selected studies.

Study	Quality Appraisal	Eligibility Status
Study 1: Loucks et al. [28]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 2: Khan et al. [29]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 3: Chowdhury et al. [30]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria

Study 4: Shammi et al. [24]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 5: Dasgupta et al. [7]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 6: Smith et al. [10]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 7: Mitra, et al. [31]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 8: UNESCO [6]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 9: Mandal et al. [16]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 10: Chakraborty et al. [25]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 11: Bose and Joshi [32]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 12: Karim et al. [33]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 13: Rahman et al. [34]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 14: Rückle et al. [19]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 15: Dutta et al. [17]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 16: Hasan et al. [35]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 17: Islam et al. [36]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 18: Ghosh et al. [37]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 19: Banerjee and Kasibhatta, [12]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 20: Biswas and Maiti [21]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 21: Mojid et al. [38]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 22: Miah et al. [39]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria
Study 23: Martínez-Fabiani et al. [40]	Complete from MMAT/AACODS appraisal sheet	Re-screen against final criteria

2.4. Quality Assessment

Quality appraisal was conducted using the Mixed Methods Appraisal Tool (MMAT, 2018) for eligible peer-reviewed studies and the AACODS checklist for eligible grey literature. The appraisal was used to assess methodological rigor and credibility rather than as an automatic exclusion criterion. The revised manuscript will report study-level appraisal outcomes in a supplementary appraisal matrix and will use appraisal results to qualify the strength of the narrative synthesis. Because the current file does not contain the completed item-level MMAT/AACODS scoring sheet, study-level scores should not be invented; the completed appraisal matrix should therefore included in the Table 4.

Table 4. Quality appraisal tools used in this review.

Source Type	Appraisal Tool	Assessment Criteria	Purpose
Qualitative studies	MMAT (2018)	Methodological quality, data collection, analysis, interpretation	Assess study rigor.
Quantitative studies of	MMAT (2018)	sampling, measurement, bias, and statistical analysis	Assess study rigor.
Mixed-methods studies	MMAT (2018)	Integration of methods, methodological coherence	Assess study rigor.
Grey literature	AACODS Checklist	Authority, Accuracy, Coverage, Objectivity, Date, Significance	Assess credibility and relevance.

2.5. Limitations of the Search Process

Although this study follows PRISMA 2020 and is presented as a systematic review, it has important limitations. The evidence is heterogeneous, some grey-literature sources are difficult to compare directly with peer-reviewed studies, and the available literature is geographically and thematically uneven. The protocol was not prospectively registered. These limitations were considered when interpreting the narrative synthesis.

3. Results

3.1. Overview of the Evidence-Based Studies

The current PRISMA flow reports 535 records identified through the three academic databases and complementary grey-literature sources. After removal of 126 duplicates, 409 records remained for title and abstract screening; 332 were excluded, leaving 77 full-text records for eligibility assessment. The current flow then reports 54 full-text exclusions and 23 included sources. These arithmetic relationships are internally consistent, but the final submitted manuscript should use the exact counts exported from the authors' search and screening records. The abstract and PRISMA figure must use the same verified count (Figure 1).

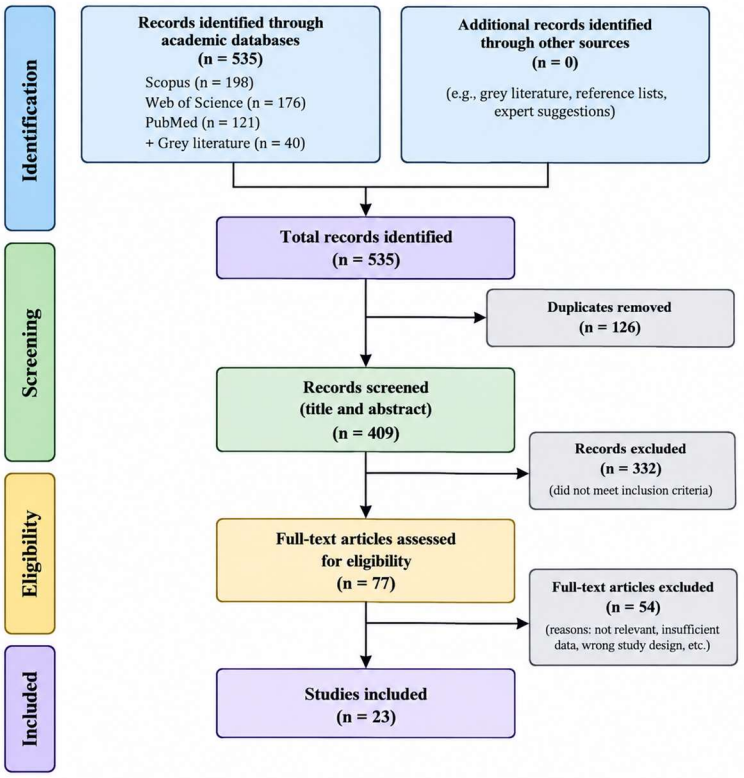

Figure 1. PRISMA 2020 Flow Diagram of the Review Study.

Among the 77 full-text records, the current screening record reports 54 exclusions: 17 for geographical scope, 11 for environmental/ecological findings without human well-being outcomes, 14 for insufficient linkage between environmental exposure and a human well-being outcome, 5 for insufficient methodological information, and 7 because the publication type was a review, editorial, or commentary. The reviewer audit indicates that some records still listed in Table 3 appear to fall into these excluded categories. Table 3 must therefore be reconciled with the screening log before final submission.

The studies also addressed climate-change-induced environmental change in the transboundary Sundarbans and explored linkages between ecosystem degradation, public health, livelihoods, migration, and governance. The evidence base consisted of quantitative, qualitative, mixed-methods, remote-sensing, epidemiological, household survey, and policy-Analysis studies across all subsections for an interdisciplinary perspective on climate-related human well-being.

As shown in Table 1, most studies used quantitative and mixed-methods approaches, with salinity, tropical cyclones, rising sea level, and mangrove degradation emerging as the most frequently studied climate drivers. The included studies span a wide geographic range and cover climate change impacts across fields—climate science, hydrology, remote sensing, ecology, public health, environmental economics,

migration studies, disaster risk reduction, and environmental governance—reflecting transboundary implications (Table 5). The Methods used to assess human and environmental interactions were remote sensing, household surveys, epidemiological studies, qualitative interviews, or policy Analysis in most of the included studies. The available evidence remains inconsistent with recent bibliometric and systematic reviews, being geographically biased in relation to the Bangladesh Sundarbans and thematically biased towards salinity intrusion, tropical cyclones, livelihood vulnerability, and ecosystem degradation, but comparatively fewer studies explicitly take a transboundary Bangladesh–India focus or assess cross-border governance mechanisms [17].

Table 5. Characteristics of Included Studies on Climate-Induced Environmental Change and Human Well-Being in the Transboundary Sundarbans (2010–2026).

Study No.	Country/Region	Study Design	Climate Driver(s)	Human Well-Being Dimension	Main Findings	References
1	Bangladesh–India	Habitat modelling	sea-level rise	Biodiversity, ecosystem services	Projected sea-level rise threatens tiger habitat and mangrove ecosystems.	[28]
2	Bangladesh	Epidemiological	Drinking-water salinity	Physical health:	Salinity exposure is associated with hypertension and pre-eclampsia among pregnant women.	[29]
3	India	Cross-sectional	Salinity intrusion	Public health:	Salinity affected drinking-water quality and increased health risks.	[30]
4	Bangladesh	Cross-sectional	Salinity intrusion	Public health	reported increased risks of skin diseases, diarrhea, and cardiovascular problems.	[24]
5	Bangladesh	Mixed methods	Sea-level rise, salinity	Livelihoods, food security	Climate change reduced agricultural productivity and livelihood security.	[7]
6	Bangladesh	Policy analysis	Freshwater diversion	Livelihoods	Human interventions intensified climate vulnerability.	[10]
7	India	Field Investigation:	Estuarine acidification	Fisheries	Acidification altered estuarine ecosystem health and fisheries.	[31]
8	Bangladesh–India	Institutional report	Cyclone Amphan	Infrastructure, livelihoods	Severe damage to coastal infrastructure, agriculture and fisheries.	[6]
9	Bangladesh–India	Review	Mangrove degradation	ecosystem services	Mangrove degradation reduced coastal protection and ecosystem resilience.	[16]
10	Bangladesh	Remote sensing	Cyclones, mangrove loss	Disaster risk reduction	Intact mangroves significantly reduced storm-surge impacts.	[25]
11	India	Policy analysis	Sea-level rise, erosion	Livelihoods, displacement	Accelerated shoreline erosion increased climate displacement.	[32]
12	Bangladesh	Spatial analysis	Salinity intrusion	Agriculture	Expansion of saline-affected land reduced crop productivity.	[33]
13	Bangladesh	Household Survey	Cyclones	Social resilience:	Social capital enhanced preparedness and post-disaster recovery.	[34]
14	Bangladesh	Qualitative	Cyclones	Mental health:	Recurrent disasters increased psychological stress and anxiety.	[19]
15	Bangladesh–India	Systematic review	Multiple climate stressors	Governance	Identified significant gaps in transboundary adaptation governance.	[17]

