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Review

Can “Integrated Multi-Trophic Aquaculture (IMTA)” adapt to climate change in coastal Bangladesh?

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ABSTRACT

The coastal aquaculture sector in Bangladesh is dominated by export-oriented freshwater prawn and saltwater shrimp farming. However, the culture of prawn and shrimp in coastal Bangladesh has been accompanied by recent concerns over climate change. Different climatic variables, including cyclone, drought, flood, rainfall, salinity, sea level rise, and sea surface temperature have had adverse effects on prawn and shrimp production. Considering vulnerability to the effects of climate change on coastal aquaculture, one of the adaptation strategies is “Integrated Multi-Trophic Aquaculture (IMTA)”. Open-water IMTA in coastal Bangladesh would be a novel process of growing different finfish and shellfish with seaweeds in an integrated farm. IMTA is considered an ecosystem approach adaptation strategy to climate change which could generate environmental and economic benefits. We suggest institutional support to facilitate IMTA in coastal Bangladesh.

Contents

1. Introduction

Bangladesh is one of the most suitable countries in the world for coastal aquaculture because of its favorable biophysical resources and agro-climatic conditions. Its coastal aquaculture sector is dominated by export-oriented freshwater prawn (*Macrobrachium*

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rosenbergii) and saltwater shrimp (*Penaeus monodon*) farming,[1] both known as "white gold" because of their export value (Islam, 2009; Ahmed, 2013). The coastal aquaculture sector has become a multimillion dollar industry in Bangladesh due to huge demand for prawn and shrimp in global markets, particularly the European Union and the United States of America (USA). In 2014–2015,[2] Bangladesh earned US$506 million from exporting prawn and shrimp (FRSS, 2016). Thus, prawn and shrimp farming play an important role in the economy of Bangladesh.

Despite economic benefits, the culture of prawn and shrimp in coastal Bangladesh has recently been threatened by climate change that could have severe effects on export earnings and further consequences for the economy of Bangladesh (Ahmed, 2013; Ahmed et al., 2014; Ahmed and Diana, 2015a, 2015b). According to the Global Climate Risk Index, Bangladesh was ranked 1st in 2012 among countries vulnerable to climate change while it is ranked 6th in 2016 (Harmeling and Eckstein, 2012; Kreft et al., 2015). Considering vulnerability of social-ecological systems in coastal Bangladesh to the effects of climate change on prawn and shrimp farming, adaptation strategies must be developed. Adapting coastal aquaculture to climate change will require a combination of strategies and policies.

One of the adaptation strategies to climate change is "Integrated Multi-Trophic Aquaculture (IMTA)" (Sreejariya et al., 2011; Chung et al., 2013; Geere, 2014; Clements and Chopin, 2016). IMTA is a process of growing different species of finfish and shellfish with seaweeds from different trophic levels in an integrated farm. IMTA is a practice in which the by-products from one species are recycled to become inputs (feed, nutrients) for another. The principle of IMTA is the co-cultivation of fed fish, organic extractive species, and inorganic extractive species (Troell et al., 2009; Chopin, 2011; Chopin et al., 2012). The concept of IMTA is to create balanced systems for environmental sustainability, economic viability, and social acceptability (Barrington et al., 2009). IMTA is currently operated in over 40 countries on experimental and commercial basis, including Canada, Chile, China, Japan, the USA, and many European countries (Chopin, 2011). In Bangladesh, IMTA has taken recent consideration for research and development to diversify production (Sarker et al., 2014; Kibria, 2016).

This review paper illustrates the impacts of climate change on coastal aquaculture in Bangladesh. Considering the effects of climate change on coastal aquaculture, this article identifies the opportunities and challenges for the development of IMTA in coastal Bangladesh. The aim of this paper is to highlight key issues in developing IMTA as an adaptation strategy to climate change.

2. Coastal Bangladesh: land of multiple disasters

Bangladesh is one of the most disaster-prone countries in the world because of its geographical location (Fig. 1). Bangladesh is considered as "nature's laboratory on disasters" due to existing most climatic threats. Coastal Bangladesh is subject to seasonal changes in climatic conditions. The increasing risk from a combination of climatic variables, including: (1) cyclone, (2) drought, (3) flood, (4) rainfall, (5) salinity, (6) sea level rise, and (7) sea surface temperature (Ahmed et al., 2013; Ahmed and Diana, 2015a, 2015b).

The entire coastal zone in Bangladesh is prone to violent storms and tropical cyclones which originate in the Indian Ocean and track through the Bay of Bengal. Between 1877 and 1995, Bangladesh was hit by 154 cyclones, including 43 severe cyclones (Dasgupta et al., 2014a). On average, a severe cyclone hits the country every three years (GoB, 2009). A cyclone in 1970 and 1991 resulted in the death of around 300,000 and 138,000 people, respectively. In November 2007, coastal Bangladesh was hit by tropical cyclone Sidr with economic losses of US$1.67 billion (DMB, 2010). In recent years, cyclone Aila, Bijli, Giri, Mahasen, and Nargis devastated coastal life in Bangladesh. The intensity of cyclones has recently increased by 5–10% (FPMU, 2013).

The typical weather of coastal Bangladesh is characterized by drought in the dry season. During the last 50 years, Bangladesh faced 19 droughts (Habiba et al., 2012). Drought in Bangladesh can be divided into agricultural, hydrological, meteorological, seasonal, and socioeconomic drought (Ramamasy and Baas, 2007). Seasonal droughts are common in coastal Bangladesh and the frequency of seasonal droughts has recently increased due to climate change. Drought is linked with lack of precipitation and global warming (Trenberth, 2005). An El Niño[3] event with global warming in the tropical Pacific Ocean can turn the monsoon into a dry mode, causing considerable reductions in precipitation with the possibility of drought (Dai et al., 2004; Conway and Waage, 2010).

Bangladesh is a flood-prone country and one-fifth of the country is normally flooded annually. Since 1980, Bangladesh encountered six extreme floods with over 35% of the country inundated (GoB, 2009). Global warming, monsoon rainfall, higher river discharge, and tidal surges from the Bay of Bengal intensify coastal flooding. It is predicted that average temperature in Bangladesh is likely to increase 1.4 °C by 2050 and 2.4 °C by 2100 (Shahid, 2012). A 2 °C increase in temperature could increase 29% of inundated area in Bangladesh (Mirza, 2011). With over 700 rivers[4] including 57 transboundary rivers, Bangladesh has little or no control over river flooding. Around 14.6 million people in coastal Bangladesh are vulnerable to flood, and this number will increase to 18.5 million by 2050 (World Bank, 2012).

