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Research Article

Aquaculture and Fisheries' Potentials in the Ecologically Critical Areas (ECAs) of Sundarbans, Bangladesh: Recommendations to Policy Making

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This paper explores the aquaculture and fisheries' potentials within the ecologically critical areas (ECAs) of the Sundarbans, Bangladesh, highlighting their socioeconomic importance and the urgent need for sustainable management practices. As the largest mangrove forest globally and a UNESCO World Heritage Site, the Sundarbans is a biodiversity hotspot and a vital source of livelihood for millions, rich in various aquatic species, including finfish and shellfish. However, the region faces significant challenges such as climate change, habitat degradation, and unsustainable fishing practices, which threaten its ecological balance and fisheries resources. Current fisheries' management is hindered by inadequate conservation efforts and limited aquaculture practices, particularly in breeding and seed supply of economically important species. Unsustainable juvenile collection methods exacerbate the depletion of local fish stocks, posing further risks to biodiversity. The study underscores the need for comprehensive research initiatives aimed at enhancing breeding technologies, developing sustainable aquaculture practices, and promoting community engagement in resource management. Recommendations include establishing hatcheries for commercially important species to produce high-quality seed, thereby alleviating pressure on wild populations and strengthening the local economy. The paper advocates for the implementation of Integrated Coastal Zone Management (ICZM), community-based resource management, and enhanced legal frameworks to support sustainable aquaculture. By adopting a multistakeholder approach that balances environmental conservation, economic development, and social equity, the Sundarbans can realize its potential for sustainable fisheries and aquaculture, ultimately improving livelihoods and fostering ecological resilience. The paper calls for proactive, scientifically informed strategies to navigate the complexities of aquaculture, fisheries, and ecological health in this critical region.

Keywords: aquaculture; ecologically critical areas (ECAs); fisheries; policy; Sundarbans

1. Introduction

The Sundarbans, acknowledged as the world's largest mangrove forest and a UNESCO World Heritage Site, serves as a critical ecological zone spanning the delta region of India and Bangladesh [1]. Beyond its title as a forest, the Sundarbans is a dynamic estuarine ecosystem and an expansive aquaculture landscape. The adjacent floodplains further magnify the region's significance, supporting the livelihoods of millions. This incomparable ecosystem acts as both a biodiversity hotspot and a lifeline for local communities through invaluable resources like fisheries and aquaculture. Positioned at the confluence of the Bay of Bengal (BoB) and the delta of the Padma, Meghna, and Brahmaputra River systems, the Sundarbans is renowned for its intricate network of tidal waterways, estuaries, and diverse flora and fauna.

Rich in biodiversity, the Sundarbans hosts a variety of aquatic species, including 53 species of pelagic fish, 124 species of demersal fish, 24 species of shrimp, 7 species of

crab, 2 species of gastropods, 6 species of pelecypods, 8 species of locust lobster, and 3 species of turtles [2]. Functioning as a crucial hub for various economic activities, fisheries and aquaculture act as a pivotal preamble in sustaining the livelihoods of tropical assemblages. The core Sundarbans protective area spans 7620 km^2, comprising 4143 km^2 of land, 1874 km^2 of rivers, streams, and canals, and 1603 km^2 of marine zone [3]. Additionally, the adjacent floodplains, constituting 3000 $h{\cdot}km^2$ under aquaculture [4], shift from brackish water to freshwater in most locations due to the monsoon's effect [5]. In Bangladesh area, Sundarbans together have three main wildlife sanctuaries (i.e., Sundarban West, South, and East) encloses approximately 23% of the total area [6].

Despite its ecological significance, fisheries management and conservation activities in the Sundarbans are narrow and face multidimensional obstacles including the strong dependence of local communities on the changing environmental conditions. Governed by forest department regulations, fisheries within the protected Sundarbans confront these challenges. Recognized as a unique and vital aquatic resource, the Sundarbans functions as a nursery ground for various fin fish and shellfish species, bearing cross-boundary importance. Vast aquaculture habitats, currently underutilized, hold the potential to contribute significantly to future endeavors related to food security, export income, and employment.

The estuarine aquatic systems and braided rivers adjacent to the Sundarbans, particularly within the Ganges tidal floodplain, offer fertile grounds for cultivating fish, shrimps, and crabs, providing direct employment to 1.2 million people and indirect livelihoods for over 10 million [7]. Gradually becoming a major contributor to fish and crustacean production in the Sundarbans region, aquaculture expansion has primarily occurred in tidal floodplains and *beels* (seasonal waterbodies), responding to the international demand for shrimp.

Despite the ecological and economic importance of the Sundarbans, fisheries management and conservation efforts are described as "narrow" and challenged by multiple factors (e.g., environmental variability and livelihood dependence). There is limited insight into the effectiveness of current management strategies or the impact of policy enforcement in protected areas. Vast aquaculture habitats in the region remain underutilized, with little data or analysis on why these areas are not optimized. There is a lack of understanding about the ecological trade-offs between aquaculture expansion and conservation of biodiversity. The impact of aquaculture on estuarine ecology, especially in terms of water quality, habitat degradation, and species diversity, remains under-researched. Specific technological, economic, or infrastructural limitations are not explored in detail. Seasonal shifts (e.g., monsoon-induced salinity changes) are mentioned, but their quantitative impact on aquaculture productivity, species distribution, and farm viability is not fully explored. While employment statistics are provided, there is a gap in understanding the socioeconomic dynamics, such as income disparity, labor rights, and gender roles within aquaculture-dependent communities.

This study helps to assess how existing governance frameworks (e.g., Forest Department regulations) impact fish stock sustainability and biodiversity conservation in protected zones of the Sundarbans and how aquaculture practices influence estuarine water quality, habitat conditions, and biodiversity, particularly in sensitive zones. It also helps to investigate the physical, technical, economic, and regulatory constraints limiting aquaculture productivity in the Sundarbans and adjacent floodplains and explore how monsoon-driven changes in water salinity and flow affect species composition, growth rates, and aquaculture output. Finally, it facilitates understanding the role of aquaculture in livelihood security, including income generation, employment trends, and resilience to environmental or market shocks.

2. Methodology

This research employs a multidisciplinary approach to recommend for policy making of ecologically critical area (ECA) of Sundarbans in context with aquaculture and fisheries potentials. The methodology was structured to integrate qualitative and quantitative data collection and analysis methods, ensuring a holistic understanding of the various dimensions of policy making on this unique ecosystem management.

2.1. Literature Review. We conducted a thorough literature search to gather existing information related to seabass, mullet, mud crab, prawn, oyster, and green mussel research in the Sundarbans and ECAs. We also reviewed technical reports, scientific articles, conference proceedings, and any other relevant sources.

2.2. Consultation With Lead and Associated Scientists. Identify and contact lead and associated scientists from various institutions involved in research on seabass, mullet, mud crab, prawn, oyster, and green mussel in the Sundarbans and ECAs. Scheduled meetings and interviews with these scientists to gather information about their research activities.

2.3. Comprehensive Report From Lead Scientists. We engaged with lead scientists (resource rersons like Chief Scientific Officer, Principal Scientific Officer, other scientists) to compile detailed reports on the research activities at their respective institutions (like Bangladesh Fisheries Research Institute Brackishwater Station, Marine Fisheries and Technology Station (MFTS), and Shrimp Research Station [SRS]) involved in finfish/crustacean breeding research related to Sundarban and ECAs.

2.4. Final Article Preparation. We compiled all gathered information, including reports from lead scientists, and literature review findings, and organized the data into a coherent and comprehensive article with recommendations to policy making.

3. Aspects of Ecologically Critical Areas (ECAs) of Sundarbans

The ECAs are ecologically precisely marked areas or ecosystems harmfully invaded by the changes occurring through public deeds. To flourish the ambience of ecosystems, in 1999, the government announced seven ECAs with diverse levels of deterioration, declining coastal areas, islands, and wetlands in different regions of the country (Table 1). Six other ECAs were declared between 2001 and 2009.

