hydrobiology

Review

Hydrobiology of Saline Agriculture Ecosystem: A Review of Scenario Change in South-West Region of Bangladesh

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Abstract: The aim of this review paper is to identify the production trends of shrimp and rice farming systems and associated hydrobiological parameters such as salinity in the coastal districts of Bangladesh. An intensive literature review has been conducted to explore salt stress-driven land use change, crop production, and changing ecosystem hydrobiology to adapt climate change impact from 2012–2022. The results indicate that a gradual extension of salt-driven land use and land cover (LULC) change has stressed agricultural production to a greater extent from 1973 to 2022 due to the high level of salinity. The unplanned expansion of shrimp culture is creating adverse consequences for the coastal ecosystem. Some suggestions have been proposed by analysing the mechanisms of crops' response to salt stress, including several physiological, biochemical, and molecular bases to mitigate the adverse effects of salinity on agricultural production. Alternatively, prawn, shrimp, and crab have similar or slightly higher economic outputs, except for the crop-based agricultural system, which is highly affected by salinity rise. However, due to low input costs, low maintenance, and less environmental impact, farmers are shifting towards crab fattening and thus changing the hydrobiology of coastal land use and land cover.

Keywords: climate change adaptation; resilience; crab farming; food security; land use land cover change (LULC); salinity; saline ecosystem; shrimp farming

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1. Introduction

Salinity rise is a complex process involving the coastal environment's meteorological, social, biological, and economic processes. Climate change concerning salinity has had varying implications in Bangladesh, including rising sea levels and an increase in unpredictable disaster events, all of which have substantial financial, ecological, and societal costs [1,2]. The people of Bangladesh are particularly vulnerable to the effects of climate change due to their geographical position and socioeconomic characteristics. Effective adaptation strategies will mitigate the negative consequences on livelihood, health, agriculture, and the environment, especially in coastal areas [3]. The Coastal Embankment Project of the early 1960s converted more than 1.2 million hectares of coastal land into farming systems in Bangladesh. A complex system of dams and drainage sluices was applied for this land conversion [4]. Approximately 32% of the country belongs to the coastal area, and more than 29% of the total population resides here [5]. The coastal south-west region is particularly vulnerable to growing salinity threats, due to natural and anthropogenic factors and climate-induced saline waterlogging [6,7]. Life and livelihoods based on the agriculture system suffer significantly, together with soil and groundwater deterioration, health issues, and long-standing effects on the ecosystem [6]. Soil data used in much research from the Soil Resource Development Institute (SRDI) has confirmed that due to insufficient flow from upstream rivers, seawater intrusion has increased soil salinity in coastal districts up to 15 km north of the coast. In the dry season, the salinity level has increased up to 160 km inland [6,8,9]. Hydrochemical analysis of monsoon season surface water indicated Ca-Mg-HCO_3 type (66%) and Na-Cl type (17.70%), while during the dry season, Na-Cl type water (52.27%) dominated, followed by Ca-Mg-HCO_3 (31.81%) in the south-west coastal districts of Bangladesh [9].

The upward stream-released alluvium deposited in the coastal areas becomes saline as seawater interacts with it, is inundated during high tide in the wet season (June–October), and enters seawater through the creeks. Tropical cyclones, tidal waves, and storm surges keep the coastal land inundated, and increased temperature accelerates evaporation and thus augments salinity. Moreover, the post-monsoon period (November to March) reduces the freshwater flow in the rivers and inland water bodies. Dam construction in the upstream rivers by neighbouring countries e.g., the Farakka barrage, has lessened the flow of freshwater, and consequently, seawater has intruded northwards. Saline water has been trapped through unplanned polder and embankment construction and management in the coastal areas. Furthermore, the unplanned and rapid shrimp cultivation expansion has further accelerated the salinity intrusion and changed the hydrobiological regime [10]. Salinity intrusion in the coastal districts of Bangladesh is primarily associated with geographical location, climate change-induced events such as temperature increase, evaporation, sea level rises, and decreased rainfall, and natural disasters such as storm surges and cyclones. Human interventions such as dam construction in upstream areas, unplanned or planned polder and embankment development, freshwater reduction, and shrimp cultivation as an adaptation measure to climate change have had significant negative impacts on the ecosystem(Figure 1).

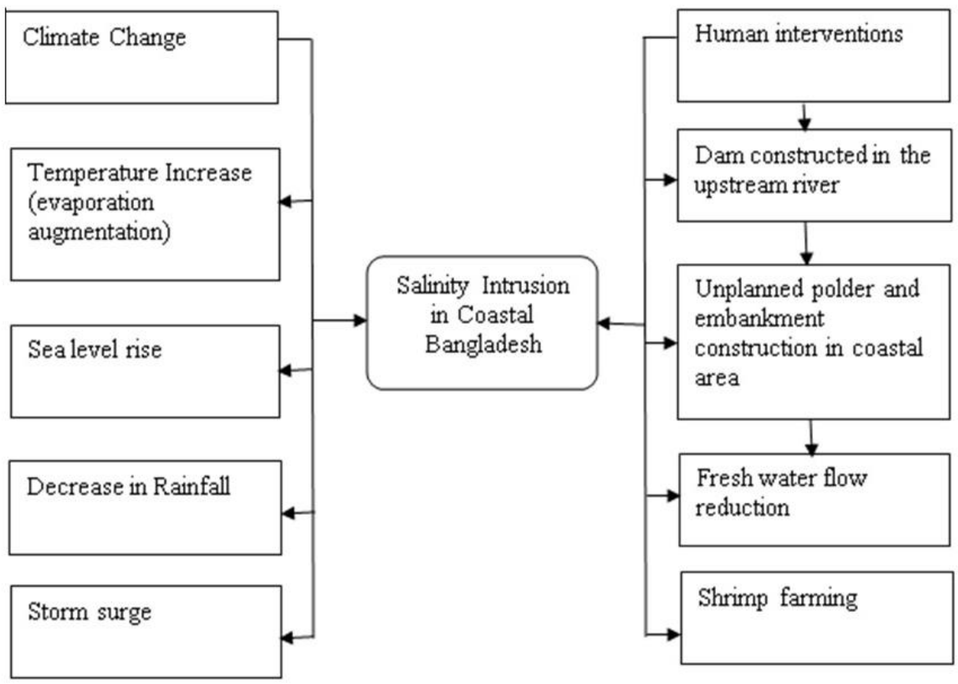

Figure 1. Pathway of salinity intrusion (Source: Modified from [10]).