Bangladesh falls in the region of massive rainfall as the country is located in the monsoon belt with the Bay of Bengal in the south and the Himalayas in the north. Annual rainfall in Bangladesh varies from 1400 to 4300 mm (Shahid, 2010). Climate change has profound effects on rainfall intensity and variability, and monsoon rainfall is predicted to intensify about 10–15% by 2030 (Jakobsen et al., 2005). There is a direct influence of global warming on changes in precipitation as the water holding capacity of air increases 6–7% for every 1 °C raise in temperature (Trenberth, 2005). Global warming and increased surface temperature of the Bay of Bengal have altered wind patterns leading to enhanced precipitation. The mean annual rainfall in Bangladesh increased at a rate of 5.52 mm between 1958 and 2007 (Shahid, 2010).

Seawater intrusion is a growing problem in coastal Bangladesh. Saltwater from the Bay of Bengal has entered over 100 km inland (Allison et al., 2003; DMB, 2010). Salinity has recently increased in coastal rivers to 4 ppt in the monsoon and 13 ppt in the dry season (Khan et al., 2011). Sea level rise, cyclones with tidal surges, and upstream removal of freshwater are likely to play a vital role in increasing salinity of coastal Bangladesh (Dasgupta et al., 2014a). About 1.05 million ha of land in coastal Bangladesh has affected by saltwater (FPMU, 2013), and two million ha of land are anticipated to be affected by 2050 (Conway and Waage, 2010). Increased soil salinity is expected to decline 15.6% of rice yield by 2050 in coastal Bangladesh (Dasgupta et al., 2014b).

[1] Prawn is a freshwater species while shrimp for marine and saltwater organism. However, prawn is a catadromous species that hatch or born in marine habitats and migrate to freshwater areas.

[2] Bangladesh fiscal year: 1 July–30 June.

[3] El Niño is the warm phase of the El Niño Southern Oscillation, refers to the cycle of warm temperatures that occurs across the tropical Pacific Ocean.

[4] Bangladesh is often called a "land of rivers".

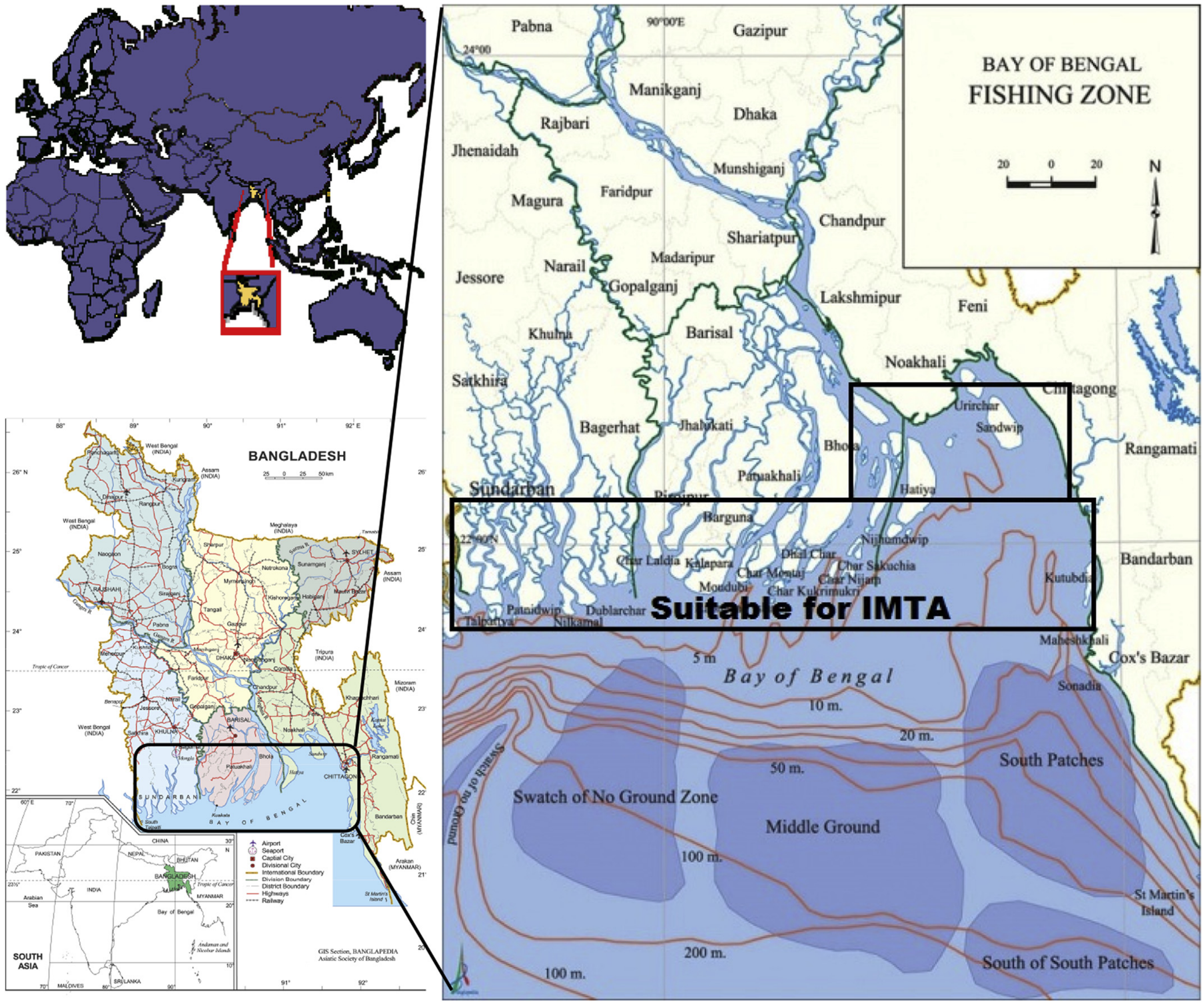

Fig. 1. Geographical location of Bangladesh, showing coastal areas vulnerable to climate change, which could be suitable for IMTA that may adapt to climate change.