According to the Environment Conservation Act, the area within the 10-km radius of the Sundarbans (Figure 1) has been announced an ECA. The ECA of Sundarbans delineated within a 10-km radius of the Sundarbans, symbolizing a fragile ecosystem necessitating special conservation efforts. Construction of any establishments or any sort of activities that destroy the natural features is completely prohibited in these areas. This paper endeavors to illuminate the importance of fisheries and aquaculture in this area, underscoring their socioeconomic importance, fisheries management, and the imperative for sustainable aquaculture practices to preserve the delicate balance of the ecosystem.

The Sundarbans serve as a critical source of fish and crustacean items, providing valuable animal protein and contributing significantly to export earnings [9]. Conservation efforts have been implemented in the region, including fishing bans and the establishment of protected areas, covering about 55% of the forested area. These measures have profound implications for the livelihoods of the fishermen in the Sundarbans [10]. With restricted access to Sundarbans resources, many families have sought alternative income sources in the ECA, turning to fish farming on lands that are marginally suitable for agriculture. The current fish farming methods, especially for seabass and mullet, are being practiced on a limited scale in tide-fed brackish water ponds, alongside shrimp/prawn farming. These practices heavily rely on the seed collected from nature. However, the fast spread of mud crab fattening and farming has led to the significant capture of crablets (juvenile mud crabs), putting immense pressure on wild populations. In the absence of hatcheries, the prevailing practice involves the harvest of postlarvae (PL) of shrimp/prawn, young fish fry, and crablets from the rivers and canals within the Sundarbans and the ECA. Fine mesh nets are commonly used for this purpose, unfortunately resulting in the unintended capture and subsequent disposal of numerous other aquatic species along the river and canal banks, leading to their demise. This practice has led to a critical situation in the coastal rivers of Bangladesh, where thousands of individuals use mosquito nets to catch shrimp/prawn fry, resulting in the sacrifice of approximately 714 larvae of various finfish and shrimp/prawn just to capture a single PL of tiger shrimp/prawn [11]. The continued and widespread use of this method is causing significant depletion of both crustacean and finfish stocks in the water bodies within and near the Sundarbans. Furthermore, the collection of wild black tiger shrimp, prawn, and crab seed has been a contentious issue, often associated with the negative impact on coastal aquatic biodiversity.

The expansion of mariculture in the productive coastal waters of the ECA in Bangladesh offers substantial potential to enhance food security, social well-being, and economic prosperity. To fully realize this potential, it is essential to develop artificial breeding and mass seed production for brackish water finfish in hatcheries. This would facilitate the growth of coastal aquaculture in land-based shore ponds, lagoons within the ECA, and offshore aquaculture in cages in suitable coastal areas. Breeding economically significant fin and shellfish species is critical to meet the growing seafood demand without overexploiting wild populations. Bangladesh also possesses significant wild seed resources, including mussels, clams, oysters, and seaweed. To harness their full potential, comprehensive research initiatives are required, focusing on breeding technology, larval rearing, and culture techniques, particularly within the ECA. Overcoming challenges, such as limited knowledge of breeding indigenous fin and shellfish species, is crucial, necessitating a deeper understanding of their reproductive biology and life cycles. Breeding programs can help reduce pressure on overexploited wild populations and conserve these species. Successful breeding and aquaculture create economic opportunities for local communities, leading to increased income, employment, and poverty alleviation. A consistent supply of high-quality seed can support the local economy, stimulate economic growth by fostering a thriving aquaculture industry, and potentially result in increased exports, revenue, and investment in the Sundarbans. Reliable access to farmed seafood enhances food security for the local population, particularly during periods of scarcity or natural disasters. In summary, sustainable aquaculture practices, supported by a consistent supply of high-quality seed, can make a substantial contribution to the growth of the local economy, foreign exchange earnings, and the preservation of the Sundarbans' ECA.

4. Salinity Intrusion in the ECA and Alternative to Crop Production

Salinity intrusion is a significant concern in the south-west region of Bangladesh, particularly in the ECA of the Sundarbans. The coastal agricultural land in this region is inherently fertile for rice cultivation, but salinity poses a substantial threat to agricultural productivity, affecting the livelihoods of the local population. Salinity deteriorates the ECA's soil health and fertility, resulting in reduced agricultural production, low income, and decreased employment opportunities for farm labor. Approximately 70% of the land in the Barishal and Khulna divisions is affected by varying levels of salinity, which hampers agricultural productivity [12]. Traditional rice varieties are not suitable for cultivation in highly saline areas, and salinity adversely affects crop yield by limiting fresh water availability. Crustaceans, Finfish, Shellfish, and Seaweeds farming has become a prevalent alternative to traditional crop production in the region due to its short-term economic

Table 1: Ecologically critical areas (ECAs) of Bangladesh including Sundarbans.

No.	Name of ECA	Type of ecosystem	Location	Area	Year of declaration
1	Sundarbans (10 sq. km landward periphery)	Coastal-marine	Bagerhat, Khulna, Barguna, Pirojpur, and Satkhira	292,926	1999
2	Cox's Bazar-Teknaf Peninsula	Coastal-marine	Cox's Bazar	20,373	1999
3	St. Martin's Island	Marine island with coral reefs	Teknaf upazila, Cox's Bazar	1214	1999
4	Hakaluki Haor	Inland freshwater wetland	Sylhet and Moulvibazar	40,466	1999
5	Sonadia Island	Marine island	Moheshkhali, Cox's Bazar	10,298	1999
6	Tanguar Haor	Inland freshwater wetland	Tahirpur, Sunamganj	9727	1999
7	Marjat Baor	Oxbow lake	Kaliganj upazila of Jhenaidah and Chaugacha upazila of Jessore	325	1999
8	Gulshan-Baridhara Lake	Urban wetland	Dhaka city	101	2001
9	Buriganga	River	Around Dhaka	1336	2009
10	Turag	River	Around Dhaka	1184	2009
11	Sitalakhya	River	Around Dhaka	3771	2009
12	Balu including Tongi canal	River	Around Dhaka	1315	2009
13	Jaflong-Dawki	River	Jaflong, Sylhet	1493	2015

Note: Source: Department of Environment [8].