16	Bangladesh–India	Field investigation	Microplastics	Fisheries	Microplastic contamination threatens aquatic biodiversity and fisheries.	[35]
17	Bangladesh	Socio-economic analysis	Climate variability	Fisheries livelihoods	Climate variability reduced fishing income and increased livelihood vulnerability.	[36]
18	Bangladesh–India	Environmental assessment	Heavy metals	Environmental health	Heavy-metal contamination increased ecological risks in estuarine systems.	[37]
19	India	Environmental study	Carbon cycling	Blue carbon	Microplastics may influence blue carbon sequestration processes.	[12]
20	India	Remote sensing	Shoreline erosion	Land resources	Machine-learning Analysis identified accelerating coastal erosion hotspots.	[21]
21	India	Public health	Cyclones	Health equity	Recurrent cyclones disproportionately affect vulnerable populations.	[38]
22	Bangladesh–India	Socio-ecological assessment	Climate vulnerability	Fisheries	Climate change threatens the long-term viability of small-scale fisheries.	[39]
23	Bangladesh	Qualitative	Climate change	Women's livelihoods	Women adopted diverse livelihood strategies to strengthen household resilience.	[41]

Research findings have risen significantly after 2020–2021, as scientific and policy interest has grown following extreme climate events, such as Cyclone Amphan (2020), Cyclone Yaas (2021), and Cyclone Remal (2024), alongside global discussion of climate adaptation, biodiversity conservation, and sustainable development dialogues in deltaic ecosystems [6,8]. Across the reviewed papers, climate-related environmental change was associated with reduced ecosystem service provision, fewer opportunities for livelihood development, unmet security around livelihoods and health needs, increased risks of climate-induced displacement, and emerging mental health challenges [38,41].

3.2. Climatic and Environmental Drivers

According to the systematic review of the study literature, four interrelated environmental drivers are consistently found to be the primary mechanisms through which climate change is reshaping the Sundarbans social–ecological system. First, land area is gradually shrinking, and coastal communities are increasingly exposed due to sea-level rise, coastal inundation, and shoreline erosion. In parts of the Sundarbans, relative sea-level rise is estimated at 3–8 mm year^{-1}, faster than the current global average due to regional land subsidence and ocean warming [8]. In the Indian Sundarbans, at least two inhabited islands, including Lohachara and Bedford Islands, have already vanished, while an estimated 210 km^2 of land has been lost to erosion and submergence over the last sixty years [32,42]. These processes are still putting towns and farmland, as well as important wildlife habitats, at risk.

Second, salinity intrusion has been aggravated due to global sea-level rise, reduced freshwater flow from upstream water bodies into the delta region, prolonged dry seasons, and periodic saline-water inundation during storm surges pushed by tropical cyclones coming from the Bay of Bengal. Saline water has gradually reached inland river systems, groundwater, and agrarian soils, unfavorably influencing drinking water quality, crop efficiency, and freshwater biodiversity [7,29]. In many coastal areas, salinity is a major driver of reduced agricultural yields and freshwater scarcity, exacerbating food insecurity and livelihood vulnerability.

Third, tropical cyclones and their related storm surges are characterized by increasing violence. The Bay of Bengal has also been a region of the most devastating cyclones in the world, and many high-impact cyclonic events have occurred during previous decades, including Sidr (2007), Aila (2009), Bulbul (2019), Amphan (2020), Yaas, Mocha (2023), and Remal (2024). Cyclone Amphan alone impacted over 10 million people in Bangladesh and India, devastated large mangrove forests, breached embankments, and inflicted wide-ranging agricultural, fisheries, and infrastructure losses [8,43]. The frequency of these events has increased markedly, raising climate risks for both ecosystems and adjacent communities.

Fourth, mangrove ecosystem degradation has become a major environmental issue. Combined with anthropogenic pressures, including land-use change, expansion of aquaculture, and upstream diversion of freshwater, climate-driven disturbances have lowered mangrove resilience more broadly [5]. Coastal protection against storm surges is diminished when mangroves are degraded; so is their carbon sequestration capacity, as well as the quality of habitat for vulnerable species and fisheries productivity. Intact mangrove belts have been shown to lower wave energy and storm-surge height and restore coastal sediment [6,30], thus providing life-sustaining organization-based adaptation services to coastal communities.

These environmental drivers act synergistically rather than independently by activating cascading effects across all physical, economic, and biological systems. They can exacerbate community vulnerability and diminish adaptation capacity, which calls for the need for integrated, ecosystem-based, and transboundary climate adaptation in the Bangladesh–India Sundarbans (Table 6).

Table 6. Principal Climate-Induced Environmental Drivers in the Transboundary Sundarbans.

Driver	Key Indicator	Documented Evidence	References
Sea-level rise & shoreline erosion	Land loss: Coastal retreat and shoreline erosion	Indian Sundarbans lost ~210 km^2 of land over six decades; the majority of West Bengal's coastline is eroding.	[32]
Salinity intrusion	Soil and drinking-water sodium	Saline intrusion has advanced more than 100 km inland from the Bay of Bengal; drinking-water sodium levels in many areas far exceed WHO guidance.	[24,29]
Cyclone intensification	frequency and severity of storms	8 major cyclones struck the region between 2019 and 2024, compared with 35 across the entire 20th century to 2002	[32,44]
Mangrove degradation	Vegetation loss; habitat quality	Cyclone Remal (2024) caused a 38.1% loss in dense vegetation; Cyclone Amphan (2020) damaged >1200 km^2 of mangroves, with 18.8% loss along the most exposed shorelines.	[25,45]
Warming waters and habitat contraction	Sea/land temperature rise; species range shifts	Sea-level rise is projected to substantially reduce Bengal tiger habitat extent by mid-century; warming waters are linked to declining fish and prawn stocks.	[28,46,47]

3.3. Impacts on Livelihoods and Economic Well-Being

Livelihoods of transboundary Sundarbans communities are highly reliant on climate-sensitive natural resources such as capture fisheries, small-scale agriculture, aquaculture, livestock production, honey collection, fuelwood harvesting, and other non-timber forest products. Approximately 4–5 million people directly or indirectly depend on the Sundarbans for food security and a source of employment as well as household income, leading to very high socioeconomic vulnerabilities in this coastal landscape in South Asia [6,7]. Climate change will therefore have significant effects on the sustainability of livelihoods and economic development in these regions.

Agricultural deterioration has led to rising soil and groundwater salinity due to waterlogging, riverbank erosion, and cyclonic storm surges. Salinity Intrusion has diminished the productivity of rice and vegetable cultivation [48], caused damage to irrigation systems [49] and turned vast regions of croplands into saline fallows, further jeopardizing household food security while aggravating rural poverty [8,20,34,50]. As an

adaptation response, coastal farmers have started to gradually transform traditional crop cultivation into brackish-water shrimp aquaculture; yet such switches have raised new environmental problems, including accelerated salinization of soil, biodiversity loss, and increased social inequity in relation to land-use change [51].

Fisheries and aquaculture, which provide important sources for protein, employment, and export revenues, are likewise highly vulnerable to climate variability. In addition, rising water temperatures, changes in freshwater inflows associated with alteration of the natural flow regime (including environmental flows), shifts in salinity regimes due to sea-level rise and tidal inundation, estuarine acidification, and habitat degradation have disrupted migratory routes for fish species between fresh/estuarine habitats and nursery habitats/spawning grounds and affected the success of spawning both individuals and populations during particular periods of the year. Commercial extraction/harvestability—inaccuracy of statewide impact—as evidenced by declining catches of several commercially important finfish (e.g., mullet; ibang) and many crustacean species such as shrimp [10,52]. One of the most economically important fish species in Bangladesh and eastern India is Hilsa (*Tenualosa ilisha*), which has shown distributional changes for this primary harvested species, spawning habitat shifts related to changing hydrological conditions, and salinity increases from climate change that threaten thousands of artisanal fishers' livelihoods [18,19]. Instead, a recent study shows that deteriorating ecosystem conditions lead to further declines in small-scale fisheries resilience, worsen coastal household income stability, and undermine food security [39,40].