Bangladesh is one of the major deltas in the world and the country lies just less than 2 m above sea level (Schiermeier, 2014). Bangladesh has a 710 km long coastline (DoF, 2016), and coastal Bangladesh is a focal zone for sea level rise due to global warming and glacier melting (Singh, 2001). Sea level may be rising by 15.9–17.2 mm each year in Bangladesh (Pethick and Orford, 2013), while global sea level rises 2–3 mm each year (Schiermeier, 2014). A 45 cm rise in sea level would inundate 11% of Bangladesh that will create millions of people homeless and they will become "climate refugees" (Mirza, 2011). Sea level could rise 1 m by 2100 (Rahmstorf, 2007), and such a rise would eliminate the Sundarbans[5] mangrove forest. Sea level rise is expected to inundate 120,000 km^2 of coastal Bangladesh (FPMU, 2013).

Sea surface temperature in the Bay of Bengal is growing rapidly than in the global oceans. Global sea surface temperature is about 1 °C more now than 140 years ago (Dailidienė et al., 2011). Sea surface temperature in the Bay of Bengal increased from 0.20 to 0.46 °C at day and 0.30–0.48 °C at night between 1985 and 2009. Sea surface temperature in the Bay of Bengal is expected to increase from 0.35 to 0.72 °C at day and 0.50–0.80 °C at night by 2050 (Chowdhury et al., 2012). Fish are sensitive to water temperature and small increases in temperature may have sub-lethal effects on tropical fish (Ficke et al., 2007). Increased sea surface temperature in the Bay of Bengal is likely to affect 3.5 million households of fishers due to declining fish populations (Chowdhury et al., 2012).

3. Coastal aquaculture and climate change: pain and gain

3.1. Revolutionary development of coastal aquaculture

As part of agricultural development in coastal Bangladesh, prawn and shrimp farming were initiated in the 1970s and began to expand rapidly in the 1980s. Since the 1980s, prawn and shrimp

[5] The Sundarbans, a transboundary mangrove forest, which is the largest continuous mangrove forest in the world, located along the mouth of the Bay of Bengal between Bangladesh and India.

culture have undergone a revolutionary development in coastal Bangladesh (Azad et al., 2009; Ahmed, 2013). Thousands of farmers have converted their low-lying rice fields to prawn and shrimp farms, locally known as "*gher*". The practice of prawn and shrimp intercropping[6] with fish in rice fields was reinforced by high prices for prawn and shrimp in the international market, and the benefits derivable from rice and fish for household consumption and sale in local markets. The combination of these factors has led to an increasing number of farmers engaging in this traditionally-based innovative coastal integrated culture (Ahmed et al., 2010a). Over 833,000 farmers are involved in prawn and shrimp production from 275,583 ha area in coastal Bangladesh (DoF, 2014; FRSS, 2016). Moreover, a significant number of coastal poor are associated with prawn and shrimp harvesting, marketing, processing, and exporting (Islam, 2008a, 2008b). In addition, the livelihoods of over 400,000 coastal poor including women are involved in prawn and shrimp postlarvae[7] fishing (Ahmed et al., 2010b).

Prawn and shrimp culture production has gradually increased from 82,661 tons in 2004–2005 to 126,077 tons in 2014–2015, an average annual growth rate of 6% over the last decade (DoF, 2016; FRSS, 2016). However, marine catch and export of prawn and shrimp have not increased at a similar rate (Fig. 2). The inland catch of prawn and shrimp has even gradually declined over the last decade, highlighting the importance of coastal aquaculture. In 2014–2015, Bangladesh exported 44,278 tons of prawn and shrimp valued at US$506 million (FRSS, 2016). Overall, the coastal aquaculture sector plays an important role in the economy of Bangladesh through food production, livelihood opportunities, income of farming households, and export earnings (Ahmed, 2013).

3.2. Impacts of climate change on coastal aquaculture

The further development of coastal aquaculture requires environmental sustainability. In recent years, however, climate change has had dramatic effects on coastal aquaculture in Bangladesh (Ahmed et al., 2014; Ahmed and Diana, 2015a, 2015b). Different climatic variables including cyclone, drought, flood, rainfall, salinity, sea level rise, and sea surface temperature have profound effects on the ecosystems of prawn and shrimp farms (Fig. 3). All of these climatic variables have adverse effects on prawn and shrimp production.

Coastal aquaculture is extremely vulnerable to cyclones with tidal surges. Cyclones devastate prawn and shrimp farms as most cyclones occur during the peak season of coastal aquaculture. Drought is also a major environmental constraint on coastal aquaculture since it reduces water availability to grow prawn and shrimp. Coastal aquaculture is vulnerable to floods as farmers often lose their total harvest of prawn and shrimp. Rainfall variation can also cause havoc on coastal aquaculture due to increased risk of flood and drought. Moreover, rainfall variation affects water salinity and temperature. Increased water salinity leads to change in the ecosystems of prawn and shrimp farms. Sea level rise is likely to have dramatic effects on low-lying prawn and shrimp farms. Last, but not least, increased water temperature affects survival, growth, and production of prawn and shrimp (Ahmed, 2013; Ahmed and Diana, 2015a, 2015b). Future climate change would have severe consequences for prawn and shrimp production in coastal Bangladesh.

[6] Prawn and shrimp mixed culture is rare in coastal Bangladesh due to habitat differences as prawn grows in freshwater while shrimp grows in saltwater.

[7] Postlarvae usually apply to animals from the time of metamorphosis up to about 60 days later. Postlarvae and fry are often interchangeably used.

4. Adaptation strategy to climate change: IMTA

4.1. Culture species

In coastal Bangladesh, IMTA would be a novel process of growing different fed fish (shrimp, finfish) and shellfish with seaweeds in an integrated farm (Fig. 4). In IMTA systems, fed fish can be placed at the upper and middle trophic levels while organic extractive species (mussels) at the middle and bottom level so that they can consume particulate organic nutrients (waste feed and faeces). Seaweeds could be placed a little far away of fed and organic extractive species so that they can consume dissolved inorganic wastes, including ammonia, phosphorus, and nitrates (Barrington et al., 2009; Troell et al., 2009; Chopin et al., 2012).

In the context of coastal Bangladesh, species selection for IMTA should consider biophysical resources, grow-out operation, and capital investments. Moreover, the culture species in IMTA should be socially acceptable, economically viable, and environmentally-friendly. Participatory approaches for adopting IMTA in social-ecological systems along the Bangladesh coast are needed. Semi-intensive culture systems can be followed for IMTA operation to avoid water pollution, parasite infestations, and disease outbreaks.