Moreover, as salinity rises, shrimp monoculture has become a common global farming strategy. This practice attracts economically desirable foreign shrimp species, which endanger local shrimp populations and change ecosystem function. Anthropocene features of the global shoreline include shrimp species' planned introduction and redistribution [11]. Consequently, agricultural farming operations shifted while increasing natural enemies, worsening the shortage of irrigation water supply, and increasing harvest losses [12]. Furthermore, conventional wild fish collection in rivers and aquaculture systems, as well as ghers, ponds, and so on, is changing in terms of use and management complexity due to climate change and salinity. From 1989 to 2000, 62.9% of water bodies were intensified, which increased to 77% from 2000 to 2011. Between 2011 and 2015, satellite image analysis revealed that about 89% of the waterlogged areas contained tidal saline water for shrimp production [7]. Land usage and land cover (LULC) analysis is a tool for studying environmental deterioration and controlling unplanned growth. Analyzing the changing trend of LULC in the past and projecting future LULC gives a unique chance to explore and influence current and future land use policies in the coastal areas [13].

Bangladesh is predicted to become a developed and higher income country by 2041, according to the Second Perspective Plan (2021–2041), with a per capita income of almost USD 12,500 [14]. As a result, it is susceptible not just because of its biophysical qualities but also because of its social characteristics. Climate change sensitivity is vital in the central and western coasts, the north-western uplands, and along the main rivers, where significant biophysical and socioeconomic vulnerabilities are predicted [15].

It is also predicted that the coastal hydrobiological regime will change significantly as a result of the changing salinity dynamics. Hydrobiology is concerned with the biology of organisms as well as of limnology, or the science of inland waters [16]. The measurement and integration of hydrological and biological processes at the basin scale in inland coasts is predicated on the premise that abiotic forces such as salinity in the coastal zones are fundamental, and become stable and predictable when biotic interactions such as crop production and aquaculture materialize [17]. The quantification includes measuring the impacts of practices such as shrimp aquaculture in a water body and monitoring of point and non-point source pollution to manage processes toward sustainable ecosystem conservation and ecosystem service management often known as ecohydrology [17]. Nevertheless, the interaction between biota and physicochemical parameters of the water of the coastal ecosystem is the core concern. In this review article, we have covered articles regarding land use change from salt stress on lands that were depicted by the land usage and land cover (LULC) method, biological stress on crops at the molecular level, and changing ecosystem hydrobiology to adapt climate change impact [16]. This study further reviews the production trends of shrimp, crab, and rice farming systems, associated hydrobiological parameters such as soil and water salinity, and the saline ecosystem in the south-west coastal districts in Bangladesh. Finally, this investigation leads to an evidence-based assessment of a climate-resilient, locally led sustainable transition from shrimp farming to a safer method to continue food security in the south of Bangladesh.

2. Review Methodology

Bangladesh has a 710-km-long coastal area with three distinct regions: the south-western, central, and south-eastern coastal zones. An intensive and systematic review of the literature has been carried out to analyse the agricultural production and associated hydrobiological parameters in the coastal districts of Bangladesh (Figure 2). Our initial search keywords, "Coastal areas of Bangladesh", considered peer-reviewed journal articles in English from databases like Springer (n = 806), Elsevier (n = 1034), and Taylor and Francis (150) from 2012–2023. The articles were further screened using keywords such as agricultural production, shrimp culture, crop production, ecosystem, climate change, salinity intrusion, hydrobiology, biological stress on crops at the molecular level, climate change adaptation and mitigation, resilience, food security, and fisheries in the coastal region of Bangladesh. In addition, we searched Google Scholar and other grey materials. A total of

101 articles were finally considered for review, focusing on land use change from salt stress, biological stress on crops at the molecular level, and changing ecosystem hydrobiology to adapt climate change impact. All the articles were indexed in Endnote, and duplication was checked before review. Four authors worked simultaneously on the literature review, analysis, and extraction of the contents. Two authors worked independently on the content checking. The overall framework of the screening articles and review procedure is shown in Figure 3.