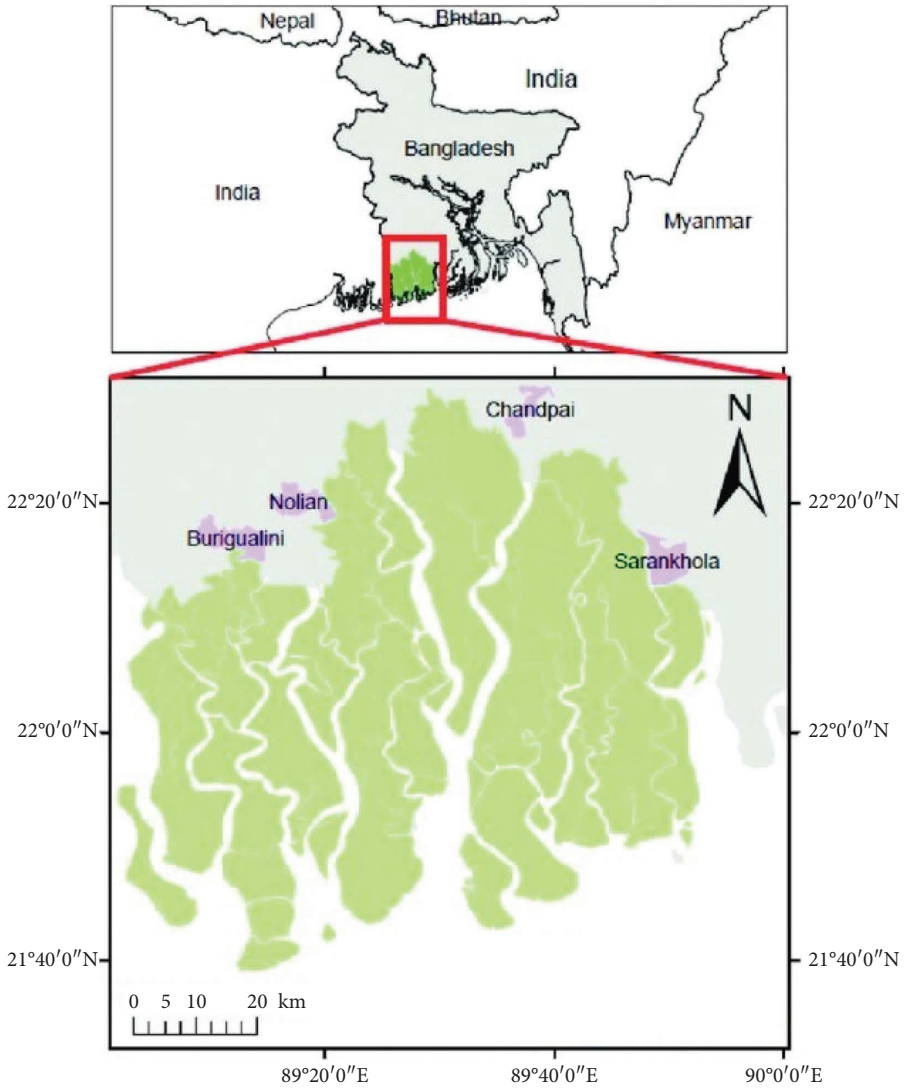

Figure 1: Map of the Sundarbans, Bangladesh.

benefits. The conversion of agricultural land into shrimp ponds has further reduced the availability of land for crop cultivation, fruit farming, and livestock rearing. Coastal aquaculture, specifically shrimp/prawn farming, is gradually replacing traditional agriculture in the region.

5. Demand and Supply of Seed of Shell and Fin Fish Species

In Bangladesh, the annual demand for shrimp (*Penaeus monodon*) PLs exceeds eight to nine billion, and over the last five years, the existing shrimp hatcheries have produced between 8 and 13 billion PLs annually. The annual demand for Prawn (*Macrobrachium rosenbergii*) PLs ranges from 1.5 to 2.0 billion, but the capacity of total production is approximately 850 million, with recent estimates suggesting only 30–50 million are being produced. To meet this substantial annual demand, approximately 80% of Prawn PLs are sourced from illegal wild catches in coastal rivers and canals, despite being banned. Additionally, 15–20% is imported from neighboring countries through informal channels [13].

While hatcheries have been successfully established for the production of shrimps and prawns, there has been limited progress in developing seed production technology with hatchery practices for popular and economically important species such as mangrove crab (*Scylla olivacea*), which is a sought-after export item, as well as other important species like the Asian Seabass or Barramundi (*Lates calcarifer*), Flathead Gray Mullet (*Mugil cephalus*), Green Back Mullet (*Chelon subviridis*) and Grouper (*Epinephelus* spp). These fish species of the Sundarbans are of great importance in the context of Bangladesh. However, very few studies have been carried out on the fishery resources in the region, with the available information primarily limited to species identification, which remains incomplete. There is a lack of authoritative information regarding the population, breeding seasons, breeding and spawning grounds, and the life cycle of various important species of finfish, shrimp, or crabs. It is worth noting that while all resources in the

Sundarbans are under the administration of the Forest Department (FD), BFRI or the Department of Fisheries (DoF) is not actively involved in the Sundarbans. This situation emphasizes the need for increased research and conservation endeavor to secure the enduring management of these vital aquatic resources in the Sundarbans.

6. Aquaculture Potential of Shell and Fin Fish Species in the ECA of Sundarbans

Aquaculture, including mariculture, has a rich history in Asia; however, its progress in several countries, particularly Bangladesh, has been impeded by factors such as the lack of suitable technology for mass seed production, geographical constraints, frequent natural disasters, and limited financial and technical support. While coastal aquaculture as well-established roots in countries like China, Japan, Taiwan, the Philippines, Thailand and Vietnam, it left over a proportionately new endeavor in Bangladesh. Currently, only a few species, including shrimp and prawn are cultivated using hatchery-produced seeds as well as collected from nature. Nevertheless, Bangladesh holds potential for mariculture with several shrimp, finfish, mollusks, and seaweeds showing promise for future development. Due to the indiscriminate harvesting of seeds from natural sources and various environmental factors, the abundance of shrimp, crab, and finfish is decreasing day by day. However, there left over major obstacles and constraints that need to be aimed in order for marine aquaculture to further exhibit and come up with to a developing blue economy in Bangladesh. For the expansion of coastal aquaculture, breeding and culture process of targeted species has to be generated. This sector needs more research activities. The potentials of some selected finfish and crustacean species with their main characteristics and success of breeding in captive condition are furnished in Table 2.

Seabass (*Lates calcarifer*), regionally known as Bhetki or Koral, is found year-round in the river mouth and coastal regions of Bangladesh. In several countries such as Australia, India, Malaysia, the Philippines, and Thailand, artificial propagation and commercial cultivation of this species have been successfully developed. However, the technology for breeding has yet to be established in Bangladesh.

Although the induced breeding and fry production process for the greenback mullet, *Chelon subviridis*, have been successfully generated at the BFRI Brackish Water Station in Paikgacha, Khulna [36], the validation and subsequent transfer of this technology to hatchery owners are encountering challenges. Successful captive breeding of the gray mullet (*Mugil cephalus*) remains a distant goal.

Groupers from the family Epinephelidae hold appreciable profit-making value in thermal and semitropical countries [37]. This family consists of more than 160 species in 16 genera worldwide [38, 39]. However, nine new species have been put on in the present decades [40–42]. Currently, research work is limited to species identification.

The availability of sea and estuarine waters with ideal salinity and warmth states makes the Sundarbans and coast line districts in Satkhira, Khulna, Bagerhat, and Cox's Bazar regions well-suited for mud crab fattening and culture. Crabs are less vulnerable to disease and more resilient to adverse weather conditions and the consequence of climate change. Consequently, many shrimp farmers in Bangladesh are transitioning to mud crab fattening and culture [43, 44]. Soft-shell crab culture, primarily focusing on *Scylla serrata*, has gained focus from buyer and seller in Shyamnagar, Satkhira, Moheshkhali, and Cox's Bazar regions. The BFRI Brackish Water Station in Paikgacha, Khulna, achieved the first successful artificial breeding and seed production of mud crab with a 5% survival rate. Recent research has shown that optimizing feed size, density, nutritional quality, and proper feeding schemes can increase the survival rate to 7% [45].

In the early 20th century, numerous prawn hatcheries were established in Bangladesh, and the hatchery business remained profitable until 2010–11. However, from 2011–12 onward, most hatcheries faced challenges, including mass larval mortality and delayed molting, resulting in significant financial losses. This leads the way to a notable reduction in the operating prawn hatcheries number, which dropped to 36 by 2014–15 and just 8 in 2017. In response, the SRS in Bagerhat, under the BFRI, initiated a close monitoring program in 2012–13. The focus was on the hatchery operation system and the inputs used, including disinfectants (bleaching, formalin), artemia, brood, and brine. This initiative aims to revitalize the prawn hatchery industry in Bangladesh, ensuring its sustainability and economic viability.

There is huge local demand for mollusk meat, and demand also comes from the poultry industry for mollusk shells, with export opportunities that provide an excellent chance for that's mariculture to come up with to the blue economy expansion. In 2015, worldwide mollusk production reached 15.26 million tons. Currently, Bangladesh give very few to the total production. However, this form of aquaculture is a small funding activity with substantial benefit. In the 2017–2018 fiscal year, Bangladesh drew US$5.51 million by exporting oysters, mussels, and scallops. Furthermore, mussel and clam culture have the potential to generate resources and employment, particularly among coast line people, including women living below the poverty line [46]. Breeding success achieved in indoor captive condition and outdoor natural close control condition by the MFTS in Cox's Bazar, under the BFRI.

Spat collection of pearl oyster could also make a significant offering to livelihoods in some coast line areas, though appropriate sites may be limited, and husbandry demands may be higher. Nevertheless, this offers a promising chance for private companies and other nongovernment organizations to produce best-quality pearl ornaments for local tourists, crafts, and supermarket chains. Pearl culture has yielded substantial export earnings in China and other countries.