As prawn and shrimp are common coastal aquaculture species in Bangladesh, both species could be selected for IMTA. Although both are able to adapt a range of salinities, shrimp is more suitable than prawn in IMTA as prawn grows in freshwater while shrimp grows in saltwater. A variety of finfish including bass, catfish, and tilapia could also be incorporated in IMTA. The culture of tilapia with shrimp is possible in saltwater as tilapia can adapt to changing climatic conditions (Lowe et al., 2012). In IMTA systems, tilapia and shrimp can utilize different niches as tilapia can filter plankton in the upper water column, whereas shrimp can graze on the bottom substrate (Fitzsimmons, 2001), thus avoiding competition for feed and space.

Although mollusk culture has not yet become popular in Bangladesh, a variety of mollusk species including mussels and oysters could be incorporated in IMTA as organic extractive species or deposit-feeding invertebrates. Blue mussel (*Mytilus edulis*) and filter-feeding oyster (*Crassostrea gigas*) are available in coastal Bangladesh, and suitable for IMTA. The culture of mussels and shrimp is more suited to the warmer climate, as for instance in the southern USA (Barrington et al., 2009).

There is a huge potential for seaweed culture in Bangladesh as the country is rich with a variety of seaweed genera, including *Caulerpa, Enteromorpha, Gelidiella, Gelidium, Halymenia, Hydroclathrus, Hypnea,* and *Sargassum* (Ahmed and Taparhudee, 2005). However, the seaweed industry in Bangladesh is an initial stage. Nevertheless, seaweed culture in IMTA is promising in coastal Bangladesh due to suitable habitats. Seaweeds can grow in complex environmental conditions with changes in salinity and temperature (Harley et al., 2012).

4.2. Designing IMTA

In coastal Bangladesh, an effectively designed IMTA needs to consider water habitats, including inland, near the coast, and offshore (Table 1). System design should also focus on the efficient allocation of water resources. IMTA could be operated in freshwater, brackishwater or saltwater conditions. Moreover, IMTA could be operated in conditions ranging from closed to open-water in coastal Bangladesh.

IMTA in closed-water may face environmental constraints in coastal Bangladesh, including water pollution, siltation, and high mortality of fish which in turn affect lower productivity as well as profitability. Moreover, IMTA in shallow water will face technical

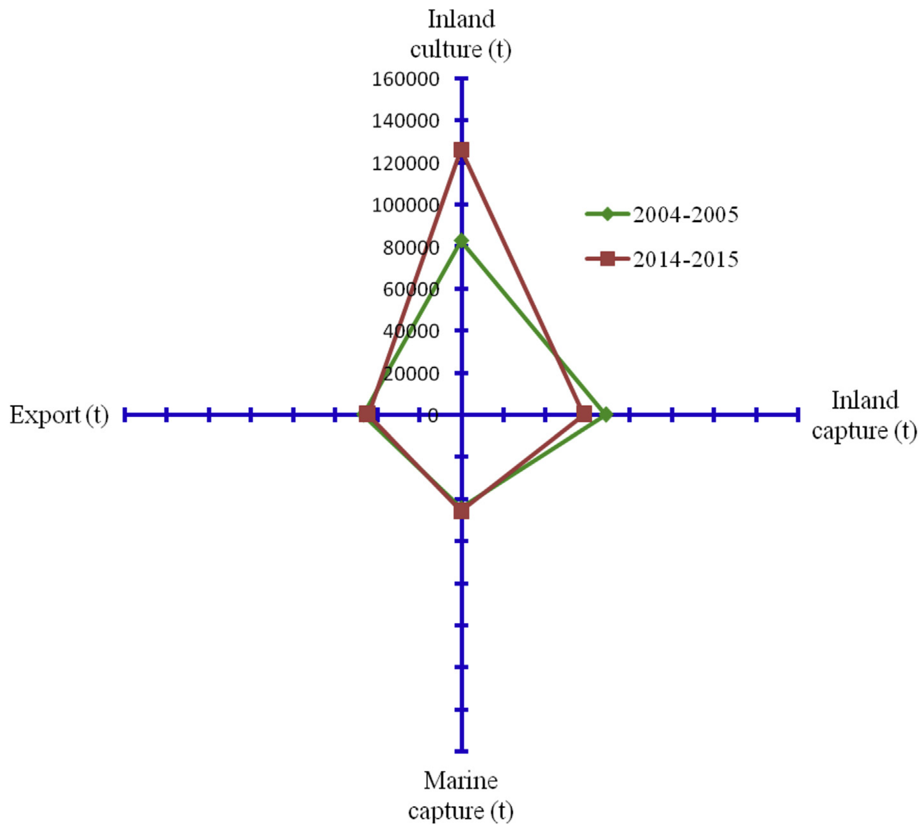

Fig. 2. Total prawn and shrimp production from inland and marine waters with export over the last decade (source: DoF, 2016; FRSS, 2016).

problems due to lower water levels. Similarly, IMTA in offshore may confront technological challenges as structural and operational components (cage materials with stocking and feeding regimes) of IMTA depend on social and economic factors. Moreover, offshore IMTA will face severe environmental problems, including the placement of different species in close proximity to water currents due to its operation in ocean-like conditions (Klinger and Naylor, 2012).

However, there are tremendous opportunities for the efficient utilization of coastal open-waters through IMTA (Table 1). The carrying capacities of coastal rivers and estuaries are not fully utilized as annual fish yield is only 205 kg/ha in Bangladesh (FRSS, 2016). There is great scope for increasing seafood production from these water resources through IMTA (Fig. 1). The integrity of IMTA means that coastal rivers and estuaries can be utilized socially just and sustainably by "linking aquaculture and fisheries". Hatchery-produced stocking operations in coastal aquaculture can help to restore declined wild fish populations through stock enhancement (Bell et al., 2006). However, user conflicts and equity issues may arise for access to coastal waters as they are considered "common-pool resources". Nevertheless, community-based fisheries management can be an option to manage water resources (Sultana and Thompson, 2007).

4.3. IMTA: resilience to climate change

IMTA is considered an ecosystem approach adaptation strategy to climate change (IFAD, 2014). Coastal open-water IMTA could play an important role in strengthening the resilience of social-ecological systems to climate change. Cage culture has already been introduced in rivers of Bangladesh to adapt climate change (Shelton, 2014). IMTA could increase the range of response and adaptation options to climate change in coastal Bangladesh (Table 2).