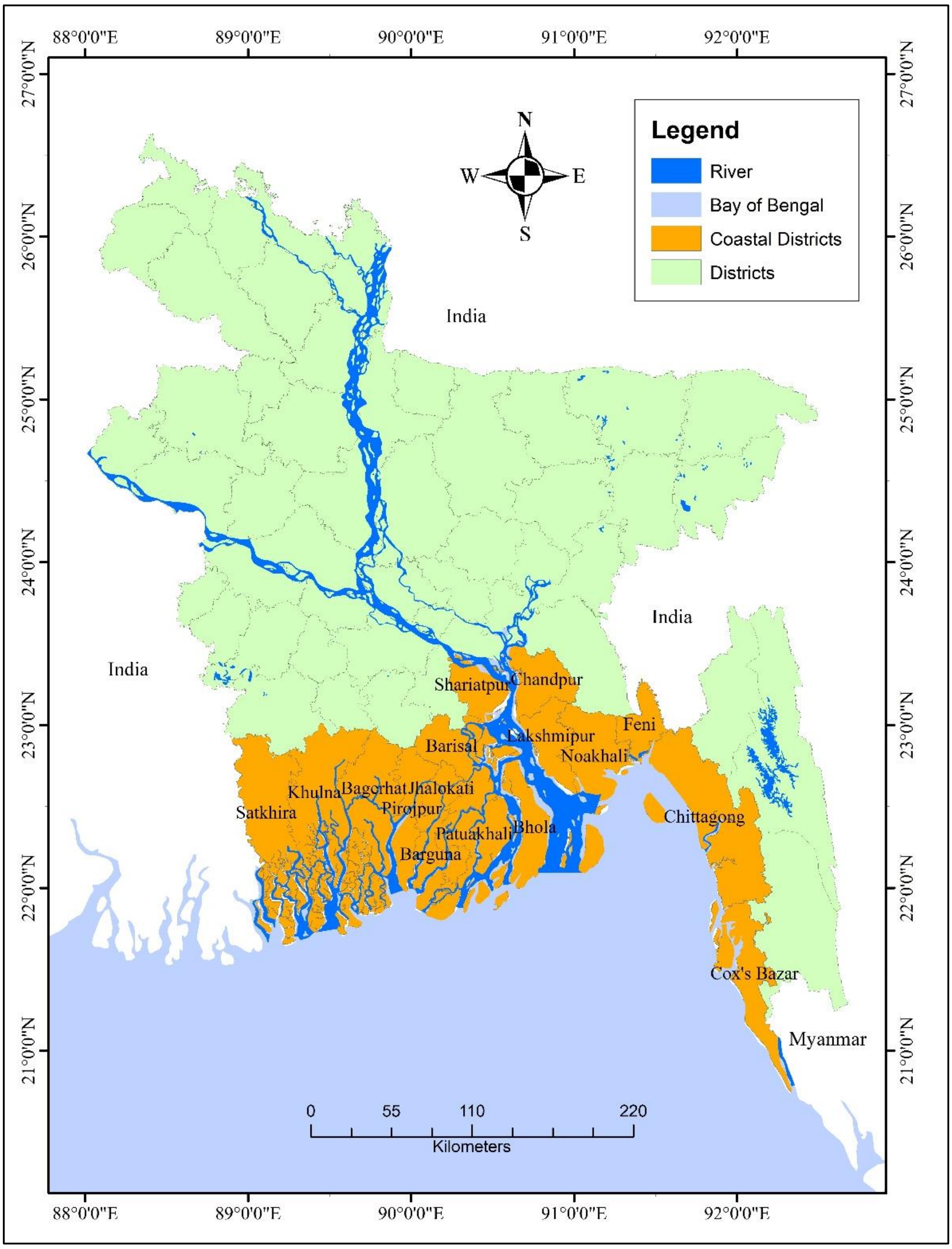

Figure 2. Map of coastal areas of Bangladesh (Source: Authors, 2023).

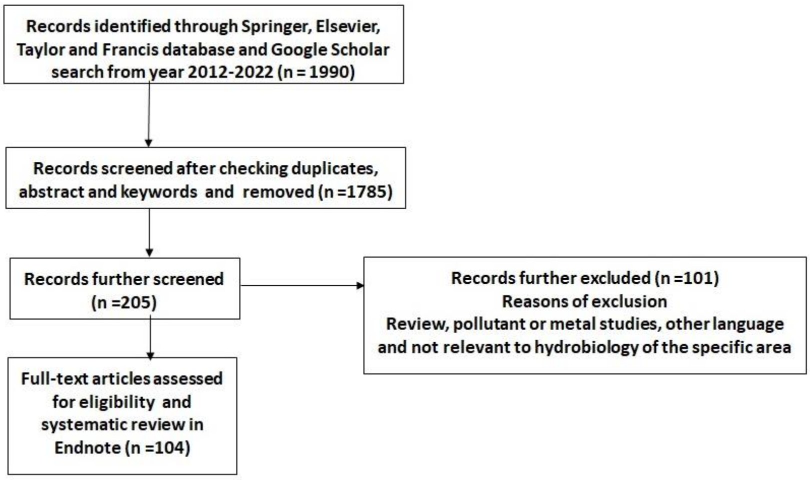

Figure 3. Review framework adopted for this study.

3. Increased Climate Change Effect and Anthropogenic Stress on the South-West Region of Bangladesh

Rising salinity is a significant concern in the coastal districts of Bangladesh. Climate change is predicted to exacerbate saltwater intrusion in coastal regions and coastal islands by increasing storm frequency and severity. Simultaneously, drainage blocks are expected to create havoc in coastal cities [18]. Figure 4 illustrates the degree of soil salinity in 1973, 2000, 2009, and 2022. More than 26.7% (0.223 million ha) of new land has been affected by salinity on different scales between 1973 and 2022. Around 96,566 ha of land have been affected by the severe level of salinity (16< ds/m). Moreover, 35,510 hectares of new land (3.5%) have been affected by varying salinity from 2000 to 2009 [19]. In 2022, more than 200 hectares of land were affected by a salinity level of 16 ds/m, while land with salinity levels 8.1–16 ds/m also rose up to 400 hectares in the coastal zones of Bangladesh [20].

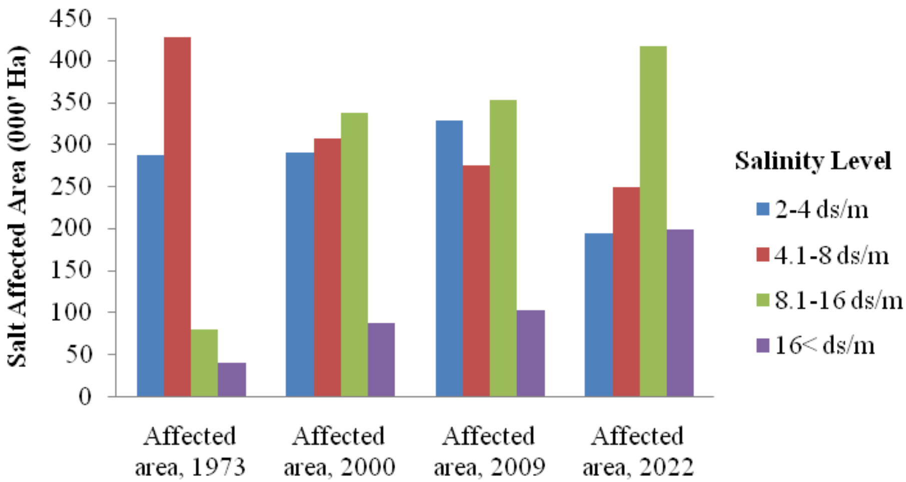

Figure 4. Saline-affected areas of the coastal region in 1973, 2000, 2009, and 2022.

Because of increasing salinity in soil and water, coastal agriculture is one of the most vulnerable sectors to climate variabilities such as temperature variations, rainfall patterns, floods, and droughts. Climate signals and dangers have put a large portion of the food production system at risk. Temperature variations appear to be causing phenological shifts (including higher night-time temperatures). Temperatures that surpass crucial limits for as little as one hour during blooming can have a significant impact on rice yields [21].

Higher temperatures may increase evaporation rates, which may increase by 10–20% by 2030, increasing crop diseases, pest attacks, and other problems in livestock, such as infections, pests, and vector-borne diseases. To deal with salinisation, additional groundwater is pumped into coastal aquifers, causing more saltwater to enter the groundwater system, causing a negative feedback loop [18]. According to recent research, rising salinity in rivers is projected to significantly impact the districts of Satkira, Jhalokati, Barisal, Pirojpur, Khulna, Barguna, Bhola, and Bagerhat. By 2050, the increase in soil salinity is anticipated to range from 26–55% in the most susceptible locations [22].