Extreme events have inflicted huge economic losses in the Sundarbans region. Cyclones Sidr (2007), Aila (2009), Bulbul (2019), Amphan (2020), Yaas (2021), and Remal (2024) collectively destroyed huge numbers of embankments, cropland, aquaculture ponds, fishing infrastructure, transport networks, and rural housing [18,41]. Due to cyclonic storm Amphan, massive saline inundation occurred, with the destruction of most agricultural fields and freshwater ponds and fish farms resulting in a major impact on household income loss as well as a postponement of livelihood recovery for many years [25,41]. Rapid-onset climate-induced disasters have driven increased household indebtedness, low productive assets, and permanent outmigration, as well as seasonal migrant families pursuing alternative livelihoods outside the delta [34,36].

This is compounded by many resource-dependent households depending on fisheries, crabs and shrimp, honey and wax, medicinal plants and fuelwood, undermining livelihood security through mangrove forest degradation due to climate emissions. Ecosystem productivity decline has compelled fishers, honey collectors, and crab harvesters deeper into protected forest areas, thereby increasing their exposure to occupational hazards and human-wildlife conflicts, particularly those with the Bengal tiger (*Panthera tigris tigris*) [5,6]. Concurrently, the decline of ecosystem services increasingly lessens natural protection against storm surges and coastal erosion by mangroves, which exacerbates economic vulnerability and disaster risk (Table 7).

Table 7. Major Climate-Induced Livelihood Impacts in the Transboundary Sundarbans.

Climate Stressor	Livelihood Sector	Major Impacts	References
Salinity intrusion	Agriculture	Reduced rice yield, soil degradation, food insecurity	[8–12]
Sea-level rise	Agriculture, settlements	Land loss, displacement, declining productivity	[15–20]
Cyclones and storm surges	Agriculture, fisheries, infrastructure	Crop loss, embankment failure, infrastructure damage	[25–28,41]
Rising temperature and altered hydrology	Fisheries	Reduced fish abundance, altered migration, lower catches	[10,41,51]
Mangrove degradation:	Forest-dependent livelihoods	Reduced honey, crab, fuelwood, and fisheries resources; increased human–wildlife conflict	[7,10,15,30]
Climate variability:	Household economy	Income instability, migration, indebtedness	[20,35,46]

The evidence reviewed here reflects that climate change is not only deteriorating natural resources but also eroding. the socio-economic base of Sundarbans. The cumulative impact of salinity Intrusion with ecosystem degradation, declining small-scale fisheries, reduced agricultural productivity, and weather-related disasters creates interlinked livelihood risks that hit low-income households (who have limited means to adapt) hardest. Thus, there is a necessity for strengthening climate-resilient agriculture, promoting sustainable fisheries management, restoring mangrove ecosystems, and enhancing transboundary policy coordination to achieve long-term economic resilience in the Sundarbans.

3.4. Impacts on Physical Health

The escalating environmental impacts of climate change in the transboundary Sundarbans pose grave public health risks primarily via enhanced salinity intrusion, drinking water quality deterioration, extreme climatic events, emerging water/food-borne diseases, and lack of sanitation. Of these pathways, the salinity of drinking water is undoubtedly the most clearly evidenced and documented pathway associated with health risk. Cyclone-induced storm surges, rising sea levels, and declining upstream freshwater discharge have greatly increased salinity of groundwater, rivers, and other sources for drinking and household needs [7,8,29,35], making millions more coastal residents dependent on excessive sodium-polluted water supplies to meet subsistence needs.

High sodium intake from saline drinking water is significantly associated with the development of hypertension, gestational hypertension, and pre-eclampsia in pregnant women in coastal Bangladesh. Khan et al. conducted a landmark epidemiological study. For example, a comprehensive study of 65 hospital births in pilot towns in rural Bangladesh conducted by Rahman et al. [34] showed a strong dose-response relationship between drinking-water salinity and maternal blood pressure, with women consuming the most highly saline water shown to be at much higher risk of pregnancy-related hypertensive disorders. Besides, population-based studies have shown an increased outbreak of hypertension and prehypertension for the salinity-exposed communities compared to unexposed populations, with a greater health impact noted among women, older adults, and socioeconomically disadvantaged households [20,24].

In addition to cardiovascular diseases, long-term exposure to saline water is associated with a wider spectrum of adverse health effects. Adam et al. [53] suggested that due to extreme saltwater intrusion and salinized tubewells, increased levels of diarrheal disease, gastrointestinal disorders, dermatological infections, dehydration, chronic kidney disease & other electrolyte imbalances have been reported in the affected coastal communities where fresh water handling has been limited [10–14]. Adolescent girls and women are particularly vulnerable due to frequent use of saline water for bathing, household chores, and menstrual hygiene management when safe freshwater is not accessible, exposing them to greater risk of skin irritation, reproductive tract infections, and other hygiene-related diseases [15–17].

Health vulnerabilities are compounded as a result of extreme climatic events by disruption of water supply systems and sanitation infrastructure, healthcare services, and food availability. In the months after major cyclones such as Amphan (2020), Yaas (2021), Mocha (2023), and Remal (2024), widespread flooding and saline inundation polluted drinking-water sources, damaged health facilities, and increased the transmission of waterborne and vector-borne diseases following disasters [20–22]. Diarrhea, dengue fever, malaria, and other climate-sensitive infectious diseases, particularly in young children and vulnerable groups such as older adults infected and immunosuppressed individuals, are encouraged by prolonged waterlogging [20].

Declining agricultural productivity, fisheries production, and access to natural resources due to climate change also indirectly bring adverse impacts on physical health by weakening household food security and dietary diversity. There has also been an increasing rate of undernutrition and micronutrient deficiencies among vulnerable coastal populations—especially women and children—in many low- to middle-income countries, exacerbated by recurrent crop failures, diminished fish catches, and reduced ecosystem

productivity [18–20]. These nutritional stresses are in addition to reduced community resilience to infectious diseases and other climate-related health threats.

The reviewed evidence indicates that the Sundarbans physical health impacts are generated through a complex of interacting pathways, not simply isolated environmental hazards. However, salinity intrusion, water quality deterioration, increased occurrence of infectious diseases, food insecurity, and recurrent climate disasters constitute a long-term public health burden that unfairly impacts women, children, older adults, and people in monetary distress. Therefore, integrated adaptation measures are needed, such as efficient freshwater supply systems for drinking water and irrigation, climate-resilient healthcare infrastructure, strengthened disease surveillance and nutrition-sensitive intervention mechanisms, and significantly expanded ecosystem-based solutions that reduce long-term exposure to climate-related environmental risks (Table 8).

Table 8. Major Physical Health Impacts of Climate-Induced Environmental Change in the Transboundary Sundarbans.

Climate Driver	Primary Health Outcome	Vulnerable Population	References
Salinity intrusion	Hypertension, prehypertension, gestational hypertension, pre-eclampsia	Pregnant women, older adults	[8–12]
Saline drinking water	Gastrointestinal diseases, dehydration, kidney disorders	Coastal households	[15–20]
Water scarcity	Poor hygiene, reproductive tract infections, skin diseases	Women and adolescent girls	[25–28,41]
Cyclones and flooding	Diarrheal diseases, injuries, disruption of healthcare	Children, older adults, low-income households	[10,41,51]
Climate variability	Dengue, malaria, other vector-borne diseases	Coastal communities	[7,10,15,30]
Food insecurity	Malnutrition and micronutrient deficiencies	Women and children	[20,35,46]

3.5. Impacts on Mental Health and Social Well-Being

The effect of climate change on human well-being is not only hitting with serious and apparent physical threats but also creating huge psychological, emotional, and social impacts as well. However, limited empirical research has been conducted with the transboundary Sundarbans specifically related to mental health, but an accumulating body of evidence indicates that chronic mental ill-health amongst coastal populations is a result of recurrent exposure to cyclones, flooding, salinity intrusion, environmental degradation, and livelihood insecurity [8,10,54]. WHO [20] stated that climate change is now recognized as one of the largest and most serious complex multi-sectoral emerging global challenges for mental health due to the unequal vulnerability faced by coastal communities across cycles of recurring disasters, compounded more often when compounded with low adaptive capacity.

The recurring exposure of people living in the Sundarbans to severe weather events such as Cyclones Sidr (2007), Aila (2009), Bulbul (2019), Amphan (2020), Yaas (2021), Mocha (2023), and Remal since 2024 has been linked with elevated prevalence of anxiety, depression, post-traumatic stress symptoms, grief, and ongoing uncertainty about livelihoods in the future. Furthermore, loss of homes and other productive assets like land for livestock or agriculture or fishing gear is frequently repeated, leading to prolonged economic insecurity [42–45] and psychological stress that lasts long after the disaster itself has passed [8–10]. Frequent outbreaks of disasters reaching a threshold of cumulative effect are often beyond the coping capacity of communities dependent on resources, especially in regions with little access to health and psychosocial support or limited financial means.