Land-based prawn and shrimp farms in coastal Bangladesh have been affected by climate change that reduces O_2 production and increases CO_2 emissions (Ahmed and Diana, 2015a, 2015b). Open-water IMTA can increase O_2 production by photosynthesis of seaweeds. Moreover, IMTA can reduce O_2 consumption by microorganism decomposition of organic matter as a result of biofiltration (Sreejariya et al., 2011). Dissolved O_2 from seaweeds may help to increase microbial activities within the sediments, which in turn allow nutrients to be efficiently recycled from dead organisms (Björk et al., 2008). IMTA can also play an important role in reducing CO_2 emissions as seaweeds absorb CO_2 for photosynthesis. Seaweeds in IMTA can act as blue carbon[8] sink (Chung et al., 2013). Moreover, shellfish can sequester carbon in their shells (Wolff and Beaumont, 2011). Blue carbon sequestration can contribute to mitigation of climate change (Mcleod et al., 2011; Duarte et al., 2013; Siikamäki et al., 2013).

IMTA can adapt to changes in water salinity as mussels, seaweeds, shrimp, and tilapia are able to tolerate wide range of salinity. Similarly, IMTA can adapt to increased water temperature due to filtration of waste particulate by shellfish and seaweeds which in turn avoid subsequent mineralization and higher water temperature (Sreejariya et al., 2011). Seaweeds in IMTA systems can help to keep water cool due to absorption of pollutants, sediments, and toxic substances (Chung et al., 2013).

[8] Blue carbon is the organic carbon stored, sequestered, and released from coastal ecosystems of mangroves, salt marshes, and seagrasses (Siikamäki et al., 2012). Other forms of carbon are dust particles "black carbon", fossil fuels "brown carbon", and terrestrial ecosystems "green carbon" (Nellemann et al., 2009).

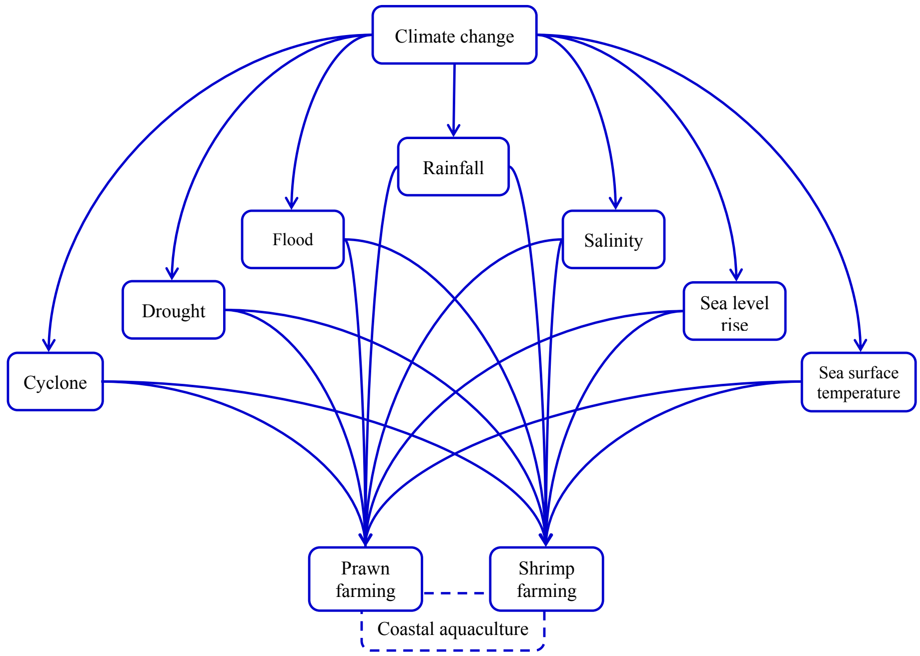

Fig. 3. Impacts of climate change on prawn and shrimp farming in coastal Bangladesh.

Table 1
Designing IMTA based on water habitat and type.

Water habitat	Water type	IMTA: system response
Coastal closed-water (*gher*, pond)	Freshwater/brackishwater	• Concern with socioeconomic and environmental aspects • Affect by different climatic variables • Inadequate water depth with poor water quality • Prevalence of parasites and diseases
Coastal open-water (estuary, river)	Brackishwater	• Resilience to climate change • Moving from closed-water to open-water ecological management of aquaculture • Efficient utilization of coastal open-waters for diverse intercropping production • Community-based fisheries management for access to water
Offshore (sea)	Seawater	• Technological challenges • Concern with social acceptability • Economic viability may uncertain • Environmental risks

Water quality of land-based prawn and shrimp farms in coastal Bangladesh is often affected by flood (Ahmed and Diana, 2015a, 2015b). Nevertheless, filter-feeders and seaweeds in open-water IMTA can withstand deteriorating water quality by removing suspended particles (Sreejariya et al., 2011). Seaweeds in IMTA can clear the water as they have the capacities for sediment trapping and binding (Björk et al., 2008). Clearing water can help penetration light into water for seaweed growth, production, and photosynthetic activities (Harley et al., 2012). Transparent water in IMTA can enhance ecological interactions among biotic and abiotic components (Troell et al., 2009).

IMTA in coastal open-waters may not be affected by flood, sea level rise, and freshwater scarcity as a result of drought and rainfall variation. Open-water IMTA can maintain water quality (Largo et al., 2016), and thus, reduce parasite infestations and disease outbreaks by water currents. Moreover, mussels and seaweeds in IMTA can remove nutrients which in turn reduce the growth of pathogens and toxic algae (Sreejariya et al., 2011). IMTA systems absorb excess nutrients, and thus, reduce eutrophication. IMTA with finfish and shellfish can remove up to 54% of particulate nutrients (Reid et al., 2010), and seaweeds can remove up to 60% of dissolved nitrogen and phosphorus (Huo et al., 2012).

5. Future prospects of IMTA

5.1. Environmental benefits

The development of IMTA in coastal Bangladesh could bring a wide range of environmental benefits, which in turn may help to tackle climate change (Fig. 5). IMTA would reduce ecological effects on natural resources as the adoption of IMTA in coastal Bangladesh can be an approach for biodiversity conservation and ecosystem services. IMTA could offer a balanced ecosystem approach that will benefit the environment and society (Chopin, 2011).