Rain-fed Aman rice (monsoon-winter), flooded Boro rice (winter), and Aus rice (summer) are the three major rice crops of Bangladesh [18]. Rice production employs 66% of the country's workforce and supplies 95% of the country's food grains. It also provides 63% of the country's calories for urban people and 71% of the country's calories for rural people. Climate change is expected to impede Aman rice production by increasing the frequency and severity of floods, while Boro rice cultivation is predicted to be hampered by limited surface water availability and groundwater depletion. It is forecast that by 2030 about 60% of rice-growing land will be affected by different seasonal droughts, alternating with increased rainfall and flooding in other areas. According to some sources, Bangladesh's total rice production will decline by about 8% by 2050 (compared with 1990). A cumulative loss of 80 million tons of rice between 2005 and 2050 is forecast, equivalent to two years' worth of rice lost over 45 years. The south is the most vulnerable: in the Khulna region, for instance, damage of 10% for Aus and Aman rice and 18% for Boro rice are expected in the 2050s, owing to rising sea levels. On average, saline flood-prone areas are more vulnerable to climate change [23].

The coastal region of Bangladesh is ecologically rich and composed of mangrove forests, tidal estuaries, and prolific agricultural land. However, salinity intrusion severely stresses agricultural production by creating special hydrological and environmental conditions throughout the year [24]. Salinisation in Bangladesh's coastal regions is the major hydrobiological characteristic that threatens the long-term growth of several sectors, such as agriculture, forestry, fisheries, livestock, and health. In response to salinisation, the hydrobiology of the aquatic agricultural systems and their surrounding livelihoods in the south-west region of Bangladesh has progressed in response to various biophysical stimuli, thresholds, and responses, including improved market availability and technical progress [25,26]. The farming systems on the coasts are very dynamic, with agriculture practice with a freshwater prawn-dominated system with low salinity, an intermediate-salinity mixed prawn and shrimp system, and a high-salinity shrimp-dominated system. Crop productivity, cropping intensity, and cost-effectiveness are best in the diverse low- to intermediate-salinity soil class, and lowest in the high-salinity soil class [26]. In the high-salinity soil class, agricultural crops cannot be produced. In addition, cropping intensity in the south-west region also increased from 135% in 1992 to 175% in 2018, identified by the LULC analysis [12]. Table 1 indicates the articles covering LULC and other methods of land conversion for shrimp cultivation. From the previous data on LULC change, it is evident that shrimp farming in coastal Bangladesh was trending and shrimp farming is Bangladesh's second-largest source of foreign income [27]. It is also the backbone of coastal aquaculture. However, coastal aquaculture is not without environmental impacts, which are reviewed in the following Sections 3.1 and 3.2.

Table 1. Satellite image analysis of land conversion trends in different studies.

Districts/Region	Change of Crop Cultivation		Land use Change Shrimp/Prawn Ghers/Ponds		Others	Method of Study	References
Satkhira Tala Upazila	-	-	0.7% of the study area (246 ha) was underwater in 1989	89% inundation by salt water inundation in 2015	64.4% reduction of fallow lands from 1989–2015	LULC analysis 1989–2015, FGD	[7]

Table 1. *Cont.*

Districts/Region	Change of Crop Cultivation		Land use Change Shrimp/Prawn Ghers/Ponds		Others	Method of Study	References
Khulna (Tildanga and Kamarkhola)	Paddy 37.2% in 1988	18% in 2017	ponds/waterbodies 16.5% in 1988	33.9% in 2017	-	LULC analysis 1988–2017	[28]
South-west coast	-	-	14,773 ton in 1986–1987	to140,261 ton in 2012–13	-	Production 1986–2012	[29]
South-west coast	Aman rice 47%	Aman 27%	Prawn 0.4%	Prawn 7%	Fallow land 30% in 1991 to 12% in 2018	Cropping intensity 1991–2018	[12]
	Boro 5%	Boro 22%	Shrimp 8%	Shrimp 17%	-		
	Aus 4%	Aus 2%	Non rice crop 6%	Non rice crop 11%	-		
Satkhira district	-	-	22% in 1990	38% in 2016	-	LULC analysis 1990–2016	[8]
Satkhira district (Assasuni Upazila)	-	-	21% bare lands transformed into Shrimp lands	25.9% increase in shrimp lands	-	LULC analysis 1989–2015	[13]
Coastal districts and islands	-	-	Aquaculture has increased by more than 100% by converting water bodies (61%) and fallow land (27%).	-	47% decrease of fallow land from 1990–2015	LULC analysis 1990–2015 and interview method	[30]

3.1. Environmental Impacts of Shrimp Aquaculture

With 0.276 million hectares already under brackish water shrimp production, Bangladesh has a considerable coastline tidal zone suited for shrimp farming [31]. Moreover, the development of Bangladesh's blue economy is deep-rooted in the advancement of shrimp aquaculture such as black tiger shrimp (Penaeus monodon), brown shrimp (Metapenaeus monoceros), Indian white shrimp (Penaeus indicus), mud crab (Scylla serata), white pomfret (Pampus argenteus), white mullet (Mugil curema), barramundi (Lates calcarifer), and so on [32–34]. Due to geographically low-lying tidal floodplains and the availability of natural postlarvae, coastal areas of Bangladesh initially prioritised brackish-water shrimp farming. The conventional cultivation method was used for the commercialised shrimp aquaculture systems in this region by trapping saltwater in more than 50 hectares without using much nutrient input [35]. Although Bangladesh's coastal agro-climate is favourable for shrimp and prawn cultivation, the accessibility of resources, as well as the ease and low cost of operations, drove the swift spread of shrimp aquaculture rather than prawn farming [29].

Moreover, because of the salinity and unfavourable habitat conditions, potential negative repercussions on fisheries have increased in the south-west coastal districts of Bangladesh. Between 1984 and 2014, typical salinisation rose more than six times, and in specific locations, 10 to 15 times [29]. From the shrimp ponds, saline water can enter the subsurface aquifers, causing groundwater salinisation and raising submarine groundwater outflow to coastal seas [36]. In south-west coastal Bangladesh, the swift transformation of croplands to shrimp farms triggered significant negative socio-ecological consequences on the coastal ecosystems, including changed land-use patterns [28,34,35]. Salinity intrusion caused by shrimp farming dramatically lowered agricultural and livestock productivity and eliminated several livelihood possibilities in the shrimp farming area [29].