7. Advancements in Shellfish, Finfish, and Macroalgae Research in Coastal and Marine Ecosystem

In the southwest part of Bangladesh, there are approximately 1.5 million hectares of brackishwater ghers, large hydrological units protected by embankments with facilities for

Table 2: Promising coastal finfish and shellfish species for aquaculture/mariculture in the ECA of Sundarbans and its history of breeding success.

Sl. no.	Local name	Scientific name	Main characteristics and success of breeding in captive condition	Sources/references
Coastal finfish				
1	Sea bass (Bhetki/Patari)	*Lates calcarifer*	• Carnivorous, high commercial value and expensive fish • Take fish, snails, crustaceans and worms as feed • Cannibalistic nature when lack of food in nature • Minimum size 400 mm when matures at second year • Passed 2–3 active breeding season, male convert to female, female generally larger • Breeding success yet to achieve	[14]
2	Mullet (Bhangon/flathead gray Mullet)	*Mugil cephalus*	• High commercial value and expensive fish • Omnivorous, takes green algae, blue green algae, large aquatic plant, diatom, detritus, small crustaceans and zooplankton as feed • Potential for commercial cultivation due to hardiness, suitable for mixed culture with shrimp • Size of fish at 250–400 mm in length when mature • Male (in first year) matures faster than female (in second year) • Breed in sea offshore because eggs need high saline water for fertilization • Breeding success yet to achieve but preliminary success achieved.	[15]
3	Mullet (Parse/green back Mullet)	*Chelon subviridis*	• Hugh demand in the domestic and international market • Found abundant in coastal traditional shrimp farms • Food type and feeding nature, fry production, etc. are as same as gray mullet • Suitable for culture with shrimps • Artificial breeding and seed production success achieved in hatchery condition	[16]
4	Grouper	*Epinephelus* spp.	• Popularly known as grouper, grow rapidly • Carnivorous, high commercial value and expensive fish • It is of 1.2 m long and over 100 kg weight • Exhibits sex reversal nature, in that case after 2–3 active breeding seasons female reverse to male • Breeding success yet to achieve	[17]
5	Indian Salmon	*Eleutheronema tetradactylum*	• Highly esteemed food fish, adaptable to ponds • Wide salinity tolerance, compatible with tilapia • They feed primarily on crustaceans and smaller fish • No current attempts at cultivation in Bangladesh	[18]

Table 2: Continued.

Sl. no.	Local name	Scientific name	Main characteristics and success of breeding in captive condition	Sources/references
6	Megalop (tarpon)	*Megalops cyprinoides*	• Euryhaline nature • Migratory nature to rivers and estuaries • Takes on fish, crustaceans, and other animals • Minimum size 250 mm, when mature becomes maximum 1000 mm • Breed in coastal waters and that happens twice a year	[19].
7	Threadfin	*Polynemus* spp	• Carnivorous, 1.2 m long and 100 kg weight • Similar species (Yellowtail) intensively cultured in cages • No attempt was made to domesticate this finfish	[20]
8	Datina (white grunter)	*Pomadasys hasta*	• High demand in the foreign market • Threatened in the coastal waters • Breeding and seed production achieved in hatchery condition	[21]
9	Chitra (spotted scat)	*Scatophagus argus*	• Endangered in Bangladesh • Breed in the sea • Breeding and seed production achieved in hatchery condition • Used as both food fish and ornamental fish in Bangladesh • Culturable in coastal area	[22].
10	Royna (silver tigerfish)/four-banded tiger perch	*Datnioides polota*	• Predatory fish • Mostly inhabits brackish habitats (estuaries, mangroves, coastal lagoons, irrigation canals) • Culturable with same size fish • Preliminary breeding success occurred	[23]
11	Bele	*Glossogobius giuris*	• Unique taste, low fat content, and high protein content • Distribution covers both freshwater and estuaries • Taposi (paradise threadfin) (*Polynemus paradiseus*): • Commercially important species and tasty fish • Catch declined in recent years	[23]
12	Taposi	*Paradise threadfin*	• Commercially important species and tasty fish • Catch declined in recent years	[23]
Brackishwater catfish				
13	Nona Tengra	*Mystus gulio*	• Euryhaline estuarine small catfish • Demand in export market • Breeding and seed production achieved in hatchery condition • Poly culturable with tilapia	[24]

Table 2: Continued.

Sl. no.	Local name	Scientific name	Main characteristics and success of breeding in captive condition	Sources/references
14	Catfish	*Poultices anguillaris*	• Feeds on various aquatic organisms and detritus • Breeds in saltwater, suitable for mariculture • No current attempts at cultivation in Bangladesh • Breeding and seed production achieved in hatchery condition	Personal observation
15	Kain Magur (Grey-Eel catfish)	*Plotosus canius*	• Primarily found in marine habitat, covers both brackish and freshwater • Commercially important species	[23]
Shellfish				
16	Prawn (giant freshwater prawn)	*Macrobrachium rosenbergii*	• High demand in world market • Current demand of 130 crore PL per year • Success achieved in hatchery condition; seed production limited with existing technology • Most of the hatchery facing mass larval mortality	[25]
17	Shrimp (tiger shrimp)	*Penaeus monodon*	• Omnivorous species • 330 mm long and 250 g weight • Highly Euryhaline species can tolerate salinities up to 45 ppt • Naturally bred during October–November and May–June • PL available in the Bangladesh coast year-round • It cannot survive below 15°C • Mass seed production technology available	[26]
18	Chaka Chingri (Indian white shrimp/ Indian banana shrimp)	*Penaeus indicus*	• Omnivorous • Survive up to depth of 90 m, and mostly found in shallow waters with sandy bottom where water depth is < 30 m • Tolerate high range of salinity • Peak breeding season during October-November and May–June • In life span, breeding performance shown minimum 5 times • 175 mm long and 40 g weight	[27]
19	Brown shrimp (Harina Chingri)	*Metapenaeus monoceros*	• Known as Ginger or Speckled shrimp • Commercially important shrimp species • Omnivorous nature • Maximum 100 mm of size • Hardy, can tolerate fluctuations in temperature and salinity, prefer low salinity • Breeding success yet to achieve	[27]

Table 2: Continued.

Sl. no.	Local name	Scientific name	Main characteristics and success of breeding in captive condition	Sources/references
20	Mangrove crab	*Scylla olivacea*	• Mostly popular as mud crab or green crab • Carnivorous in habit, poses a threat to shrimp farming • Carapace length 150 mm, breadth 215 mm, and weight 2 kg • Grows in the tidal mud flats and breed in offshore area of the sea • Chelipeds is massive and highly priced • Breeding and seed production technology developed with 5% success	[28]
21	Oyster	*Crassostrea* spp.	• Known as backwater oyster colonies • Commonly found in estuaries, backwater, ports and harbors • Consume green algae, blue green algae and diatom as feed • Breed in March to April • 110 mm length in 17 months • Oyster mussels are traditionally consumed only by some tribal people, but high export value • Boiled oyster meat is being used as feed for cultured shrimp • Breeding success achieved in indoor captive condition and outdoor natural close control condition by the BFRI	[29]
22	Pearl oyster	*Pinctada* spp.	• Filter feeders with pearl-producing potential • Golden yellow in color, stay attached to rocks and dead coral by byssus threads at 2–10 m of depth • In a year breed twice, once in April–May then September–October • No current attempts at cultivation in Bangladesh	[30]
23	Green mussel or green-lipped mussel	*Perna viridis*	• Popularly known as green mussel or green-lipped mussel • Feeds on diatom, algae, and detritus • Mostly living in coast line, harbors, and estuary • Tolerate long range of salinity, stay at a depth of 3 m • Generally fastened to hard bedrock • Became mature in 150 days • Peak breeding season March–October • Attains a maximum size of 100 mm • Mussels are traditionally consumed only by some tribal people • Breeding success achieved in indoor captive condition and outdoor natural close control condition by the BFRI	[31]

Table 2: Continued.