Climate-related environmental hazards further interrupt social ties, cultural identity, and community identity. Beyond local livelihoods, the mangrove forests, rivers, and fisheries of the Sundarbans also underpin traditional knowledge systems, culture, and community identity. Decline of ecosystem services, ongoing reductions in fisheries productivity, and restrictions on access to forest resources such as fuelwood

have undermined traditional livelihood systems and eroded social resiliency [5–8]. Communities facing continuous and repeated environmental losses often report a decreased sense of environmental security, reduced institutional trust, and lowered confidence in future livelihoods [19–21].

Climate change imposes psychosocial burdens with a gender bias. The loss of economic viability of livelihoods has increased female HBHs by documenting male out-migration for an undisclosed duration, often sending remittances home, leaving women with a larger share of responsibility regarding income generation [18,20,55]; managing childcare, elder care [55], disaster preparedness, and post-disaster recovery while having limited secure access to land ownership [49,50], financial resources, education [56,57], and healthcare (Table 9).

Table 9. Major Mental Health and Social Well-Being Impacts Associated with Climate Change in the Transboundary Sundarbans.

Climate-Related Stressor	Mental and Social Impacts	Most Vulnerable Groups	References
Cyclones and flooding	Anxiety, depression, post-traumatic stress, grief	Disaster-affected households	[54,57]
Livelihood loss	Chronic stress, financial insecurity	Farmers, fishers, daily wage earners	[41,51,56]
Ecosystem degradation	Loss of cultural identity, reduced social cohesion	Forest-dependent communities	[7,8,15]
Male out-migration	Increased caregiving burden and psychosocial stress	Women and female-headed households	[1,10,15]
Weak governance	Reduced institutional trust and recovery capacity	Marginalized communities	[10,58]

WHO [20] found that women are most likely to experience gender-based violence, social exclusion, and reproductive health challenges following climate-related disasters, further increasing psychological vulnerability in the disaster-affected areas. Psychological resilience is less about having top-tier psychological research and more about social support networks, community organizations, labor unions, and good jobs that matter to people, but also local institutions. Research has demonstrated the clear benefits for recovery of strong social capital, community empowerment, early warning systems, and inclusive disaster governance, reducing longer-term psychosocial stress after extreme weather events [20,35,41,56]. Therefore, the Sundarbans would benefit from climate-resilient community adaptive planning, which accommodates mental health and provides support systems that build on indigenous knowledge for mental well-being and response to disasters with due concern for gender-oriented interventions.

3.6. Migration and Displacement

Due to climate change, migration driven by environmental stress has emerged as one of the most important socioeconomic impacts in the Sundarbans. Households increasingly make decisions to migrate temporarily, seasonally, or permanently as a result of both rapid-onset disasters and slow-onset environmental degradation. A combination of sea-level rise, riverbank erosion, salinity intrusion and/or declining agricultural productivity, fisheries degradation, and cyclones leads to compounded losses of livelihood opportunities and increased susceptibility among coastal communities; these are important motivating factors for migration [10,59,60].

The frequency of such extreme weather events has caused recurring large-scale movements across the region. One of the strongest ever recorded in the Bay of Bengal, cyclone Amphan (2020), impacted more than 14 million people across Bangladesh and India and caused extensive damage to housing, embankments, agricultural land, fisheries, and public infrastructure [43,51]. Bangladesh remains among the countries with the highest disaster displacement in the world, with tens of thousands still displaced each year by cyclones, flooding, riverbank erosion, and storm surges [1,59]. Even though in most cases people are displaced at the

same time, eventually back home, climate hazards also encroach on the loss of houses and land, aggravating longer or repeated displacement among disadvantaged coastal communities.

Slow-onset environmental changes have also emerged as important drivers of migration. The ecosystem and the population that relied on it have continued to be undermined by progressive salinization of agricultural soils, declining freshwater availability, coastal erosion, and reduced fisheries productivity, increasingly worsening rural livelihoods and affording seasonal and permanent migration flows towards adjacent towns and metropolitan regions, including Khulna, Kolkata, Dhaka, and other urban centers [1,10,35,59]. The patterns of migration have also shifted away from a predominance of male labor migration to family-based forms and young people and women making greater contributions to household mobility choices [51].

Climate migrations have strong implications for social equity and human well-being. Displaced households often face unemployment, housing insecurity, limited access to education and health-care services, social exclusion, and increased susceptibility to labor exploitation and human trafficking [41,59]. Displacement severely limits access to formal social protection systems and worsens pre-existing socioeconomic inequalities, making women, children, older persons, and persons with disabilities more vulnerable. The multidimensional nature of those vulnerabilities reinforces the need to see climate mobility as a development and human rights question.

IPCC [8] and UNDRR [58] mentioned that existing disaster management policies, as well as strategies of India and Bangladesh, utilized a broader techniques that have prioritized emergency response and post-disaster recovery over the long-term considerations regarding relocation planning, livelihood restoration, or legal protection for environmentally displaced groups. In the face of rising attention given to climate displacement, there remain large policy gaps across the transboundary Sundarbans. Accordingly, the importance of enhancing transboundary cooperation, mainstreaming climate mobility into national adaptation plans/processes, including provisions for expanding opportunities for resilient livelihoods and adjusting social protection benefits and delivery mechanisms cannot be overstated in ensuring decreased displacement risk and improved human well-being going forward [35,46,51].

The literature reviewed here highlights climate change migration and displacement as arguably the most significant impact of environmental change in the Sundarbans within an international transboundary context. More and more, both rapid-onset hazards like tropical cyclones and slow-onset processes such as sea-level rise, salinization, riverbank erosion, and declining agricultural/fisheries productivity have been increasingly forcing households to resort to temporary/seasonal/permanent migration as an adaptation strategy. The repercussions of some recent disasters in the region, especially Cyclones Amphan (2020) and Remal (2024), include forced displacement, destroyed homes, damaged livelihoods, and essential infrastructure that has driven urban migration on an unprecedented scale throughout Bangladesh and India (Table 10). Slow-onset environmental degradation has also shifted migration trends from male-dominated labor migration to whole-household and increasingly female-driven migration, subjecting vulnerable populations to increased risk around poverty, exploitative labor conditions, and human trafficking [32,41,51,61]. In Table 10, we summarize key climate-related displacement events and migration processes found in the literature we reviewed.

Table 10. Documented Displacement Associated with Major Climate Hazards in the Sundarbans.

Event/Process	Year(s)	Indian Sundarbans and	Bangladeshi Sundarbans	References
Cyclone Amphan	2020:	~2.4 million displaced; ~28% of the Indian Sundarban region destroyed; >100,000 farmers affected;	~2.5 million displaced; damage to >2.8 million homes region-wide	[62]
Cyclone Remal	2024:	Wildlife deaths reported (e.g., spotted deer); vegetation and shoreline damage	38.1% loss in dense vegetation; extensive flooding and inundation	[17,26,45]

Cumulative major cyclones	2019–2024:	8 major cyclones affecting the delta; ~250 deaths and ~USD 20 billion in losses across both countries combined	(shared totals with Indian Sundarbans, above)	[30,51,61]
Slow-onset salinization & erosion migration	Ongoing, 2019–2025	Shift from male-only to whole-household and female out-migration; rising labor-exploitation risk.	Migration driven by land loss, salinity, and fishery decline; documented trafficking and unpaid-labor cases	[46,51,61]

3.7. Transboundary Governance and Adaptation Responses

The transboundary Sundarbans is a coupled social–ecological system in which forest condition, hydrology, fisheries, coastal protection, and human livelihoods cross national and administrative boundaries. Governance therefore needs to address ecological processes as well as the distribution of benefits, risks, and responsibilities among governments, communities, and resource users.

The literature reviewed in this manuscript shows that diverse ecosystem-based and community-based adaptation measures have been applied in the Sundarbans over the past 10 years. Mangrove restoration is one of the major significant blue, natural-based adaptation strategies because intact mangrove forests are efficient in reducing wave energy or storm surge, coastal erosion, and cyclone-induced flood height while at the same time increasing biodiversity conservation and blue-carbon synthesis [10,15,35,41].

There have been verifiable advances as to disaster risk reduction throughout the whole area. Investments to turn multi-purpose cyclone shelters into disaster-resistant hubs, satellite-based forecasting, mobile early-warning systems, and community-based volunteer networks are all contributing towards preparedness and speed of evacuation. With more than 4000 operational cyclone shelters and a national Cyclone Preparedness Programme with an estimated 76,000 trained volunteers, cyclone mortality has dramatically declined in recent decades [30,46,51,59]. Despite this, subsequent cyclones such as Amphan (2020) and Remal (2024) have repeatedly smashed through embankments, flooded freshwater ponds, cropland, and aquaculture facilities, and destroyed rural infrastructure—demonstrating that structural adaptation measures are still ineffective in the context of more intensive climate extremes [46,51,61].