The disease burden has also increased subsequently across all shrimp farms and has become increasingly polarised with fewer particular infections. White spot disease, produced by the white spot syndrome virus, causes widespread mortality and commercial losses in the shrimp industries across South and Southeast Asia [37,38]. Growers also described physical anomalies, nutritive deficiencies, and unidentified illnesses, indicating poor-quality stock. Despite a slight decrease in antimicrobials, shrimps were subjected to a broader spectrum of pollutants throughout cultivating period. In response, growers used more chemical treatments (5.2 remedial action/farm in 2008 versus 28.8 remedial action/farm in 2016), which resulted in a 424% increase in different active chemical compounds including antibiotics entering the shrimp ghers/ponds.

Consequently, a concern for human health and ecological well-being necessitates more investigation to discover possible dangers from the breakdown of chemical products [38]. The primary drivers of shrimp farming's negative consequences on the ecosystem are related to conventional farming practices, unsatisfactory planning for water management in the ghers, unsustainable seed supplies, irrigation infrastructures and so on [39]. Effective methods for preventing adverse environmental effects from shrimp aquaculture development are now required. Diverse scientific and indigenous knowledge is being used to deal with the changing hydrobiological regime.

3.2. Impact of Salt Stress on Crop Production

Salinity and shrimp farming are responsible for the deficiency of fresh and irrigation water on the coasts [6]. Intensive shrimp aquaculture has resulted in the extinction of fruit species and other indigenous flowering species, fresh and brackish water species, scarcity of safe drinking water, poverty, unemployment, social conflicts, unrest, and forced migration [28,33,39,40]. Furthermore, the threatened states of these systems have further created ecosystem conflicts with human health and socioeconomic factors [2]. Mangrove deterioration, biodiversity loss, sedimentation, saltwater intrusion, pollution, and disease outbreaks have all been cited as significant ecological impairments leading to unsustainable aquaculture practices. The prime crop of south-west coastal Bangladesh is rice, e.g., Aus, Aman, and Boro. However, high salinity discourages farmers from cultivating Aus rice [10]. It is predicted that the loss in Aus and Aman rice production will be 7580 tons and 19,620 tons by 2030 [41]. Around 15354.38 MT and 355.50 MT would reduce Boro rice and wheat production in 2100 against the base year 2010 [6]. Other crops like jute, sesame, groundnut, mustard, and winter vegetables are also being cultivated on a partial scale [10].

The climate change-driven rise in salinity has caused a radical production decline of major crops, e.g., cereals, potatoes, pulses, oilseeds, vegetables, species, and fruits. Various fruit trees, such as mango, betel nut, date palm, giant taro, jackfruit, blackberry, etc., are endangered significantly. A radical drop has been observed in the case of betel nut, papaya and banana. Yield loss in the coastal areas has been estimated to be nearly 1.4 million tons per annum, which is 20–40%. In addition, 24% of the inland native freshwater fishes are threatened, 19% are endangered, and 12% are already extinct in the coastal region [42], while 25% of shrimp and 10% of marine fish have disappeared due to high salinity [43].

Each year, salinity intrusion affects around 200 ha of grazing land or fodder crop areas. Therefore, livestock production in the coastal region suffers from food deficiency [42]. Salinity intrusion erodes the coastal zones' green belt and catalyses the increase in temperature, heavy showers, drought, etc. [10]. It was estimated that the ecosystem service value (ESV) of coastal agriculture dropped from 2.89 (US$ $\times$ 10^9/year) in 1980 to 1.48 (US$ $\times$ 10^9/year) in 2016 [44]. The significant impacts of rising salinity in the coastal hydrobiology of Bangladesh are summarised below in Figure 5.

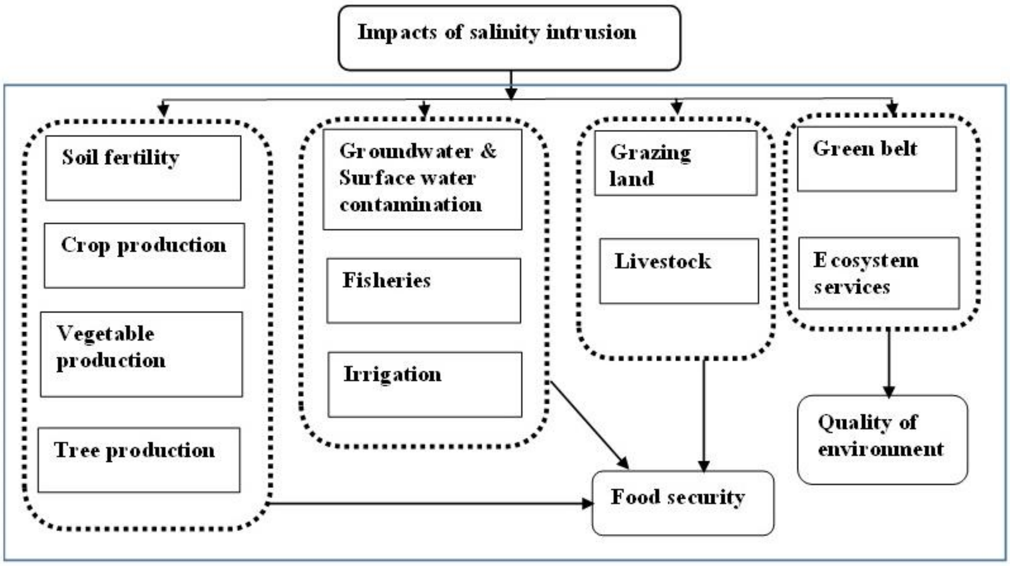

Figure 5. A summarized impact of salinity on crop production and the subsequent impact on food security (Source: Authors, 2022).

In dry seasons, soil salinity is a significant yield-limiting aspect of crop production [45,46]. Salt concentration in the soil increases in the dry season as the water evaporates, leaving a combination of stored salts in clay loam and groundwater capillary movement [47,48]. This recurrent occurrence in coastal zones affects around 63% (1,056,000 hectares) of farmed land [49]. As a result, soil salinity can considerably impede agricultural production, increasing vulnerability to food poverty and potentially affecting the lives of around 38.5 million coastal residents [50–52].