Sl. no.	Local name	Scientific name	Main characteristics and success of breeding in captive condition	Sources/references
24	Brown mussel	*Perna indica*	• Mostly called brown mussels • Feeds on phytoplankton and detritus • Generally binds to piers, poles, rocks, ropes by byssus drifts like green mussel • Stays between 6 m depth of water • Peak breeding season is June–August • Maximum length recorded is 118 mm	[32]
25	Clams	*Meretrix meretrix*	• Popularly famous as Bay clam, hard clam or great clam • Feed on plankton and detritus • 75 mm long and 40 g weight • Spawning season extends from September–October • No current attempts at cultivation in Bangladesh	[33]
26	Clams	*Meretrix casta*	• Feeds on phytoplankton and detritus • Euryhaline species • Moderately big with thick shell and dull yellowish or brown color and generally available in all river mouth • Grow up to 38 mm length and 30 mm in breadth, in 3 years it becomes 60 mm long maximum • Breeding season extends from July–August • Not found in Bangladesh, cultured in India	[34]
Macro algae				
27	Seaweeds (macro-algae)	*Hypnea musciformis* or *Gracilaria* sp.; *Ulva lactuca*; *G. tenuistipitata*; *U. intestinalis*; *Dictyota dichotoma*; *G. tenuistipitata*	• Those are macrophytes, growing mostly in intertidal and subtidal environment on rocks and other plants or substratum • Commercially important species for potential cultivation • Seaweed utilized as a source of human food, animal feed, fertilizer, fungicides as well as herbicides • Culture practice developed by the BFRI	[35]

controlled drainage and irrigation infrastructure joint with coast line rivers. Currently, around 217,000 ha are utilized for brackishwater aquaculture, primarily focused on traditional farming of brackishwater shrimp/prawn, with or without finfish [13]. The cultivation of this fish in coastal encloser, locally known as *ghers*, is gaining significant popularity in Bangladesh. Presently, farmers rely on wild fry for stocking their *ghers*, with the exception of shrimp, which benefits from mass seed production technology. However, due to uncontrolled harvesting from natural sources and climatic factors, the availability of this fish is diminishing. There is a pressing need for an alternative supply of fish fry from induced breeding to protect natural biodiversity and enhance fish production.

To address this challenge, the BFRI scientists and researcher of some universities has taken proactive steps to induce breeding in a few species. Not only has breeding been undertaken, but successful cultivation of various species, including different types of oysters and seaweed, has also been achieved in coastal areas. The progress in research activities of some target species in this regard and the current situation were briefly described (Table 3). To harness in detail the past and present knowledge on the research activities of different scientists of the national research institution, Department of Fisheries (DoF) and other technical Universities, a short study would be conducted considering the following tasks:

8. Current Drivers of Change in Fisheries and Aquaculture Along Sundarbans and Adjoining ECA

The Sundarbans and its adjoining ECA face a unique set of challenges in their fisheries and aquaculture sector. This section excavates into the current drivers of change, examining the complex interplay of environmental and socioeconomic factors impacting the sustainability and dynamics of fisheries and aquaculture in this region.

8.1. Environmental Drivers

8.1.1. Climate Change and Sea Level Rise. Climate change is a primary environmental driver affecting fisheries and aquaculture. Increasing temperatures, changes in drastic patterns, and ocean acidification directly impact the availability and affluence of fish species and influence aquaculture practices. In Sundarbans, human-caused climate change frightens the exquisite balance between land, air, and sea [68]. The Sundarbans is particularly susceptible to environmental change, with sea levels rising and switching weather types affecting fish habitats and migration routes. This influences both wild fisheries and aquaculture operations. CEGIS [69] stated that dry lands in the Sundarbans would be decreased to 7% in 2100 due to 88 cm rise of sea level compared to 43% under base condition in 2001, i.e., about 84% of present dry lands would be disappeared. Keeping in mind the present (4 cm) relative rise of sea level [70] 3.14 mm per year, it is approximated that by the year 2050, the worsened sea level upgrading would become nearly 1 m [71]. The findings says that environmental change has continuous monsoon drastic patterns, caused rise of sea level, increase of sea surface temperatures, lethal weather events, storm surges, flooding, erosion, embankment breaching, land subsidence, waterlogging, salinization and other challenges in the Sundarbans [72, 73]. Masum [74] showed that some of the warning signs of the adverse effects of environmental change such as rise of sea level, logging of water, poor drainage, siltation, and intrusion of seawater are already started in the Sundarban region. Loucks et al. [75] assumed that 28 cm of sea level rise occurs in the next 50–90 years if the current rise of sea level predictions and local conditions do not change.

8.1.2. Habitat Degradation and Loss. Rapid urbanization, industrialization, and land-use changes contribute to habitat degradation and loss, impacting the breeding and nursery grounds of many fish species. Mangrove deforestation, pollution, and increased human activities contribute to habitat degradation in the Sundarbans. The loss of critical breeding grounds affects the abundance and diversity of fish species. Uddin et al. [76] stated that as the potential environmental change would switch the geological circumstances of the fish nursery ground would alter the composition of harvesting fish not only from inside the Sundarbans but also from the adjacent no saline and high saline regions, which would have an effect on the regional and national finance. The potential environmental change would alter the geological state, and the assisting facilities of the Sundarbans would be greatly influenced [77]. The changes in the supporting services of the Sundarbans due to climate change and sea level rise would be largely visible on the provisioning services, primarily on the trees and fisheries production. Rahman [78] revealed that sea level rise make dune greenery, animals, and reptiles vulnerable. Future forecast recommend that 30%–40% of coast line wetlands, and 100% of mangrove forests could disappear in the next hundred years if present rates of reduction carry on [77, 79]. In every instance, there has been a notable decrease in mangroves; the losses increase with sea level rise and if current management continues, the mangroves of the Indian Sundarbans could vanished between 42% and 80% of their current area by the end of the century [80]. Species that depend on specific habitat conditions, such as the Bengal tiger, spotted deer, and various fish species, are facing habitat loss and changes in prey availability [81]. Losing of the Sundarbans means great disappearance of heritage, destruction of biological diversity, decline of fisheries community, loss of existence, and maintenance and after all decrease of very high high-yielding ecological habitat [82]. Hazra et al. [71] showed that an analytical assessment of the major harvest of Hilsa (*Tenualosa ilisha*) in the Hooghly-Matla estuary of the Sundarbans shows a reducing trend since the 80s.

8.1.3. Salinity Intrusion and Water Quality. Changes in salinity levels and water quality, often linked to environmental change and human activities, impact the distribution

Table 3: Name of the institutions involved in research related to Sundarbans and ECAs.

Sl. no.	Institute/university	Studied species	Field of study	Sources/references
1.	Bangladesh Fisheries Research Institute (BFRI)			
1.a	Brackish Water Station, Paikgacha, Khulna	Mud crab, Mugil, Brown shrimp	Brood development and breeding of mud crab and mullet	[47] [16]
1.b	Shrimp Research Station, Bagerhat	Prawn	Quality brood development and mass seed production of prawn	[48]
1.c	Marine Fisheries and Technology Station, Cox's Bazar	Seabass, oyster, mussel & seaweed	Breeding of mullet, seabass, mud crab, mussel, oyster and seaweed	[15] [50] [51] [23]
2.	Department of Fisheries (DoF), Cox's Bazar	Mud crab	Brood development, breeding and Mass seed production	[52]
3.	Bangladesh Agricultural University, Mymensingh (BAU), Mymensingh (Faculty of Fisheries)	Prawn, green Mussle (*Perna viridis)*	Quality brood development and mass seed production of prawn Reproductive biology, ecology, feeding behavior and farming of green mussle	[53] [54]
4.	Sher-e-Bangla Agricultural University (SAU), Dhaka (Faculty of Fisheries, Aquaculture and Marine Science)	RAS, mud crab, seabass	Marine biodiversity, genetic diversity, population structure and demographic history of mud crab & seabass	[55] [56]
5.	Khulna University (Fisheries and Marine Resource Technology Discipline)	Mud crab, mullet (*Liza parsia*), seabass, prawn	Taxonomy, ecology and reproductive biology of mud crab Growth & feed efficiency of different sized seabass Mono- & Polyculture of prawn	[57] [58]
6.	University of Chittagong, Chattogram (Institute of Marine Sciences and Fisheries)	Seabass, prawn	Breeding and cage culture of seabass Re-maturation of hatchery used wild spawners of prawn Breeding of Grey mullet	[59] [60] [61] [62]
8.	Noakhali Science and Technology University (NSTU), Noakhali (Department of Fisheries and Marine Science)	Mud crab, goldspot mullet (*Liza parsia*)	Food & feeding habit of mud crab Hormone induced captive breeding of mullet	[63] [64]
7.	Chattogram Veterinary and Animal Sciences University (CVASU), Chattogram (Faculty of Fisheries)	Marine fish larvae, green mussel	Marine fish larvae biodiversity Reproductive biology & selective breeding of mussel	[65] [66]
8.	Nowabenki Gonomukhi Foundation (NGF), Shyamnagar, Satkhira	Mud crab	Crablet production, promotion of sustainable crab farming	[67]