Shrimp culture in open-water IMTA can be environmentally-friendly while land-based shrimp farming has adverse impacts on biodiversity, ecosystems, and society (Primavera, 1997, 2006; Hall et al., 2011). Shrimp culture in coastal Bangladesh has devastating effects on mangrove forests (Paul and Vogl, 2011; Ahmed, 2013). Over 9700 ha of mangroves in Bangladesh were converted to shrimp farms (Shahid and Islam, 2002; EJF, 2004). Translocation of shrimp culture from mangroves to open-water IMTA can help to protect mangroves through plantation, regeneration, and avoiding deforestation. Mangrove plantation and regeneration would help to increase resilience to climate change through protection of cyclones, floods, erosion, sea level rise, and tidal surges (Alongi, 2008; Huxham et al., 2010; Duarte et al., 2013). Mangrove plantation and

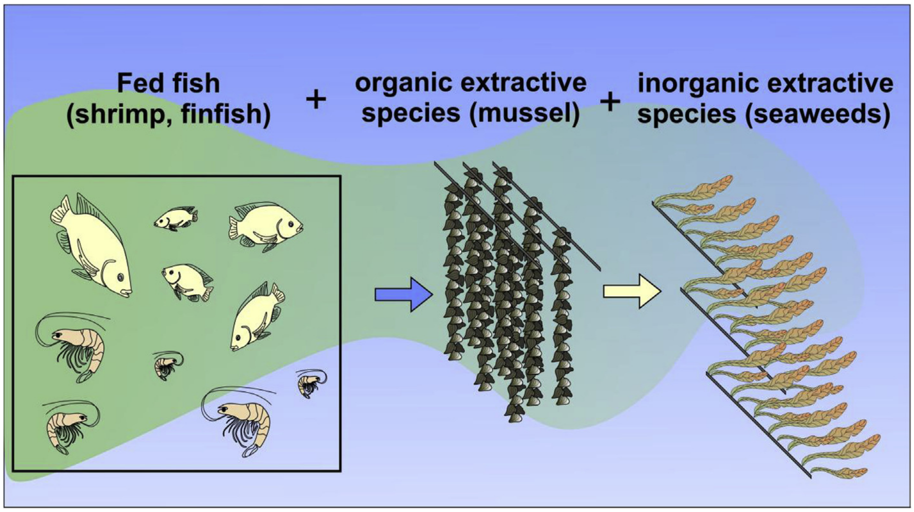

Fig. 4. Proposed IMTA for adoption in coastal Bangladesh.

regeneration has been instrumental in maintaining ecosystems and conserving biodiversity of the Sundarbans, which could provide a wide range of ecosystem services (Hoq, 2008; Roy and Alam, 2012). Mangrove forests have long been recognized for the conservation of biodiversity for many ecologically and commercially important species, including crabs, fish, mussels, and oysters, and provide habitats for many species of amphibians, birds, crustaceans, and mammals (Mumby et al., 2004; FAO, 2007). Biologically rich mangrove ecosystems provide important goods and services that support human well-being, including livelihoods, income, and food security (Glaser, 2003; Walters et al., 2008; UNEP, 2014).

Mangrove restoration would help to reduce ecological footprints as mangroves act as blue carbon sink (Nellemann et al., 2009; Mcleod et al., 2011; Siikamäki et al., 2012; Alongi, 2014). Translocation of shrimp culture from mangroves to open-water IMTA could reduce blue carbon emissions which would in turn increase the storage of blue carbon through restoration of mangroves. It is well recognized that carbon emissions are contributing to global climate change (IPCC, 2014). To tackle climate change, it is important to conserve mangrove forests for increasing its role in sequestering blue carbon (Donato et al., 2011; Houghton, 2012; Alongi, 2014). Conservation of mangroves can help carbon offsets by payments for mangrove ecosystem services (Locatelli et al., 2014).

Open-water IMTA can reduce intensive fishing pressure from capture fisheries in coastal Bangladesh. IMTA could be placed in intensive fishing areas that may reduce trawl net and set bag net fishing. Currently there are 243 trawlers and 40,824 set bag nets operational in coastal Bangladesh (FRSS, 2016). Trawl fishing has been identified as one of the most destructive fishing practices (Clark et al., 2016). Trawl fishing has devastating effects on seagrasses as bottom trawling destroys shoots and rhizomes of seagrasses (Murray et al., 2011). Moreover, set bag nets are used for fishing of wild prawn and shrimp postlarvae with high levels of bycatch that has severe impacts on biodiversity and ecosystems (Ahmed and Troell, 2010). Set bag net fisheries have also dramatic effects on the shallow coastal ecosystems of the Bay of Bengal (Nabi and Ullah, 2012). Open-water IMTA may create an obstacle to destructive fishing which in turn would help to restore coastal ecosystems. IMTA may also help to restore seagrasses that could enhance coastal and marine ecosystems for blue carbon sequestration (Greiner et al., 2013). Eventually, IMTA in coastal Bangladesh would increase the availability of wild fish, and thus, fish catch. IMTA can increase biodiversity at aquaculture sites (Clements and Chopin, 2016), which in turn enhances the resilience of coastal ecosystems (Worm et al., 2006; Levin and Lubchenco, 2008).

5.2. Economic growth

IMTA could be an option for adding economic value to open-waters in coastal Bangladesh. IMTA can increase profitability and

Table 2
Impacts of climate change on coastal aquaculture with its responses by IMTA.