Alteration of salinity might decrease the yield and alter crop quality [53] by hampering photosynthesis, causing damage to stomata and chloroplast structure and leading to malfunctioning chlorophylls and enzymes [54]. Abnormal root-shoot formation in seedlings, and delayed flowering and fruiting patterns are observed from salt stress despite the presence of self-defence mechanisms in the plants [55]. Salt stress negatively affects seedlings' growth and ion contents, except for sodium (Na^+) ions. The high Na^+ and Cl^- ion concentration causes imbalanced cellular homeostasis and nutrient uptake, nutrient shortage, and oxidative stresses, followed by cell death [56,57]. Increased concentrations of Na^+ and Cl^- ions in the cell reduce water and nutrient uptake by lowering osmotic pressure in the nutrient-containing medium and drastically affect plant morphological traits [58,59].

The mechanisms of how crops react to salt pressure comprise several biological, biochemical, and molecular bases [60]. These responses could be classified into osmotic tolerance, ion exclusion, and tissue tolerance. Long-distance signals inhibit shoot development in osmotic tolerance, positively controlling the synthesis of suitable solutions to sustain leaf expansion and stomatal conductance [61]. The transportation of Na^+ can be excluded in the root zone to prevent the accumulation of the ion from reaching toxic levels in plant leaves. Na^+ could be trapped in the vacuoles despite having a high salt concentration in the leaves, causing the tissues to tolerate the salt stress. Proline and glycine betaine accumulation was reported in osmoprotectant mechanisms in maize [62,63]. Glycine betaine, a reactive oxygen species (ROS) scavenger, was found to be accumulated in wheat and responsible for hormone modulation [64].

The hereditary base of salt tolerance was also studied. Salt overlay sensitivity (SOS) homologs in rice (*Oryza sativa*) *OsSOS1*, CBL-interacting protein kinases *OsCIPK24*, and calcineurin B-like *OsCBL4* were reported to be involved in salt exclusion. In wheat (*Triticum aestivum*) *TaSOS1* and (*Triticum durum*) *TdSOS1*, and corn (*Zea mays*), Na^+/H^+ exchangers *ZmNHX7* were reported as Na^+/H^+ antiporters in maize [65]. The tonoplast-based *NHX* group sequestrated Na^+ in the vacuole. The overexpression of *OsNHX1* and *VIVIPAROUS1*-like *OsVP1* in rice could improve salinity tolerance. Similarly, several Na^+ sequestrator *NHX* genes were characterised in the vacuoles, including five *NHX* genes in rice (*OsNHX1* to *OsNHX5*), four in wheat (*TaNHX1*, *TaNHX2*, *TaNHX3*, and *TaNHX4-B*) and six in maize (*ZmNHX1* to *ZmNHX6*)[66]. High-affinity potassium (HAK) transporters also help to induce salt tolerance; 27 *HAK* genes in rice and maize and 56 in wheat were reported [67,68]. Besides ionic mechanisms, phytohormones such as abscisic acid, salicylic acid, and jasmonic acid also mediate salt tolerance in rice, wheat, and maize [63,69–71].

Designing salt-tolerant crop cultivars is vital in improving production on salty soils [72,73]. High-throughput phenotypic screening for recognising biotic or abiotic stress responses can capture variances in phenotypes which are not easily noticeable by the human eye, such as plant biomass, leaf area, water use efficiency, growth rate, or transpiration [74–77]. Salt-tolerant plants must adopt one or more characteristics, such as higher osmotic pressure, enhanced exclusion of ions such as Na^+ and Cl^- when present in excess, and compartmentalisation of Na^+ and Cl^- ions into cell organelles [78]. Some differently regulated genes directly protect plants from salt stress, whilst others activate multiple signalling pathways linked to variations in reactive oxygen species, lipid phosphatase, and cyclic nucleotides. Some salt-tolerant plants prohibit Na^+ and Cl^- from leaves by limiting them during uptake by root or during transportation from root to shoot, or plants accumulate compatible solutes in their cytoplasms, such as proline, glycine betaine, and polyamines, to osmotically balance the toxic ions sequestered in the vacuole [79].

A recent study revealed that soil plant analysis development (SPAD) value, plant height, shoot dry matter, panicle number per plant, filled/empty grain percentage, thousand grains' weight, grain yield, harvest index, and irrigation-water productivity of rice were significantly affected by water salinity [80]. Another study on the accumulation of primary and secondary nutrients in Indian spinach (*Basella alba*), papaya (*Carica papaya*), and okra (*Abelmoschus esculentus*) in the Barguna and Patuakhali districts revealed that the accumulation trend in these vegetables was Ca > Mg > P > K > S in saline areas. The study suggested papaya, Indian spinach, and okra as moderately saline-tolerant vegetable crops [81]. BARI Sarisha-18 (Canola) and BARI Sarisha-16 were found to be suitable for combining coastal cropping patterns in recent research on mustard varieties in Shatkhira, Koyra, and Bagerhat [82]. Several Bari varieties of tomatoes (BARI-T 1, BARI-T 2, BARI-T 3, BARI-T 4, and BARI-T 5) could not tolerate moderate salinity stress (>4 dS/m) and accumulated salt in the soils [83]. Further investigations and saline-tolerant varieties were recommended for improvement.

As a biotechnological approach, inoculating a salt-tolerant plant-growth-promoting bacteria (PGPB), namely *Brevibacterium sediminis*, offered a great advantage to combat salt stress in seedling growth of salt-tolerant BINA dhan-10 and salt-susceptible BRRI dhan-29 rice varieties [84]. The PGPB has remarkable impacts on ensuring normal growth and development of plants under salinity [85]. Many bacterial strains, such as *Bacillus* spp., *Pseudomonas* spp., *Frankia* spp., and *Rhizobia* spp. have been identified that are capable of aiding plants to tolerate various environmental stresses, including salinity [86]. Six ethyl methanesulfonate (EMS) mutagenised wheat lines originating from BARI Gom-25, a moderately salt-tolerant variety, were found promising in saline conditions based on K^+, Na^+, and Cl^- accumulation in leaves, water use index, 1000 seed weight, and phenotypic analysis [87]. Constant green manuring with dairy manure, biochar application, and balancing K^+ improve soil chemical characteristics on the coasts by lowering salinity, modifying pH, and increasing soil organic carbon, and accessible N and P [88–90]. Reducing salt stress on crops, therefore, requires balanced technological approaches blended with socio-environmental situation and political willingness. It also requires a shift in paradigm on economical and ecosystem perspectives for adopting various techniques.