and health of brackishwater species crucial to the local fisheries and aquaculture. About 77% regions of whole Sundarbans would be overwhelm by more than 1-m depth due to 88 cm rise of sea level in 2100. Additionally deepening overwhelm, salinity figures would change in the Sundarbans due to rise of sea level and swap in upstream freshwater run. The freshwater region (0–1 ppt) would shorten from 10.8% in base situation (2001) to 4.0% with 88-cm sea level rise in 2100 [69]. Chakraborty and Ghosh [70] indicate that the integration of global warming moderate salinity intrusion with enormous erosion has generated the moving of low saline water (0–1 ppt) adoring mangroves. Patra [81] showed that saline level fluctuation of the Sundarbans was roughly comparable during the summer (29.0 30.0 ppt) and monsoon (12.0–14.0 ppt). Rise of sea level would be the reason of salinity increase in the water and soil of the Sundarbans [82]. Enlarged salinity would alter the natural territory figure of the jungle. Sundari, the most dominating trees of the Sundarbans, is decreased day by day due to lethal disease caused by increased salinity [83]. Aquatic species should move toward the inside for rise of salinity too. Rise of sea level would switch the overwhelm and salinity level in the Sundarbans that should influence the worthy region for the trees [77]. Among the various threats fisheries (poor peoples in the area consumed 83 species of fish) in the southwest coast line area and Sundarbans mangrove jungle would face because of environmental effect, unfavorable effects (lose number of species are about six times more frequent than regions obtaining number of species) from the rise of salinity because rise of sea level have been picked out as one of the considerable challenges [84].

8.1.4. BoB Health and Pollution. Increasing pollution, including plastic pollution and chemical contaminants, negatively affects the health of BoB marine ecosystems and poses risks to both wild fish populations and aquaculture operations. Rise of sea level may extend the chance of health problems like diarrhea, cholera, etc. Cholera is identified as most familiar disease of the human's small intestine in coast line regions of Bangladesh [82]. However, the level of chances of cholera and the deepness of malnutrition is a matter of more advanced research.

8.1.5. Technological Advancements. Recent advancements in technology, including fish tracking systems, aquaculture automation, and data analytics, are transforming the efficiency and productivity of fisheries and aquaculture operations. Technological advancements can have both positive and negative effects on fisheries and aquaculture practices. Innovations in fishing gear and aquaculture technologies may enhance efficiency but also pose risks to sustainability.

8.2. Socioeconomic Drivers

8.2.1. Population Pressure and Livelihoods. As the global population continues to grow, there is increasing pressure on fisheries and aquaculture to meet the rising demand for protein. This demand influences fishing practices, aquaculture intensification, and resource allocation. The growing population in and around the Sundarbans places increased pressure on fisheries and aquaculture resources, impacting both livelihoods and the demand for fish products. Hazra et al. [71] demonstrated that there is a steady rise in population size in the Sundarbans, which is frightening; if this continues, it would surely have extensive consequence on the overall ecosystem of the region. Uddin et al. [76] stated that the livelihood design specifies that most residents are occupied in harvesting fish (each fisher's family annually earns nearly US$ 390 from the Sundarbans), followed by fuel wood (US$ 25 per household annually), crab (US$ 290), honey, and golpata (US$ 220), rather than timber cutting because since 1989 the Forest Department embargo on timber destroying. Rural families face difficulties retrieving enough and best-quality food due to insufficient income from regional agro-fishing works because of risk of water matter. Ultimate environmental effects and increased price of food have further decreased source to food [72]. Masum [74] reported that the most (80.1%) of poor family heads in the Sundarbans livelihoods are farmers (34.4%), day laborers (21.6%), housewives (14.0%), and small business owners (10.1%). He also noted that more than one-tenth (12.4%) of family heads have suffered illness; more than one-fourth (28.5%) have experienced accidents, cyclones, tornadoes, or other natural disasters; and nearly one-fourth (23.3%) of respondents have reported negative impacts on health due to environmental change. On the other hand, more than one-third (37.5%) of family heads indicated that the sickness of the main breadwinner (family head) has a serious negative effect on family income. The Sundarbans and their biological diversity are critical to the lives of millions of Bangladeshis (and Indians) who share the coast and welfare from the ecological favors (e.g., defense from cyclones, food and building supplies, fisheries, and carbon cycling) provided by the Sundarbans [85–89]. Patra [81] stated that human communities living in and around the Sundarbans are severely troubled by cyclones, with homes, infrastructure, and livelihoods being destroyed. The loss of mangroves, which act as a natural barrier against storm surges, exacerbates the vulnerability of these communities. The Sundarbans is a considerable source of maintenance for nearly 10 million people [89]. Hazra et al. [71] stated that fisheries represent a major source of family income for tens of thousands of poor people in the southwest coast line region of Bangladesh living near the UNESCO Heritage Sundarbans mangrove forest, and they provide a notable portion of protein for millions.

8.2.2. Economic Development and Tourism. Economic development and urbanization lead to changing dietary preferences, with an increasing demand for fish products. This shift influences the types of species targeted and the methods used in fisheries and aquaculture. Economic development and tourism in the Sundarban region influence the socioeconomic landscape, affecting the types of fisheries and aquaculture activities undertaken and introducing new challenges. Islam [90] mentioned that mangrove-dominated

coastal area has tourist attraction in the Sundarbans. All the tourist facilities in the coast line zone should be influenced by rise of sea level directly or indirectly [82]. He also indicated rise of sea level, by influencing this promising sector would affect the national economy and heritage of Bangladesh.

8.2.3. Governance and Policy Changes. Changes in governance structures, policies, and regulations significantly influence fisheries and aquaculture practices. The development of sustainable management policies is critical for long-term sector viability. Changes in governance structures and policies play a crucial role in shaping fisheries and aquaculture practices. Effective and adaptive policies are essential for sustainable resource management.

8.2.4. Social Equity and Community Resilience. The socio-ecological dynamics of fisheries and aquaculture are influenced by issues of social equity, including access to resources and benefits. Building community resilience is crucial for sustainable practices.

8.2.5. Interactions and Feedback Loops. Exploration of the interconnectedness of environmental and socioeconomic drivers in the Sundarbans and ECA emphasizes feedback loops and how changes in one aspect can amplify or mitigate the impact of others.

8.2.6. Future Scenarios and Adaptation Strategies. Considering potential future scenarios for Sundarbans fisheries and aquaculture initiative taking into account for ongoing environmental and socioeconomic changes, we should explore the adaptation strategies for the sector to enhance resilience and sustainability.

9. Critical Needs for Action/Research in Fisheries and Aquaculture in Sundarbans and Adjoining ECA

Research in fisheries and aquaculture in the Sundarbans and its adjoining ECA is crucial for sustainable resource management and the livelihoods of communities dependent on these ecosystems. Due to the study's bigger scale, more intentness is required to conduct micro-level experimental research involving numerous stakeholders to add location-specific awareness to the results and move forward the research arena. Research also requires finding way to protect the country's wide range of biological diversity, threatened by the forthcoming event. The following guiding outlines are the critical needs for research in this region, focusing on key areas that require attention and investigation.