Conservation of blue carbon and ecosystem-based financing are being increasingly recognized as potential complementary climate adaptation and mitigation strategies. Green component: Sundarbans mangrove forests store inordinate amounts of carbon, both above and below ground, and serve as a buffer protecting coastal dwellers from storm surges and erosion [10,15,41].

Potential policy instruments include public conservation finance, payment for ecosystem services, carefully designed carbon-market mechanisms, community forest-management arrangements, environmental assessment, monitoring systems, and regulatory safeguards for critical habitats. Their suitability should be assessed against ecological effectiveness, equity, administrative feasibility, monitoring requirements, and the rights and interests of local resource users. Forest governance literature also emphasizes that effective sustainability governance generally requires combinations of instruments rather than reliance on a single intervention [61,63].

Despite progress in national adaptation planning, the reviewed evidence identifies continuing governance challenges across the transboundary Sundarbans, including institutional fragmentation, uneven monitoring capacity, uncertainty in ecosystem trajectories, differences in policy implementation, and limited mechanisms for joint assessment and benefit sharing. Table 11 explores the major climate change adaptation strategies and governance management practice in the Transboundary Sundarbans.

Table 11. Major Climate Adaptation Strategies and Governance Responses in the Transboundary Sundarbans.

Adaptation Strategy	Major Activities	Documented Benefits	Remaining Challenges	References
Mangrove restoration	Afforestation, restoration, shoreline stabilization	Coastal protection, biodiversity conservation, carbon sequestration	Land-use conflicts, funding limitations	[30,46,51]
Community-based adaptation	Raised homesteads, floating agriculture, rainwater harvesting	Improved household resilience and food security	Limited financial resources	[20,35,49]
Disaster risk reduction	Cyclone shelters, early warning systems, volunteer networks	Reduced mortality and improved evacuation	Infrastructure maintenance	[45,61]
Climate-smart agriculture	Salt-tolerant crops, improved irrigation	Increased agricultural resilience	Salinity and water scarcity	[47,51]
Blue-carbon financing,	REDD+, carbon markets, PES	Conservation incentives and climate finance	Carbon accounting and governance	[51,61]
Transboundary governance	Joint monitoring, data sharing, fisheries management	Improved regional climate resilience	Institutional fragmentation and policy differences	[46,51,61]

Governance of the transboundary Sundarbans forest involves overlapping ecological, political, and institutional dynamics in India and Bangladesh. Recent scholarship identifies governance failures, especially fragmented jurisdiction, weak coordination, and uneven enforcement, as undermining both ecological integrity and livelihood security. Subroto et al. [56] show that governance regimes tend to reproduce livelihood (in)justice, making forest-reliant communities more precarious because of restrictive conservation rules, elite capture, and limited participation in decision-making. Their analysis shows that forest governance institutions favor territorial control and bureaucratic compliance over community rights and adaptive co-management, leading to unequal access to forest resources and uneven exposure to climate hazards.

The deltaic geography of the Sundarbans exacerbates transboundary governance challenges because hydrological flows, forest boundaries, and human settlements cross national borders. The chapter Navigating a Transboundary Terrain in a Delta highlights the strong interlinkages between water and forest governance in the region: upstream freshwater diversion, embankment failures, and salinity intrusion directly affect mangrove health and the sustainability of forest-based livelihoods[45]. Different studies argue that governance fragmentation between India and Bangladesh, and among agencies in both countries, leads to policy mismatch and inconsistent enforcement, eroding the ecological resilience of the transboundary mangrove system [46,53,61].

Legal analyses also show structural deficiencies in international and bilateral governance arrangements. Shawon et al. [51] found that UNESCO, Ramsar, and CBD frameworks impose obligations for transboundary conservation, but enforcement mechanisms are heavily reliant on voluntary compliance and diplomatic pressure. This has enabled environmentally risky projects like the Rampal power plant even with documented threats to the ecological integrity of the Sundarbans. The different findings also find that without binding cross-border enforcement, joint monitoring systems, and a legally empowered transboundary authority, forest governance will remain fragmented and insufficient to meet increasing climate and anthropogenic pressures [46,51,59].

Bose & Joshi [32] explored that hydrological processes, fisheries migration and sediment transport, conservation of biodiversity as well as climate hazards exceed political borders; yet climate adaptation policies are hardly implementation rather than planning. Bangladesh has several well-thought-out policy instruments, e.g., Bangladesh Climate Change Strategy and Action Plan (BCCSAP) National Adaptation Plan (2023–2050), Mujib Climate Prosperity Plan, and updated NDCs while India framed the National Action Plan

on Climate Change (NAPCC)and National Disaster Management Plan [1,20,46,51]. Little exists presently in terms of mechanisms for joint climate-risk assessment; ecosystem monitoring; disaster information-sharing; climate finance allocation or the integrated management of transboundary ecosystem services.

Finally, the literature also highlights that optimal climate adaptation will involve moving away from sector-specific measures and developing more integrated, transboundary governance frameworks that combine ecosystem conservation with disaster risk reduction, climate-resilient livelihoods, and social protection. However, with joint scientific monitoring by India and Bangladesh, harmonized climate change adaptation information approaches, shared hydrological databases, collaborative fisheries management, integrated mangrove restoration programs, and transboundary climate finance mechanisms, regional adaptive capacity against the impacts of severe weather will improve materially [64–67]. Equally important within this decision-analytic framework are efforts to bring Indigenous knowledge, traditional ecological practices and planning, gender-responsive assessment, and participative decision-making into the realm of adaptation in ways that locally situated knowledge can supplement scientific evidence for enhanced long-term resilience throughout the Sundarbans social–ecological system [10,25,46,51].

Summarizing, the evidence suggests that while there has been significant progress in disaster preparedness and ecosystem-based adaptation, sustaining the Sundarbans over time will need enhanced transboundary governance mechanisms, including collaborative climate finance, integrated management of natural resources, and coordinated policy responses to rapidly developing disasters as well as gradual environmental change.

Forest governance also requires explicit treatment of uncertainty. Forest trajectories are shaped by interacting climate hazards, salinity, sediment dynamics, freshwater flows, land-use pressures, and resource use, while information and institutional capacity remain uneven across the two countries. This uncertainty strengthens the case for adaptive management, transparent monitoring, participatory decision-making, and policy instruments that can be adjusted as evidence changes. Climate-change impact assessment can provide a structured mechanism for linking climate exposure, adaptation options, distributional effects, monitoring, and planning decisions [67,68].

3.8. Contextual Ecosystem and Biodiversity Evidence

Ecological and biodiversity studies that did not report explicit human well-being outcomes were not treated as formal included studies. However, such studies can provide context for longer-term community resilience by documenting changes in mangrove condition, shoreline stability, carbon storage, biodiversity, and habitat quality. This contextual evidence is particularly relevant for economically and culturally important resources such as fisheries and mangrove-derived products, as well as for the coastal-protection function of mangroves. An ecological study can establish ecosystem change or a plausible pathway to human well-being, but it should not be presented as direct evidence of a measured health, livelihood, or social outcome.

The Sundarbans is one ecological mangrove system that straddles both Bangladesh and India, but its forests and waters are managed under separate national jurisdictions. The Indian Sundarbans is particularly rich in biodiversity. The Sundarbans Biosphere Reserve has 81 species of mangrove plants and about 1586 species of animals. Over 40 species of mammals, 163 species of birds, 56 species of reptiles, 165 species of fish, 23 species of molluscs, 15 species of prawns and 67 species of crabs are recorded in this fauna by UNESCO. The numbers indicate the significance of the Indian Sundarbans not only as a mangrove forest but also as a highly productive estuarine and aquatic ecosystem that supports a large diversity of fish, crustaceans, molluscs, birds, reptiles and mammals [6,10,68]. The Bangladesh Sundarbans also has extremely high biodiversity. The Bangladesh World Heritage site has recorded 334 species of plants under 245 genera of 75 families, 165 taxa of algae, and 13 species of orchids. The recorded fauna includes 49 mammals, 59 reptiles, 8 amphibians, 315 bird species, 210 fish species, 24 prawn species, 14 crab species

and 43 mollusc species, which shows the wide ecological spectrum within the Bangladesh part of the ecosystem [6,20,25]. Table 12 reported biodiversity of the Indian and Bangladesh components of the transboundary Sundarbans ecosystem. Species numbers represent published or institutional inventories and should not be summed across countries because geographic coverage, taxonomic scope, survey period, and inventory methodology differ among sources.

Table 12. Biodiversity inventory of the Indian and Bangladesh Sundarbans.