3.3. Paradigm Shifting and Changing Ecosystem Services- Various Adaptation Techniques

Changing ecosystem services is another significant observation reviewed from the south-west region of Bangladesh. Conventional wild fish collection in rivers and aquaculture systems, such as ghers, ponds, and crab collection stations, is being transformed in terms of usage and management intensity, and is being influenced by climate change [91]. Compared with the previous decade (1999–2008), most farmers (95.5%) had to modify at least one of their farming operations from 2009–2018 onwards, triggered by climate change and shrimp aquaculture [92]. The detrimental consequences of shrimp farming as a climate change adaptation method have received little attention, even though the effects of climate change and shrimp farming have been thoroughly investigated. Existing policies are often thought to be more focused on making commercial fishing more resilient without considering that the adverse effects of traditional activities might worsen other social and economic problems. River water discharge (1500 to 2000 m^3/S), climate (28 °C), and soil salinity (4 to 10 dS/m) are biophysical limits that influence societal situations. If these thresholds are exceeded, the complex socio-ecological systems may soon lose resilience, increasing the chance of regime transitions [25].

There are primarily 12 crab species in Bangladesh. Giant mud crab (*Scylla serrata*) fattening was initiated as an adaptation plan in coastal regions [93]. Crab fattening, which had an export value of more than USD 37 million in the 1992–93 financial year, is very popular for various reasons such as low saline water (15 to 30 ppt), low cannibalism rate, accessibility to operations, and high demand in the national and international markets such as Singapore, Malaysia and Hong Kong, but also faces several problems such as a lack of credit return in time, little knowledge of crab biology, and poor marketing operations [34,94,95]. However, increments in crab fattening and harvesting in low salinity also surprised the shrimp production industry, which also makes valuable export earnings for Bangladesh, because crab fattening needs lower salinity than shrimp production, and has other factors such as a minimum wage, high production rate, etc. [96]. However, Satkhira, Khulna and Bagerhat are the three major districts where crab fattening is more prevalent than in other coastal areas, because the right level of salinity is one of the essential abiotic factors influencing the distribution, abundance, general physiology, survivability, and well-being of crustaceans [97]. The average river water salinity level was 8.21 ppt in the dry season and 0.64 ppt during the wet season in 1998–2000. However, in recent years, this level has increased to 22.6 ppt in the dry season and 12–16.7 ppt during the wet season. Water salinity of 12–16 ppt is ideal for shrimp farming. The orange mud crab (*Scylla olivacea*) demands salt levels ranging from 10 to 20 ppt, and became an incidental crop during shrimp and mixed salt-tolerant rice–fish farming. As an alternative livelihood, crab fattening has become an adaptive technique for coping with salt intrusion [98,99]. However, despite having a large coastal area, only a few sites such as Chittagong, Barishal, Noakhali, Satkhaina, Potuakhali, Kutubdia, and Sandwip are prevalent in three kinds of aquaculture, namely inland culture (821,923 hectares), inland capture (3,890,828 hectares), and marine water (11,881,300 hectares), and the production of crab, shrimp, prawn, finfish, and rice, due to higher demand in the international market, higher economic returns from small investments, lower operational costs, and favourable government policy [34,35]. The recently exploited integrated multi-trophic aquaculture (IMTA) models such as shrimp + crab, shrimp + fish, shrimp + sea cucumber, shrimp + jellyfish + clam, shrimp + crab + clam, shrimp + crab + clam + fish, and ridge trail white shrimp polyculture operate in a combination of saline–alkaline water. The model is tailored to fit local conditions and the organisms' characteristics. The eco-friendly IMTA culture models utilise pond culture resources to maximise output with little extra feed and labour inputs while lowering effluents and treatment costs [100]. Our literature review identifies agroecological systems' biophysical parameters (Table 2) suitable for shifting towards crab fattening and others that can be blended with the saline agriculture ecosystem.

Table 2. The biophysical and hydrobiological limits of agroecological systems in the south-west region of Bangladesh.

Ecosystem	Temp	Salinity	Remarks	Factors to consider	References
Agriculture	28 °C air	✓ 4dS/m (soil)	Decreased due to high salinity and climate change	Irrigation water unavailability, surface and groundwater salinity Saline-tolerant crop species	[26,92,101]
Fisheries	27–29 °C water	✓ 0–5 ppt (water)	Freshwater fisheries also decreased due to high salinity, climate change	Saline surface water, less profit	[26,92]
Shrimp	25–32 °C water	✓ 7.80–39 dS/m or between 10 to 20% salinity	✓ Diseases, Environmental degradation, social conflicts ✓ Cultivation decreased in Khulna and Chittagong	✓ High saline environment ✓ Operational facilities and poor quality control and quality assurances (QC & QA) ✓ Failure in export ✓ Less profit	[26,92,101]
Mud crab (*Scylla serrata*)	22–30 °C water	✓ Tolerate a wide range of salinity (3 to 35%), even still grows in 0% salinity but below the average productivity. ✓ 10‰–20‰ salinity is optimum for good production	✓ Increased cultivation in Cox's bazar and Satkhira ✓ hardy nature ✓ easy farming techniques ✓ low investment and production cost ✓ lower susceptibility to diseases ✓ women can participate ✓ eco-friendly ✓ integrated with horticulture, forestry, rice farming, finfish and shrimp species ✓ 3 weeks (fattening) to 6 months (grow-out adult) harvest time ✓ 2018–19—exported USD 42.9 million live and frozen crabs to 17 countries ✓ low-quality feed is acceptable ✓ comparatively minimum icing and processing than shrimp ✓ less competition with other species ✓ more resistance to adverse conditions ✓ Wasted crab shells require management but can be made into value-added products	✓ Seed supply ✓ Operational facilities ✓ QC & QA ✓ Wild seed collection ✓ Land use ✓ Infrastructure ✓ Soil quality ✓ Water sources ✓ Seed sources ✓ Market facilities ✓ Support services	[93,97,98,101–103]

3.4. Challenges and Opportunities of Saline Ecosystem

Due to sea level rise, salinity stress, incorporated with drought, heat, and waterlogging, is expected to rise during this century [104]. As a result, climate change is predicted to alter the viability and profitability of agricultural options and cropping patterns throughout the region, posing problems for farmers and their communities. Climate change forecasts imply that less diverse agricultural systems may face future problems [105]. Fish polyculture and agriculture, such as mixed rice–shrimp culture, mixed salt-based rice–crab blending, and salt-tolerant rice production can be adopted as an alternative to adapt to the economic uncertainty of climate change, and changing hydrobiology and ecosystem services [11,33,43,102]. Due to climate change, farmers are adopting various strategies such as mixed rice–shrimp production, mulching for vegetables, salt-tolerant rice verities, crab fattening, soil flushing, fishing from open marine water, changing crop patterns, harvesting rainwater, and using sand-pond filter systems for drinking water. Fish polyculture is a widespread practice in pond aquaculture, where different fish species are grown together to provide a multi-output production system. Fish polyculture may be an adaptation method to respond to environmental change in Bangladesh's south-west coastal area. Farmers in the coastal region increasingly employ fish polyculture practices to deal with the shifting scenario. The return from incorporating more than one species in shrimp ponds is reasonable and economically helpful for producers [33]. Table 3 indicates some techniques for adaptation in the rising saline ecosystem that were found economically viable.