9.1. Environmental Research

9.1.1. Climate Change Impacts. The specific impacts of environmental change on the Sundarbans and ECA, including rising sea levels, changing temperatures, and altered precipitation patterns, should be assessed to investigate how these changes affect fish habitats, migration patterns, natural breeding, juvenile abundance and overall ecosystem health. Although historically the management of approach for the Sundarbans targeted on the revenue collection from the jungle through methodical handling [91], new paradigm of handling should look forward bearing in mind the possible effects of environmental change, ecological integrity, long-lasting catching, and ensuring sustained ecological services of the Sundarbans for next generations of human as well as the ecosystem itself. Continuous research should be done to monitor the impacts of climate change on the Sundarbans ecosystem and local communities, providing data for informed decision making. Long-term monitoring programs are needed to track changes in biodiversity, water quality, and land use. The protected areas that are under prospective threats of rise of sea level should be examined highly to point out the difficulty of the regions from environmental point of view and to find out the solutions.

9.1.2. Mangrove Ecosystem Dynamics. Research on the dynamics of mangrove ecosystems in the Sundarbans is needed, exploring the impact of habitat degradation, biodiversity loss, forest health in changing water quality parameters, and resilience of mangrove ecosystems. Reforestation initiatives by planting mangroves in degraded areas enhance coastal protection. These mangroves act as natural blockade against storm surges and erosion. Biodiversity conservation by protecting the diverse plant and animal of the Sundarbans, including endangered species like the Bengal tiger, is critical. This includes creating buffer zones and restricting human activities in core areas. The recommendations from the Delphi study suggest that bringing back the ecological heritage of the Sundarban by plantations of mangrove and well-designed embankments would hugely advantage the four pillars of food security. A detailed study on quantify the exact sea level rise, sedimentation in the delta, and amount of subsidence and uplifting should be done scientifically and elaborately.

9.1.3. Salinity Intrusion and Water Quality. Investigation of the extent and outcome of salinity intrusion in the Sundarbans waterways, especially how it influences the distribution, abundance and availability of fishes and juveniles in particular, and health of brackishwater ecosystem is needed, including monitoring of water quality issues and their implications for both wild fisheries and aquaculture.

9.2. Socioeconomic Research

9.2.1. Livelihoods and Community Resilience. The socio-economic dynamics of communities dependent on fisheries and aquaculture in the Sundarbans should be studied In order to assess the impact of changing resource availability on livelihoods and explore strategies to enhance community resilience in the face of climatic and socioeconomic changes. Livelihood diversification to reduce dependence on natural

resources and initiatives have been introduced to promote alternative livelihoods such as sustainable aquaculture, honey production, and ecotourism. Consciousness and knowledge programs for local peoples are being conducted about the effects of environmental change and the significance of conservation. Training programs on sustainable practices are being provided. Comanagement models by collaborative management involving local communities, NGOs, and government agencies have been adopted to ensure more inclusive and effective conservation efforts. For suitable and specific business for their region, peoples must be motivated and trained. For specific activities for livelihood, coastline poor people should be provided small-scale loan at a less than 5% interest rate [82]. The harsh reality is poor people in this country face many difficulties to reach government financial institute. That is why, they always deprived from governmental financial help.

9.2.2. Economic Valuation of Fisheries. Economic assessments of fisheries and aquaculture activities, including valuation of ecosystem services, are needed to evaluate the economic contributions of these activities to local communities and the broader economy.

9.2.3. Social Equity in Resource Access. Issues of social equity in the access to and benefits from fisheries and aquaculture resources are investigated to identify barriers to equitable resource distribution and propose solutions to promote social justice.

9.3. Governance and Policy Research. A sustainable management policy including bank protection, divided Sundarbans due to its amount of vulnerable condition, systematic disaster management operation and the defense of saline resistant grain and seeds of different food should be developed.

9.3.1. Integrated Coastal Zone Management (ICZM). This is a holistic approach that promotes the long-lasting use of coast line assets by integrating environmental, socioeconomic, and governance aspects. This approach aims to balance development needs with conservation efforts. Policy intervention through strengthening policies related to land use, coastal zoning, and resource management are essential to mitigate the effects of environmental change on the Sundarbans.

9.3.2. Economic Development and Tourism. For the development of tourism in coast line area, principles of ecotourism must be in followed. Polder, for protection of tourism infrastructure, must be relocated because its construction is not feasible from environment point of view. So, construction of infrastructure for tourism should be done with full thought of rise of sea level.

9.3.3. Policy Impact Assessment. The effectiveness of current fisheries and aquaculture policies in the Sundarbans and ECA should be assessed to identify gaps, evaluate implementation, and suggest policy adjustments to enhance sustainability and resilience. Infrastructure development by construction of cyclone shelters and elevated platforms in vulnerable areas helps protect lives during extreme weather events. Improved forecasting by enhanced early warning systems and disaster preparedness plans have been implemented to reduce the risks associated with cyclones and flooding. To minimize the rise of sea level effect in this country, successful adjustment policies and reduction measures should be generated and executed. An institutional framework for monitoring the rise of sea level and coping contingency plans is needed for the policy.

9.3.4. Community-Based Management Strategies/Co-Management. Community-based management strategies/comanagement for fisheries and aquaculture should be researched and developed to explore the different models of co-management involving local communities, government agencies, and other stakeholders. Awareness building on the ability of group of poor to face and survival against multifaceted environmental risk is higher than single poor. The adjustment options should be emphasized on fishermen and farmers (most of the people in coast line community of Bangladesh belong) to mitigate the effects of the anticipated issues.

9.3.5. Legal Frameworks and Enforcement. The adequacy and enforcement of legal frameworks governing fisheries and aquaculture should be evaluated to identify the challenges in enforcement and propose improvements to ensure compliance with sustainable practices. Cross-border cooperation should be increased. Since the Sundarbans spans India and Bangladesh, enhanced cooperation between the two countries is crucial for effective management and conservation. Legal frameworks will be enhanced by updating and enforcing legal frameworks to protect the Sundarbans, including stricter regulations on deforestation, pollution, and illegal fishing activities.

9.4. Technology and Innovation

9.4.1. Sustainable Aquaculture Practices. Innovative and smart technologies should be researched and developed for validating and addressing climate and promoting sustainable aquaculture practices suitable for the Sundarbans in order to investigate the feasibility of integrated multitrophic aquaculture and low-impact aquaculture technologies.

9.4.2. Technology Adoption and Capacity Building. The adoption of technologies by the farmers in ECA should be assessed to identify the barriers to technology adoption and propose capacity-building measures for local communities to enhance their technological capabilities. One of the key adjustment measures must remind on achieving food self-sufficiency for the poor households. It is must have environmental adjustment aiming in such a way that conserves

and sustains the ecological systems and help the poor and provides food for the growing generation. For environment-sensitive areas, the policy should take into account the unique natural characteristics of the area.

Participatory planning: The planning and decision-making processes for adjustment policy are developed with local peoples to tailor their requirements and experience.

Resilience building: Programs aimed at raising the flexibility of local peoples to environment change through capacity building, financial support, and infrastructure development are developed.

9.4.3. Traceability and Certification. The implementation of traceability and certification systems for fisheries and aquaculture products should be explored to examine their potential benefits in enhancing market access and ensuring sustainability.

9.5. Interdisciplinary Research/Action

9.5.1. Interactions Between Environmental and Socioeconomic Factors. Interdisciplinary research to understand the complex interactions between environmental and socioeconomic factors in the Sundarbans and ECA should be conducted to explore feedback loops and cumulative impacts to inform holistic management approaches.