Climatic variable	Impact on land-based coastal aquaculture	Response by coastal open-water IMTA
Cyclone, drought, flood, rainfall, salinity, sea level rise, and sea surface temperature	• Reduce photosynthesis, decline O_2, limit primary productivity	• Seaweeds in IMTA produce O_2 by photosynthesis
	• CO_2 emissions, low water pH, increase waste metabolites	• Seaweeds absorb CO_2 and shellfish sequester carbon in their shells
	• Changes in water salinity and habitat pattern	• IMTA deals with euryhaline species that tolerate wide range of salinity
	• Changes in water temperature, hinder ecological interactions	• Seaweeds and shellfish can withstand water temperature through biofiltration
	• Deteriorate water quality by pollutants, water turbidity, erosion, and sedimentation	• Seaweeds and shellfish make clear water by accumulating pollutants, sediments, and suspended particles
	• Reduce water level and decline fish habitat by drought and rainfall variation	• Coastal open-water IMTA may not affect by drought and rainfall variation
	• Inundation of ponds, prevalence of parasites and diseases	• IMTA may not affect by flood and sea level rise; reduce parasite infections and disease outbreaks by maintaining water quality

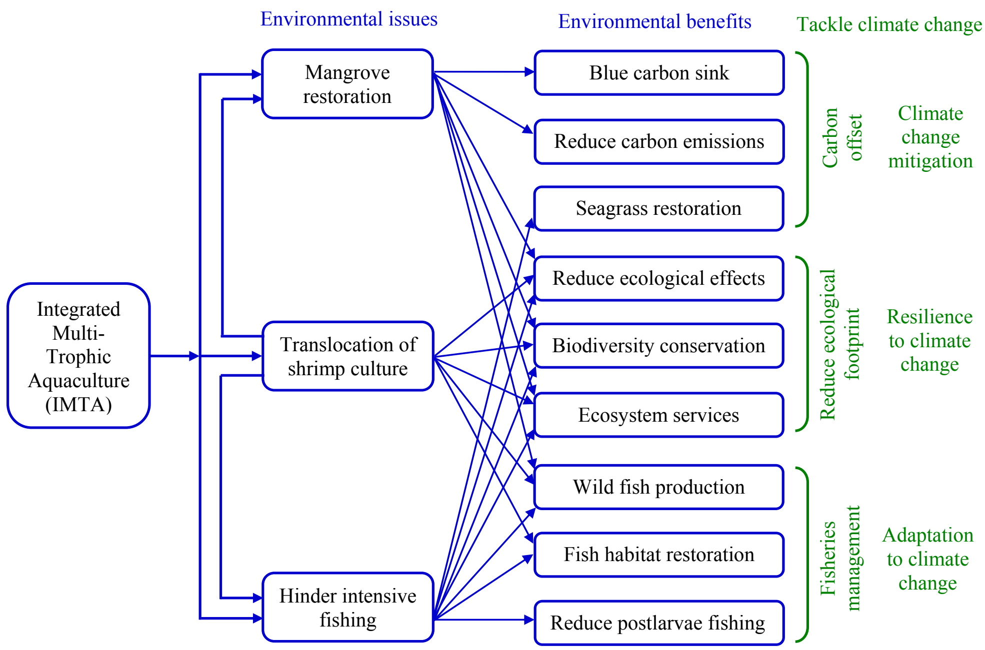

Fig. 5. Environmental benefits from open-water IMTA which in turn could help to tackle climate change in coastal Bangladesh.

reduce risks through crop diversification and production in different seasons (Chopin et al., 2012). After discussion with stakeholders (government fisheries officers, policymakers, and researchers), it is estimated that around 21,000 ha of coastal rivers and estuaries are suitable for IMTA in Bangladesh.[9] If shrimp farming with finfish, mussels, and seaweeds expanded to 10% of this potential area, the country would obtain an additional 730.8 tons of shrimp annually (Table 3). Similarly, Bangladesh would get an additional 743.4 tons of fish per annum. Eventually, mussel and seaweed production would obtain 39,900 and 18,900 tons per annum, respectively. Bangladesh could earn an additional US$8.04 million annually through exporting shrimp. Similarly, Bangladesh could earn an additional US$40.19 million annually if IMTA expanded to 50% of the potential area. Further export earnings are possible if seaweed market to be established. Seaweed culture is vibrant in many Asian countries (e.g., China, Indonesia, and Japan) due to export potentials for food additives with medicinal and nutritional values (FAO, 2016).

The export earnings of IMTA can make a significant contribution to overall economic growth and poverty alleviation in Bangladesh. The productive use of coastal open-waters through IMTA may provide additional income and employment opportunities for coastal poor. In addition, there appears to be considerable potential for improving food supply and nutritional benefits by IMTA, if appropriate inclusive common pool models for IMTA can be developed. Care must be taken not to oust coastal poor from current *de facto* open access waters which their livelihoods depend on. IMTA has the potential to provide a wide range of socioeconomic benefits in Galicia, Spain (Guerrero and Cremades, 2012). The development of IMTA can support the blue economy in Indonesia (Sugama and Radiarta, 2014).

[9] Total river and estuary area in Bangladesh is 853,863 ha (FRSS, 2016), of which one-fourth (213,466 ha) could be coastal open-waters. According to discussion with relevant stakeholders, about 10% of coastal open-waters (21,000 ha) may be suitable for IMTA. Around 30 stakeholders were conducted through interviews during November 2015–January 2016.

6. Challenges for IMTA

In spite of potential benefits and adaptation to climate change, the development of IMTA in coastal Bangladesh could face various social, economic, technological, and environmental challenges. IMTA is a rather new feature of the aquaculture industry in Bangladesh, and thus, social acceptability is a prerequisite for its development (Barrington et al., 2010). The adoption of IMTA in coastal Bangladesh could face various social conflicts including theft, robbery, and vandalism, and thus, negative perception towards IMTA development. Nevertheless, evidence exists from around the world about social acceptability of IMTA (Ridler et al., 2007).

The development of IMTA in coastal Bangladesh may be influenced by its economic viability. However, the economic viability of IMTA is still uncertain that will need to be ascertained (Klinger and Naylor, 2012). Various economic factors, including high production costs, market adaptability, and consumer acceptance may raise concerns over the development of IMTA in coastal Bangladesh. The cost of aquaculture operation has increased significantly in recent years as a result of the increasing costs of inputs (seed, feed) (Ahmed and Diana, 2015a). Moreover, the price of IMTA structure with its open-water placement may costly. Although export markets for Bangladeshi shrimp have grown in volume and value over the decades, a good reputation for quality will need to be maintained. Consumers in export markets are willing to pay a premium for quality products (Roheim et al., 2011). Consumer acceptability of IMTA products could be sold with eco-labels that may enhance profitability (Chopin, 2011; Klinger and Naylor, 2012).

Technical knowledge, including understanding and managing water currents are key concerns for IMTA placement in coastal Bangladesh as IMTA relies on water currents to move nutrient-rich water from fed species to extractive species (Klinger and Naylor, 2012). The placement of IMTA could affect tidal waters as coastal currents can be variable, depending on the location and season (Soto, 2009). Nevertheless, further technological innovation with better coastal modeling could help IMTA placement (Klinger and

Table 3
Potential for food production and export earnings from IMTA in coastal Bangladesh.