Table 3. Adaptation techniques in the changing saline ecosystem.

Regions	Adaptation Methods	Assessment Types	References
Satkhira (Shyamnagar Upazila)	Fish polyculture	Economic assessment	[33]
Both south-east and south-west coast	Changes in farming systems	Random questionnaire survey and random forest classification model	[92]
South-west coast: Khulna, Bagerhat, and Satkhira	Adaptation pathways for salinisation	Random household interview, key informant interview and DPSIR analysis	[2]
Satkhira and Chittagong	Adaptation tipping points approach to investigate threshold yield loss	Semi-structured interview, key informant interview	[106]

Subsistence-orientated smallholder farmers in south-west Bangladesh's shrimp-producing districts widely use crop diversification strategies in response to adverse environmental changes and crop failure concerns. Farmers have planted less rice in the dry season, with salinity-related yield loss being the primary cause. Due to yield losses, most rice farmers anticipate they will cease planting rice this season. On the other hand, shrimp and salt farmers have already curtailed rice production for the same reason and turned to shrimp and salt farming because they believe these businesses are more profitable and need less labour than rice growing [106]. Cultivating several crops (including rice, non-rice crops, shrimp/fish, vegetables, and animals) in different combinations throughout the year may be a sustainable agricultural adaptation since it reduces economic and environmental risks. It may also encourage women's engagement in subsistence agricultural activities such as household gardening and cattle keeping [35]. The economic advantages of adopting rice–prawn aquaculture, replanting rice, and salt tolerant and short-duration rice types have been discovered to outweigh the other adaptation alternatives. Investing USD 10 in such adaption options yields a net return of USD 22, USD 4, USD 2, and USD 2, respectively [1]. Despite higher production costs, prawn-based systems generated net income nearly three times higher (USD 3410 to 4470) than shrimp-based systems (USD 1570 to 1790) because dyke crops added about 25% extra income [29,107]. The prawn–rice farming system generates diverse job possibilities and a substantial increase in agricultural crop yield. On the other hand, mud crab production had variable and total expenses of USD 4293 and USD 6104, respectively. The net return was USD 4418/hectare, and the benefit–cost ratio (BCR) was 1.72, which is similar to the shrimp-based system [94,98].

The coastal bio-physical and socio-economic factors change the LULC and modify the socio-ecological system significantly in Bangladesh, which has been reviewed in this article [4]. It is therefore evident that the strategic integration of policies, plans, and programmes should be developed for the protection of hydrobiological regimes in the coastal zones of Bangladesh. Although prawn, shrimp, and crab have similar or slightly higher economic output, due to low input costs, low maintenance and less environmental impacts, farmers are shifting towards crab fattening. Crablets, feed, and bamboo fences (known locally as bana) all increased output in crab fattening. Based on the review, we have drawn up a conceptual model suitable for the hydrobiological regime of coastal Bangladesh. The farming system changes and changing aquaculture systems can be modified to suit the environment and climate change adaptation based on the solution of nature-based local resources (Figure 6). Salt-tolerant gene modification for diversified crop species can be adopted, developed, and trialled by the local institutes. In addition, research and development should be focused on multi-trophic aquaculture and fish polyculture ponds. The government should provide critical guidelines integrating aquaculture, agriculture, and farming management to improve the hydrobiological regime of the coastal zones of Bangladesh.

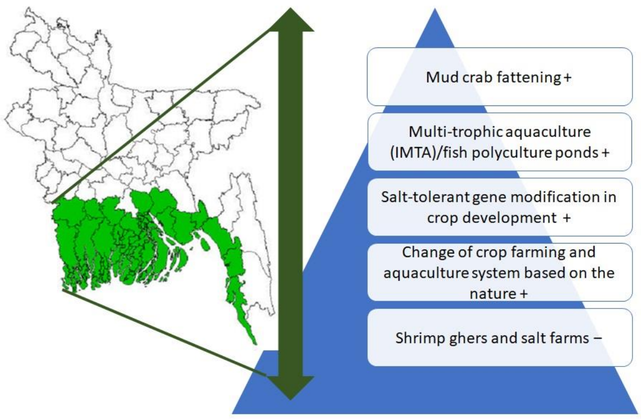

Figure 6. A conceptual model for changing aquaculture and farming systems modified to suit the environment and climate change adaptation based on a solution of nature-based local resources. + means a positive environmental impact while − means a broadly negative environmental impact.

4. Concluding Remarks

To explore salt stress-driven land use change, biological stress on crop production, and changing ecosystem hydrobiology to adapt climate change impacts, an intensive literature review has been conducted. In 2022, soil salinity assessment shows that more than 200 hectares of coastal land were affected by a salinity level of 16 ds/m, while land with salinity levels 8.1–16 ds/m also rose to 400 hectares in Bangladesh. The steady expansion of salt-driven land use change puts a higher strain on agricultural productivity. The uncontrolled expansion of shrimp cultivation is harming the coastal ecology. Some proposals for mitigating the negative impacts of salinity on agricultural productivity have been given by analysing the processes of crops' reaction to salt stress, which include numerous physiological, biochemical, and molecular bases. To combat the current climate change-induced salinity intrusion, several adaptation measures are recommended, including changing agricultural practices, integrated multi-trophic aquaculture, crop diversification, and ridge trail white shrimp polyculture in a combination of saline–alkaline water, and further investigation and promotion of ecosystem services. Although prawn, shrimp, and crab have similar or slightly higher economic outputs, due to low input costs, low maintenance, and fewer environmental impacts, farmers are shifting towards crab fattening. The farming system changes and changing aquaculture systems can be modified to suit the environment and climate change adaptation based on a solution of nature-based local resources.

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