Major Biodiversity Group	Indian Sundarbans	Bangladesh Sundarbans	Transboundary Interpretation	Principal Source
Mangal/mangrove plants	81 species	334 plant species	Bangladesh figure includes broader plant flora, not only true mangroves; therefore not directly comparable	[8,10,12]
Algae	Not separately reported in current UNESCO MAB profile	165 species	Aquatic primary producers; Bangladesh figure should not be interpreted as whole-transboundary total	[15,20,35]
Orchids	Not separately reported	13 species	Included within Bangladesh floral inventory	[1,11,41]
Mammals	>40 species	49 species	Includes terrestrial and aquatic mammals; several taxa are transboundary or use connected aquatic habitats	[2,5,35]
Birds	163 species	315 species	Different survey scopes and periods; includes resident and migratory birds	[2,25,41]
Reptiles	56 species	59 species	Important shared group including crocodiles, turtles, snakes and monitor lizards	[10,35,46]
Amphibians	Not separately reported in current UNESCO MAB profile	8 species	Indian detailed inventories may contain additional records; absence from the MAB breakdown does not mean absence	[45,51]
Fish	165 species	210 species	Major ecological and livelihood group; national inventories should be harmonized before producing a transboundary total	[20,25]
Prawns/shrimps	15 species	24 species	Separate terminology reflects the respective inventories; should be harmonized taxonomically in a species-level checklist	[20,45]
Crabs	67 species	14 species	Large difference likely reflects differences in inventory scope and taxonomic coverage	[45,51]
Molluscs	23 species	43 species	Counts are not directly additive because inventories may use different geographic and taxonomic coverage	[45,51]
Other invertebrates	Included in Indian overall 1586 animal species	Included in broader Bangladesh wildlife estimates	Detailed group-by-group numbers are not equivalent between the two inventories	[33,46,61]

Protozoa/microscopic fauna	Included in some historical Indian inventories	Not consistently reported in UNESCO Bangladesh table	Should not be compared without harmonized taxonomy	[8,10]
Total animal species	1586 species	693 species in the UNESCO World Heritage property inventory; ~1136 wildlife species in a broader Bangladesh review	Do not add these totals; they represent different inventory scopes	[45,51,61]
Overall plant/animal biodiversity	81 mangal plants + 1586 animals	334 plants + 693 listed wildlife species, with a broader review reporting ~1136 wildlife species	Best presented as country-specific inventory estimates rather than one combined total	[20,35,46]

When the two national inventories are put together, the transboundary Sundarbans is one of the most biologically significant mangrove ecosystems in South Asia. However, the biodiversity numbers from Bangladesh and India cannot be simply added together to give a single species total, as many species occur on both sides of the international boundary and national inventories differ in geographic coverage, survey methods, taxonomic treatment, and reporting periods. Rather, the two inventories should be used as complementary parts of a transboundary biodiversity assessment. The transboundary perspective is especially important, as ecological processes that affect biodiversity operate independently of political boundaries. Changes in freshwater discharge, salinity, sediment deposition, tidal dynamics, cyclones, erosion, sea level rise, habitat fragmentation, and human resource use can affect species and habitats on both sides of the Sundarbans.

4. Discussion

This systematic review indicates that climate-driven change in the transboundary Sundarbans is best understood as a connected pathway from climate hazards and environmental change to ecosystem-service disruption, livelihood and health effects, mobility and social vulnerability, and adaptation and governance responses. Sea-level rise, salinity intrusion, coastal erosion, tropical cyclones, and hydrological change interact with non-climatic pressures such as pollution, aquaculture expansion, and upstream water management. Treating these drivers separately can obscure cumulative risk and the institutional choices that shape vulnerability.

The authors found that salinity intrusion is one of the most hazardous and widely replicated impacts on public health in affected communities. Over a decade of epidemiological studies in coastal Bangladesh also consistently link higher drinking-water salinity, supporting significant associations with hypertension, gestational hypertension, and pre-eclampsia in pregnant women [10,25,46]. This review study integrates the present analysis that climate change vulnerability and risks in the Transboundary Sundarbans should be observed and viewed as a system of cascading as well as compounding hazards, and that each environmental stressor exacerbates the effects of another, increasing overall vulnerability [25,46,59].

Recent global climate-health assessments also acknowledge that excessive exposure to salinity, often taking the form of increasing saltwater intrusion inland in land-dependent areas [20], is a growing public-health trajectory or public health concern in low-lying coastal regions where freshwater resources are being increasingly threatened by sea-level rise and saltwater intrusion [41,46]. In addition to having a large focus on cardiovascular health, the research considered other exposure-attributable disease burdens with long-term salinity exposure, including gastrointestinal illness, dermal manifestations, hydration ailments, reproductive ill-health, and sanitation issues related to the availability of safe drinking water, especially for women and children [15,20,46]. These findings imply that upscaling climate-resilient freshwater supply systems, rainwater harvesting, community desalination technologies, and maternal health surveillance should be integral to regional climate adaptation approaches.

It also reviews the far-reaching effects of climate change on the viability of livelihoods and the flexibility of economic performance. FAO [18] mentioned that while agriculture, fisheries, aquaculture, and forest-resource collection continue to be the primary livelihoods for millions of Sundarban households, all are becoming increasingly sensitive to salinity intrusion, hydrological change, habitat degradation, and repeated cyclone events. Declining crop yields, diminished fish landings, and losses of aquaculture infrastructure and ecosystem services combine to raise household poverty levels and lower incomes, with most food insecurity effects impacting the rural poor [20,25]. Using data from all these analyses collectively, this paper shows analogous patterns observed in other prominent Asian deltas such as the Mekong and Ayeyarwady, where climate-related ecosystem degradation continues to undermine food systems and rural livelihoods [15,30].

The findings of the review study further underscore the importance of implementing integrated adaptation strategies that combine climate-smart agriculture, sustainable fisheries management, ecosystem restoration, and livelihood diversification.

An especially relevant result from this review is the differentiated climate vulnerability by gender. Due to gender inequality in relation to both access to land ownership and socio-economic conditions (access to financial resources, education, health care, and decision-making), women have been shown globally to be more affected than men in terms of physical, psychological, or socio-economic impacts during disaster situations [30,35,51]. The decline of viable livelihoods from (male out-) migration also adds to women taking on a household and care burden, and disaster preparedness and post-disaster recovery responsibilities, as well as shrinking chances for engagement in economic development. The pervasive and detrimental impact of climate-driven sea level rise on women has been observed in other areas vulnerable to climate change. Thus, the formulation of effective adaptation policies must be grounded in gender-responsive planning rather than a blanket assumption that all groups are equally vulnerable [14,61]. Increasing the representation of women in local government, improving social protection programs, improving access to financial services, and promoting female leadership positions around community-based adaptation initiatives would greatly strengthen adaptive capacity.

Another emerging but relatively under-studied dimension of climate vulnerability is mental health. Despite a general dearth of studies on psychological well-being in the Sundarbans per se, evidence of increasing anxiety, depression, post-traumatic stress symptoms, grief, and uncertainty following the increasingly severe impact of recurrent climate disasters and environmental degradation is available [25,30]. These findings are consistent with the current global systematic reviews exploring the increased risk for adverse mental health outcomes associated with repeated exposure to floods, cyclones, and climate-related displacement [51,59]. This review therefore highlights an important gap in longitudinal research assessing climate-linked mental health, especially among women, adolescents, older adults, and Indigenous persons and communities, as well as forest-dwelling populations.

One major adaptive response to environmental change is adaptive migration in the Sundarbans; rapid-onset disasters and slow-onset environmental degradation are increasingly leading to seasonal, temporary, and permanent migration. In Bangladesh and India, rural out-migration to urban centers has been driven by riverbank erosion, saline intrusion, decreasing productivity of agricultural activity, and fisheries/human security [61,63].

As a result, migration should not only be viewed as a humanitarian issue but also as an integral part of planning sustainable climate adaptation and development for the long term. This review further highlights that despite significant advances in ecosystem restoration, disaster preparedness, and community-based adaptation, transboundary governance continues to be among the most difficult flaws to resolve for sustained climate-resilient development. While the Sundarbans comprises a single ecological-social-ecological system, separation of adaptation and development policies in national-level sectors has led to uneven ecosystem management, discontinuity of monitoring systems, poor data sharing, and weak

coordination at climate finance levels [25,30,41]. In other internationally shared river basins, such as the Mekong and Ganges-Brahmaputra systems, integrated river-basin management has been shown to enable more effective governance at both national and transboundary levels than less cohesive national efforts [30,41]. Therefore, enhancing bilateral cooperation between Bangladesh and India through conjoined environmental monitoring, shared water data exchange, coordinated mangrove restoration, transboundary fisheries management, and collaborative climate-finance mechanisms should be a regional priority.