9.5.2. Adaptive Strategies for Changing Conditions. Adaptive strategies for fisheries and aquaculture communities to cope with changing environmental and socioeconomic conditions should be investigated to develop practical tools and guidelines for communities and policymakers to enhance adaptive capacity. This guideline emphasizes the critical research needs for fisheries and aquaculture in the Sundarbans and adjoining ECA. A comprehensive approach that addresses environmental, socioeconomic, governance, and technological aspects is essential for fostering sustainable practices and resilient communities in this ecologically sensitive region.

10. Major Constraints and Challenges in Adopting Mariculture

The adoption of mariculture in Bangladesh faces numerous constraints and challenges across various dimensions. These challenges encompass environmental, economic, infrastructural, and managerial aspects, making the development and sustenance of mariculture ventures a complex undertaking.

10.1. Environmental Sensitivity

- Marine organisms are highly sensitive to water quality parameters such as salinity, temperature, pH, dissolved oxygen, nitrate, and ammonia.
- Natural and anthropogenic activities, including cyclones and pollution (e.g., oil spills, microplastics, industrial and municipal waste), pose significant threats to mariculture operations.

10.2. Infrastructure Gaps

- Lack of specialized infrastructure for coastal finfish breeding hinders the development of this sector.
- Existing facilities, such as modified prawn hatcheries, may not be suitable for diverse species.

10.3. Political Will and Governance. Effective implementation requires strong political will and governance at local, national, and international levels. Study on legal and institutional reforms should be done to abolish jurisdictional overlapping and establish effective climate governance.

10.4. Community Engagement. Sustained community engagement is essential for the success of conservation efforts, but it requires addressing the immediate needs and concerns of local populations.

10.5. Seed Availability and Broodstock

- Overreliance on wild sources for fish seed poses a threat to biodiversity.
- Availability of broodstock and seed is essential, and for some species, dependence on wild broodstock, especially in the initial stages, may lead to unsustainable practices.

10.6. Cost and Availability of Feed

- Certain species, like tiger shrimp and carnivorous coastal finfish, require intensive feeding with high-quality live and supplementary food, increasing production costs, and the risk of diseases.
- The availability and cost of patent and live feed, crucial for successful mariculture, pose financial challenges.

10.7. Skills Gap

- While the government has resources for extension and training services, both public and private sectors lack well-established practical skills and technical knowledge for mariculture.
- Building human capacity in the private sector is essential for the sustainable development of the industry.

10.8. Market Dynamics

- Markets, both domestic and international, play a crucial role in the success of mariculture ventures. Understanding market limitations and dynamics is vital for planning and sustainability.

- Import dynamics must be considered, as it may be more cost-effective to import certain products than to produce them domestically.

10.9. Financial Considerations

- Limited financial and technical resources pose significant challenges to implementing adaptive strategies.
- Availability of finance is crucial for the growth of mariculture. However, past experiences of subsidies and enthusiastic promotion without thorough economic analysis can pose challenges.
- Proper sectoral and enterprise analysis is required to attract finance and mitigate risks.

10.10. Logistical Challenges

- Transport costs and inadequate internal delivery systems can hinder the distribution of mariculture products, particularly those with a low value/weight ratio.
- Accessibility to mariculture farms in specific regions, such as Cox's Bazar, Teknaf, Satkhira, and Sundarbans, poses logistical challenges.

10.11. Environmental Issues

- Intensive mariculture systems can be polluting, raising concerns about nutrient pollution, especially in semi-intensive shrimp farms.
- The use of high-quality fish protein and oil resources in feeds raises sustainability and environmental efficiency concerns.

10.12. Biosecurity Concerns

- Disease outbreaks, such as white spot syndrome virus and EMS pose significant risks to shrimp culture.
- The absence of domesticated broodstock and the exposure of wild broodstock to pathogens underscore the need for robust biosecurity measures.

10.13. Climate Change Impact

- The Sundarbans, a vital area for mariculture, faces challenges due to climate change, including cyclones and tidal surges.
- Climate change exacerbates environmental challenges, necessitating a scientific knowledge-based management approach.

In addressing these challenges, a holistic and scientifically informed management approach is crucial for the sustainable development of mariculture in Bangladesh. This should involve collaboration between the government, private sector, and various stakeholders to address environmental, economic, and social dimensions of mariculture development.

11. Conclusion

In conclusion, the Sundarbans stands as a unique and vital aquatic resource, serving as a crucial nursery ground for a diverse array of fin fish and shellfish species with transboundary significance. The expansive aquaculture habitats within this region hold immense potential for future contributions to food and nutrition security, export income, and employment opportunities. However, unlocking this potential necessitates a carefully crafted plan that acknowledges the interconnected interests of fisheries and aquaculture, grounded in robust scientific foundations.

To harness the benefits of the Sundarbans effectively, there is a pressing need for the development of a comprehensive and collaborative approach. This should involve the strengthening and activation of multistakeholder coastal zone management, aimed at the conservation and sustainable management of fisheries, the enhancement of aquatic and wetland biodiversity, and the judicious intensification of aquaculture practices. Moreover, proactive measures to monitor and mitigate environmental and societal impacts are imperative to ensure the responsible development of these critical ecosystems.

Balancing the coexistence of aquaculture and fishery within the delicate mangrove ecosystem is of paramount importance. The future trajectory should focus on optimizing the vast fertile area of the Sundarbans to enhance fish and shrimp production, thereby uplifting the livelihoods of the local communities. Strategic land zoning for different aquaculture products, adopting a landscape-based integrated approach to safeguard fisheries, and embracing technological advancements for sustainable and resilient aquaculture are key directions for the continued growth and improvement of fisheries and aquaculture in this ecologically significant region.

In essence, the Sundarbans present a promising opportunity for harmonious and sustainable development, emphasizing the intricate interplay between ecological well-being, economic prosperity, and societal welfare. By embracing a forward-looking strategy that integrates scientific insights and embraces collaborative management, the Sundarbans can emerge as a model for responsible and thriving fisheries and aquaculture practices.

Appendix A: Recent Initiatives in the Sundarbans by the Donors

Appendix A1: German Development Cooperation (GIZ). GIZ has been actively involved in sustainable development projects in Bangladesh. A recent study commissioned by GIZ focused on assessing the impact of climate change on fisheries in the Sundarbans. The study emphasizes the need for adaptive strategies to address changing environmental conditions.

Appendix A2: United States Agency for International Development (USAID). USAID's interventions in the

Sundarbans have centered on community-based fisheries management. A project initiated by USAID aimed to enhance the capacity of local communities for sustainable fisheries practices. The findings highlight community engagement as a key factor in successful fisheries management.

Appendix A3: European Union (EU). The European Union has supported a collaborative research project with local institutions to study the biodiversity of the Sundarbans. The research emphasizes the importance of preserving the unique aquatic ecosystems within the ECA and identifies potential threats to fisheries.

Appendix A4: UN Agencies, UN Agencies. Various United Nations agencies, including FAO and UNDP, have collaborated on a comprehensive assessment of aquaculture practices in the Sundarbans. The report discusses the socioeconomic impact of aquaculture and suggests policy recommendations for sustainable development.

Appendix A5: World Fish. World Fish, in collaboration with local partners, conducted a study on the potential of integrated multitrophic aquaculture in the Sundarbans. The study explores the feasibility of combining fish farming with other aquaculture practices to enhance environmental sustainability.

Appendix A6: Winrock International. Winrock International's initiatives in the Sundarbans focus on capacity building for sustainable fisheries management. Training programs have been conducted for local fishermen, emphasizing responsible fishing practices and resource conservation.

Appendix A7: Department for International Development (DFID). DFID has supported a project aimed at enhancing the resilience of coastal communities in the Sundarbans. The project includes measures to improve the adaptive capacity of fisherfolk in the face of climate change and other environmental challenges.

Appendix A8: International Union for Conservation of Nature (IUCN). IUCN has been actively involved in advocacy for the conservation of biodiversity in the Sundarbans. Recent studies commissioned by IUCN highlight the need for a holistic approach to fisheries management, considering both ecological and social dimensions.

Data Availability Statement

All data are available upon request from the corresponding author.

Ethics Statement

No ethical approval was needed for the study.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Khan Kamal Uddin Ahmed and Md Shariful Islam contributed equally.

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