Potential IMTA area (ha)	Convert to IMTA[a] (%)	Area for IMTA (ha)	Shrimp yield[b] (kg/ha/yr)	Total shrimp yield (t/yr)	Fish yield[b] (kg/ha/yr)	Total fish yield (t/yr)	Mussel yield[c] (kg/ha/yr)	Total mussel yield (t/yr)	Seaweed yield[d] (kg/ha/yr)	Total seaweed yield (t/yr)	Shrimp export price[b] (US$/kg)	Shrimp export earning (million US$/yr)
	10	2100		730.8		743.4		39,900		18,900		8.04
	20	4200		1461.6		1486.8		79,800		37,800		16.08
21,000	30	6300	348	2192.4	354	2230.2	19,000	119,700	9000	56,700	11	24.12
	40	8400		2923.2		2973.6		159,600		75,600		32.16
	50	10,500		3654.0		3717.0		199,500		94,500		40.19

[a] Initially 10% of potential area could be converted to IMTA and gradually expand more.
[b] Shrimp and fish yields with export price are from FRSS (2016).
[c] Mussel yield is from Nunes et al. (2011).
[d] Dry weight seaweed production is from Zhou et al. (2006).

Naylor, 2012). Valuing local environmental conditions and human innovations may help the development of IMTA in coastal Bangladesh (Diana et al., 2013).

IMTA operation in coastal Bangladesh may be accompanied by a range of environmental constrain. Fishing of wild species to stock IMTA operations may cause the depletion of wild fish populations (Ahmed and Troell, 2010). The close placement of various species in IMTA can also intensify pathogen exposure, and thus, pose health risk to consumers (Klinger and Naylor, 2012). Moreover, disease affected IMTA species may lead to disease and parasite transmission to wild fish populations (Toranzo et al., 2005; Krkošek et al., 2007). Nevertheless, IMTA is a balanced ecosystem management approach that takes into consideration the operational limits for environmental benefits (Troell et al., 2009).

In spite of various challenges, the potential for IMTA in coastal Bangladesh is positive but requires institutional support to deal with social, economic, technical, and environmental processes. A number of institutional factors could help for sustainable development of IMTA, including extension service, training program, technical assistance, and credit support (Fig. 6). Extension service can disseminate practical knowledge on IMTA in a systematic and participatory manner. Farmer-to-farmer extension service with printed materials including booklets, leaflets, manuals, and posters can help to improve the conceptual skills in IMTA. Training on biological experiments of IMTA through demonstration and pilot projects is likely to be the most successful way of technology transfer. Community-based participatory group training on IMTA is also helpful. Technical assistance in breeding, fry nursing, fish rearing, harvesting, and processing is also needed for IMTA development in coastal Bangladesh. The Department of Fisheries (DoF) with relevant non-governmental organizations (NGOs) may give particular attention for providing extension service, training, and technical assistance. Credit may be one of the policy mechanisms to facilitate IMTA in coastal Bangladesh. National banks and NGOs should provide credit at reasonable interest rates for IMTA development. Bangladesh has success in inclusive approaches including microcredit,[10] rural bank, and social business to rural development (Yunus et al., 2010), which need to be called upon so that IMTA can be developed in coastal Bangladesh.

7. Conclusions

The coastal aquaculture sector in Bangladesh is particularly vulnerable to climate change. Different climatic variables, including cyclone, drought, flood, rainfall, salinity, sea level rise, and sea surface temperature have had adverse effects on land-based prawn and shrimp farming. Open-water IMTA could be developed to cope with the challenges of vulnerability to the effects of climate change on coastal aquaculture. There are great opportunities for the development of IMTA in coastal Bangladesh as an ecosystem approach for adapting to climate change.

The prospects for the development of IMTA in coastal Bangladesh are positive due to environmental and economic benefits. The adoption of IMTA in coastal Bangladesh could reduce ecological effects of shrimp culture on the Sundarbans mangrove forest as well as reduce pressure from capture fisheries. IMTA in coastal Bangladesh has great potential for increasing food production, income, and livelihood opportunities. It could also increase export earnings and economic growth of the country.

The development of IMTA in coastal Bangladesh, however,

[10] The *Grameen* Bank - a specialized rural bank providing microcredit that was awarded the Nobel Peace Prize in 2006.

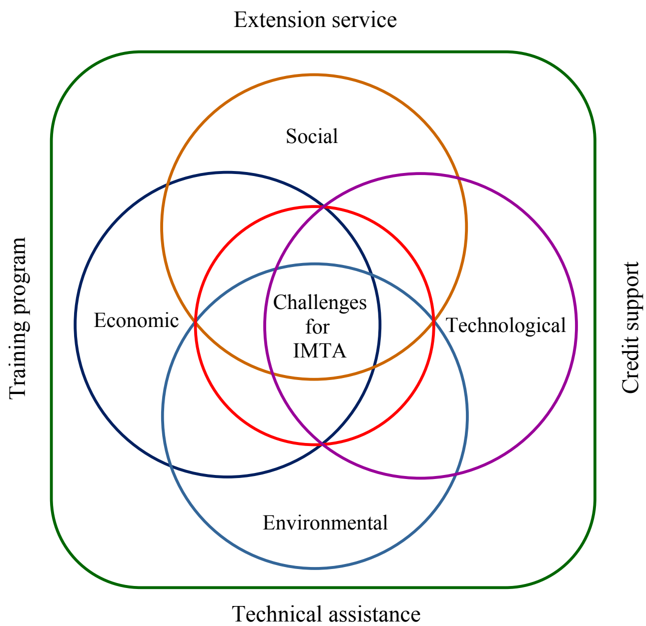

Fig. 6. A conceptual framework to overcome various challenges for the development of IMTA in coastal Bangladesh through institutional support.

requires institutional support. A number of institutional interventions, including extension service, training program, technical assistance, and credit support are essential for developing IMTA in coastal Bangladesh. The DoF with the help of relevant NGOs may give particular attention for providing institutional support. Government, NGOs, private sectors, and coastal communities must also work together for its development plan. The initial development of IMTA in coastal Bangladesh can be planned on a pilot basis. The development of IMTA may also need mapping of potential coastal areas. More research and development work is also needed for better understanding of IMTA to meet social, economic, and environmental challenges for adaptation to climate change.

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