Finally, the review study highlights some major gaps in knowledge within the current literature. Available studies mostly focus on the Bangladesh Sundarbans; however, fewer studies focus more directly on a transboundary or comparative Bangladesh–India perspective. In addition, while the evidence base is still mainly driven by studies on individual hazards (*i.e.*, cyclones or salinity intrusion), only a few studies have focused on cumulative climate risk, compound hazards, ecosystem services effects, mental health and well-being, and Indigenous knowledge for adaptation plan formulation, as well as climate justice and integrated governance frameworks [43,51]. Interdisciplinary, long-term, participatory studies that integrate climate science, public health, ecology, economics, and social sciences to understand the interactions amongst these drivers are therefore well warranted in the transboundary Sundarbans to comprehensively evaluate how development choices influence human well-being.

The results of the review study suggest that integrated adaptation strategies for the Sundarbans need to protect environmental conservation, health, livelihoods, disaster risk reduction, social equity, and approaches to transboundary area governance in a synergistic way if long-term sustainability is to be ensured. More importantly, nature-based solutions, climate-resilient infrastructure, and community-based and gender-responsive adaptation should be considered as complementary actions to strengthen bilateral cooperation between Bangladesh and India, not as separate or stand-alone components of sustainable climate resilience (Table 13).

Table 13. Principal Findings of the Systematic Review and Their Policy Implications.

Theme	Major Findings	Policy Implications	References
Environmental change	Sea-level rise, salinity intrusion, cyclones, and mangrove degradation are interconnected drivers	Integrated ecosystem-based adaptation	[30,46,51]
Physical health	Salinity increases hypertension, maternal health risks, and waterborne diseases	Freshwater supply, desalination, maternal health monitoring	[20,35,49]
Livelihoods	Agriculture, fisheries and aquaculture increasingly vulnerable	Climate-smart agriculture and livelihood diversification	[45,61]
Mental health	Repeated disasters increase anxiety, depression, and psychosocial stress	Community mental health services and social protection	[47,51]
Migration	Environmental degradation drives seasonal and permanent migration	Climate mobility policies and livelihood restoration	[51,61]
Governance	Fragmented Bangladesh–India adaptation limits resilience	Joint monitoring, shared climate finance and ecosystem management	[46,51,61]
Research gaps	Limited transboundary, interdisciplinary and longitudinal studies	Integrated research and harmonized monitoring programmes	[30,46,51]

5. Research Gaps, Policy Implications, and Future Research Directions

5.1. Research Gaps

This systematic review identifies several major knowledge gaps on climate-driven environmental change and human well-being in the transboundary Sundarbans that remain to be addressed. While publications have increased significantly since 2020, notably after Cyclones Amphan (2020) and Remal (2024), evidence remains unevenly distributed across disciplines and geographic areas. While many of

these studies are focused on the Bangladeshi Sundarbans, relatively few take a more explicitly transboundary view, simultaneously addressing ecological processes and human well-being across Bangladesh and India using instances from both countries [25,46,51].

A second major gap relates to the dominance of single-hazard studies. Most of the existing literature focuses on individual climate drivers (sea-level rise, salinity intrusion, or cyclones) in isolation. But the results of this review make it clear that climate risks in the Sundarbans are collectively interacting and reinforcing. Future studies should thus focus on the integrated assessment of multiple climate risks (including compounded climate hazards, ecosystem degradation and socioeconomically vulnerable groups, as well as human health outcomes) within a single framework [10,25,30].

A third important gap in research is mental health. Despite the fact that physical health complications associated with drinking-water salinity are relatively well known, there have been fewer longitudinal studies of adaptive outcomes such as climate-related anxiety, depression, post-traumatic stress disorder, eco-anxiety, or psychosocial resilience in coastal populations [20,25]. The challenges do not stop there; similar limitations exist in relation to children's health, older populations, persons with disabilities, Indigenous peoples, and forest-dependent households who are probably more vulnerable to the impact of climate change [14,22].

Moreover, only a small number of studies have estimated the contribution of ecosystem services to human well-being. Despite mangrove ecosystems offering vital services such as coastal protection, fisheries habitat, blue-carbon storage, and biodiversity conservation, few studies have combined ecosystem-service valuation with health, livelihood, and climate-adaptation impact assessments. More interdisciplinary research of this kind will help translate results into decision-making on ecosystem-based adaptation and climate investments [30,47].

Most of the existing studies are based on either cross-sectional surveys or short-term follow-up. Thus, long-term monitoring programs that integrate visions of change across multiple disciplines, e.g., remote sensing, hydrological observations, ecosystem service assessments, environmental epidemiology, and climate modelling, are very much warranted to be able to monitor and predict the interplay between ongoing anthropogenic changes as well as natural climate processes on both long-term environmental and social change in this region.

5.2. Policy Implications

Therefore, this review has important implications for climate adaptation, public health, biodiversity conservation, and regional governance. Given that climate impacts have simultaneous implications for ecological, economic, and social systems, adaptation policy needs to shift from siloed sectoral planning toward integrated social-ecological resilience-based planning.

Freshwater security has to be treated as one of the top public health priorities. The extent of health risks from drinking-water salinity, especially among pregnant women and children, could be considerable, requiring the expansion of alternative interventions [20,28,30], such as rainwater harvesting in communities with reliable aquifers; use of community-level desalination plants; implementing managed aquifer recharge to restore groundwater levels after over-extraction; and climate-resilient water supply infrastructure.

Future planning of climate change adaptation should center around nature-based solutions. Roy et al. [47] and Bhargava & Friess [5] mentioned that invasive species removal, large-scale mangrove restoration, conservation of tidal wetlands, sustainable fisheries management, and ecosystem-based disaster risk reduction can simultaneously enhance biodiversity conservation, improve livelihood security, increase blue-carbon storage, and strengthen coastal protection against storm surges. Higher attention needs to be given by policy for livelihood diversification and their should be complemented by climate finance, insurance, and social protection targeting vulnerable households [14,20,35].

Different studies indicated that, given the Sundarbans' role as a single productive ecosystem, improved transboundary governance between India and Bangladesh is a significant prerequisite. According to bilateral cooperation, hydrology, fisheries management, and biodiversity conservation, as well as coastal erosion and climate hazards, should be monitored together. Shared climate databases, coordinated disaster preparedness, harmonized ecosystem restoration programs, and collaborative climate finance mechanisms would provide a considerable boost to regional resilience [8,10,45].

Finally, adaptation planning also needs to be more inclusive and co-created by integrating Indigenous knowledge systems, local ecological knowledge (LEK), gender considerations, youth engagement, and a participatory approach into policy development and implementation. Using participatory modes of governance has also shown consistent evidence of increased effectiveness and sustainability across different types of coastal social-ecological systems [30,46].

5.3. Future Research Directions

The sustainability of the transboundary Sundarbans in the future would depend on the creation and implementation of multidisciplinary, transboundary, as well as policy-relevant research that integrates environmental sciences, public health, ecology, and economics. To that end, future research should use coupled social-ecological system frameworks to conduct integrated assessments of compound climate hazards alongside ecosystem services, human well-being, and adaptive capacity.

Integrating satellite remote sensing, drone observations, hydrological modelling, climate projections, and field-based ecological surveys across multiple sites will provide vital estimates of potential changes in mangrove extent, shoreline dynamics, salinity intrusion, biodiversity, and fisheries productivity with a range of Shared Socioeconomic Pathways (SSPs) scenarios over the long term. These approaches would enhance predictions of future ecosystem risk and inform management responses.

Epidemiological studies on the effects of climate change in relation to such health endpoints as cardiovascular disease, maternal and child health, nutritional outcomes, infectious diseases, and climate-related mental health disorders need to be conducted. Longitudinal cohort studies combining environmental exposure assessment with household socioeconomic data will provide the strongest evidence base for climate-health adaptation.

Research needs to measure the effectiveness of ecosystem-based adaptation, blue-carbon financing, climate-smart agriculture, community-based adaptation, and disaster risk reduction with standardized markers. Comparative studies across Bangladesh and India, however, will help identify best practices to harmonize local policy based on evidence.

Focus on climate mobility, environmental justice, gender equality, indigenous knowledge systems, and climate finance should be zeroed in. Integrated decision-support tools that combine geospatial analysis, ecosystem-service valuation, socioeconomic modelling, and participatory governance are urgently needed to facilitate climate-adaptation planning across the transboundary Sundarbans.

In the end, future research directions should focus less on documenting climate impacts and more on creating practical, scalable, fair adaptation solutions with the potential to simultaneously benefit biodiversity conservation whilst maximizing human well-being and climate resilience in one of the most vulnerable coastal ecosystems worldwide.

6. Conclusions and Recommendations

This systematic review synthesizes the existing knowledge of climate change-driven ecosystem change and impacts on human well-being in a transboundary site—the Sundarbans, the world's largest and most climate-vulnerable mangrove ecosystem. The results reveal that climate change impacts the Sundarbans through numerous interconnected pathways: sea-level rise, salinity intrusion, more intense tropical cyclones, riverbank

erosion, hydrological alteration, and mangrove degradation. These pressures—heatwaves, floods, and droughts—have a cumulative effect that erodes ecosystem services and causes indirect, wide-ranging effects on public health, livelihoods, food security, migration (displacement), mental health, and social well-being.

Among the aforementioned climate stressors, frequent tropical cyclones and salinity intrusion are more widely and uniformly recognized as leading drivers of human vulnerability. We found robust epidemiologic evidence linking higher drinking-water salinity to hypertension, gestational hypertension, and deteriorating maternal health, and recurrent cyclones again harm agricultural systems, fisheries, housing infrastructure, healthcare infrastructure, and local economies. The cascading effects of climate change on food systems increase inequalities, particularly for women, children, older persons, and forest- and fishery-dependent households.

The review also shows that climate change is increasing the risk of livelihood insecurity and environmental migration through declining agricultural productivity, fisheries degradation, ecosystem-service loss, and an increase in disaster frequency. Ecosystem degradation and social vulnerability, meanwhile, are amplified by one another in ways that establish feedback paths that weaken adaptive capacity over the longer term. While interventions focused on ecosystem restoration, community-based adaptation, and disaster risk reduction have strengthened resilience in many local contexts, current adaptation efforts are too fragmented and limited to manage the combined effects of climate change across this transboundary landscape.

One of the major contributions of this review can be seen in the identification and acknowledgment of persistent governance and research gaps. Although they behave as one ecosystem and hydrological system, the Sundarbans continues to be managed bilaterally by both countries through national policies that coordinate sporadically at best between Bangladesh and India. In addition, the literature is geographically imbalanced and dominated by studies from Bangladesh and single climate hazards rather than integrated socio-ecological processes. Stronger transboundary collaboration, coupled with interdisciplinary research and evidence-based governance, is required to overcome these limitations and enable long-term climate resilience.

Lastly, these study findings highlight that this imperative of protecting the future of the Sundarbans can only be achieved through inclusive and integrated responses combining actions to conserve ecosystems while enhancing livelihoods and public health and promoting disaster risk reduction to increase resilience alongside equitable governance. Thus, climate adaptation should be conceived not only as an environmental necessity but also as a public health, socioeconomic, and sustainable development objective for the tens of millions of people reliant on this globally important delta.

The authors suggested the following recommendations for strengthening climate resilience and human well-being across the transboundary Sundarbans based on evidence synthesized in this systematic review.

- Priority should be given to increasing access to freshwater, particularly through rainwater collected for safe public use; functional aquifer recharge systems located within communities for managed aquifer recharge; community desalination technologies that remove all constituents from seawater at the coastal interface; novel land-use planning to limit certain pollutant loading in national and regional watersheds; and freshwater management policies driven by continuous drinking-water quality monitoring.
- Prioritize and expand large-scale mangrove restoration, wetland conservation, sustainable fisheries management, and blue-carbon-inclusive climate initiatives to improve coastal protection, biodiversity conservation, carbon sequestration, and ecosystem resilience. Ecosystem-based adaptation must be mainstreamed in national climate change and disaster risk reduction strategies.
- Governments should reduce dependency on climate-sensitive natural resources by promoting climate-smart agriculture, decision-making on sustainable aquaculture, Pacific Diversified Fishes, and ecotourism, including development for small-scale enterprises & vocational training. Assist families in vulnerable groups in accessing climate finance, agricultural insurance, and social protection programs.
- Psychosocial support services: Climate adaptation programs need to systematically include psychosocial support services, such as those provided by community-based mental health interventions,

disaster counselling, and trauma-informed healthcare. The psychological toll of recurring climate crises, displacement, and livelihood loss requires more attention.

- Women should be involved in climate governance, disaster preparedness, natural resource management, and adaptation planning. Through policies to mitigate access injustice in education, finance, healthcare, land ownership, and decision-making while enhancing the role of social protection in improving female-headed households.
- Bangladesh and India should institutionalize joint environmental monitoring, hydrological data sharing, coordinated mangrove restoration and fisheries management, and preparedness for disasters and climate finance, as well as loss-and-damage estimates. The establishment of a bilateral coordination platform would strengthen the management of our ecosystems, increasing our regional climate resilience.
- National adaptation strategies must formulate comprehensive policies to address climate-forced migration and displacement, including relocation plans, livelihood restoration programs, urban integration strategies, and legal protection for environmentally displaced people.

Future studies must focus on longer-term interdisciplinary questions utilizing climate science, ecology, public health, economics, remote sensing, and the social sciences. In particular, compound climate hazards, ecosystem-service valuation, climate-related mental health outcomes, Indigenous and local ecological knowledge, climate justice, and transboundary governance should be prioritized. If separate databases for both countries, as a product of these harmonized field-based monitoring systems with open access, were shared, it would help in producing evidence-based projections that could lay the foundation for sound adaptation planning.

This systematic review's outcomes emphasize that combating climate-induced ecological change in the cross-border Sundarbans needs integrated, multi-sectoral, and cross-border action. Climate resilience is achieved not only through ecosystem rehabilitation but also through strengthening public health systems, ensuring livelihoods, implementing gender equality measures, building capacity, and enhancing institutional cooperation between Bangladesh and India. Based on synthesized findings of the reviewed literature, some strategic recommendations are provided for sustainable adaptation, biodiversity protection, and human well-being in the Sundarbans area (Table 14).

Table 14. Strategic Recommendations for Enhancing Climate Resilience in the Transboundary Sundarbans.

Strategic Area	Key Recommendations	Expected Outcomes	Priority Stakeholders
Water security	Rainwater harvesting, desalination, managed aquifer recharge	Reduced salinity exposure and improved public health	National governments, local authorities, NGOs
Public health	Climate-resilient healthcare, maternal health surveillance, disease monitoring	Improved community health and reduced climate-related disease burden	Ministries of Health, WHO, local health providers
Ecosystem conservation	Mangrove restoration, blue-carbon projects, biodiversity conservation	Enhanced ecosystem services and coastal protection	Forest departments, IUCN, UNESCO
Climate-resilient livelihoods	Climate-smart agriculture, sustainable fisheries, livelihood diversification	Improved food security and household income	FAO, fisheries agencies, agricultural extension services
Disaster risk reduction	Early warning systems, resilient infrastructure, cyclone shelters	Reduced disaster losses and improved preparedness	Disaster management authorities, UNDRR
Gender and social inclusion	Gender-responsive adaptation, women's participation, social protection	Reduced social inequality and increased adaptive capacity	Government agencies, UN Women, community organizations
Climate migration	Planned relocation, livelihood restoration, migration policy	Reduced displacement vulnerability	IOM, national governments
Transboundary governance	Joint monitoring, climate finance, ecosystem management, shared databases	Strengthened regional cooperation and long-term resilience	Bangladesh and India governments, regional organizations

Future research	Long-term monitoring, interdisciplinary research, integrated modelling	Improved evidence-based policymaking	Universities, research institutes, funding agencies

The future sustainability of the transboundary Sundarbans will depend on integrating ecosystem conservation, climate-resilient development, public health, social equity, and transboundary governance into a unified adaptation framework that protects both biodiversity and the well-being of the millions of people who depend upon this globally significant mangrove ecosystem.

From an ecological-civilization perspective, long-term resilience requires ecological protection and community well-being to be treated as mutually reinforcing objectives. Government investment should support locally appropriate adaptation to sea-level rise, salinity, erosion, and cyclones while strengthening freshwater security, ecosystem restoration, climate-resilient livelihoods, early warning, community-based monitoring, social protection, and meaningful participation. Forest governance should combine regulatory safeguards with participatory and information-based instruments, transparent benefit sharing, and adaptive management. Transboundary coordination is essential because hydrology, fisheries, sediment transport, biodiversity, and climate risks cross the Bangladesh–India boundary.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used AI (Microsoft Copilot and Google Gemini) for reference formatting and grammar checking to ensure the manuscript is error-free for the journal.

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Author Contributions

A.M.: Conceptualization; Methodology; Writing—Original Draft; Writing—Review & Editing; Visualization; Table Preparation; P.B.: Conceptualization; Methodology; Writing—Original Draft; Writing—Review & Editing; Visualization; Table Preparation; T.D.: Methodology; Writing—Review & Editing; Visualization; C.B.: Investigation; Resources; Data Curation; Reference Management; N.N.: Investigation; Resources; Data Curation; Reference Management.

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