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Seeking environmentally sustainable solutions for inland aquaculture in Bangladesh

Konstancja Woźniacka [a,*], Lisa K. Bickley [a,b], Richard D. Heal [c], Ilya M.D. Maclean [d], Neaz A. Hasan [e], Mohammad Mahfujul Haque [f], Grant D. Stentiford [b,c], Regan Early [g], Michelle Devlin [h], Charles R. Tyler [a,b,*]

[a] Biosciences, University of Exeter, Exeter, UK
[b] Centre for Sustainable Aquaculture Futures, University of Exeter, Exeter, UK
[c] Weymouth Laboratory, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth, UK
[d] Environment and Sustainability Institute, University of Exeter, Penryn, UK
[e] Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj, Bangladesh
[f] Department of Aquaculture, Bangladesh Agricultural University, Mymensingh, Bangladesh
[g] Centre for Ecology and Conservation, University of Exeter, Penryn, UK
[h] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, UK

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ABSTRACT

Inland fresh- and brackish aquaculture is a key component of global food security, however, its rapid growth has impacted adversely on the environment. The future growth of the aquaculture industry will need to balance food production more effectively against the exploitation of natural resources. This review considers the case for inland aquaculture in Bangladesh – currently the world's fifth-biggest inland aquaculture producer with nearly 3 million tonnes of aquaculture production (2022). Current practices associated with different forms of inland aquaculture in the country are outlined, with their associated demands on the environment highlighted. Future projections for aquaculture expansion are assessed for their potential to impact on and be limited by the availability and quality of natural resources, including freshwater, and concerns for its contamination and salinisation. The effects of land use changes, exploitation of wild populations, introduction of invasive species, and spread of diseases on potential production are also examined. The paper addresses how these challenges may be met, both for achieving production aspirations and for limiting impact on nature. The review offers a viewpoint on potential collective actions for sustainable aquaculture, aligned with Bangladesh's socioeconomic characteristics, and in collaboration with in-country partners. To achieve the projected 14% increase in production by 2025, Bangladesh's aquaculture sector must balance growth with the effective management of finite freshwater and land resources. Key recommendations include prioritising adaptations by farmers for sustainable intensification of their production and facing changing climate impacts. Aquaculture policy needs to support the provisioning of the necessary knowledge, tools, and adequate resources to enable farmers to implement resource-efficient management strategies.

1. Introduction

Globally, seafood consumption has risen five-fold since the 1960s, while the output from capture fisheries has remained relatively constant since the 1990s (FAO 2022). This has mainly been facilitated by an increase in aquaculture production, which in 2020 accounted for 56% of aquatic foods produced, and is expected to grow a further 22% by 2030 (FAO 2022). However, achieving this projected increase for inland (freshwater and brackish) aquaculture sustainably will be challenging and likely to require both spatial expansion and intensification (Zhang et al. 2022). By 2050, land and freshwater requirements for aquaculture are estimated to be approximately 440,000 km^2 and 469 km^3 respectively, with an additional 616,000 km^2 of space required for growing aquafeeds (Mungkung et al. 2014, Waite et al. 2014). Historically, the expansion of some aquaculture systems has resulted in extensive degradation of aquatic ecosystems, including widespread degradation of

* Corresponding authors.
E-mail addresses: k.wozniacka@exeter.ac.uk (K. Woźniacka), c.r.tyler@exeter.ac.uk (C.R. Tyler).

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natural mangrove forests and wild fisheries nursery grounds to facilitate shrimp aquaculture (Hossain and Hasan 2017, Nobi and Islam 2021). Future aquaculture needs to minimise pressures on vulnerable habitats and biodiversity(Ali et al. 2016, Henriksson et al. 2018a, Boyd et al. 2020, FAO 2022) which may be facilitated by more effective technologies to increase productivity (Boyd et al. 2020) and optimising the use of natural resources. The need to balance aquaculture expansion with environmental sustainability is recognised as a key part of the One Health approach to attain optimal health for people, animals and our environment (Stentiford et al. 2020). Thus, as aquaculture looks to expand further to meet future food security demands globally, there is an imperative to better understand the current and potential environmental impact of the aquaculture industry as well as the type and state of the aquatic environment that aquaculture will require to thrive. It furthermore requires that this knowledge is embedded in future national development plans for the expansion of the sector (Stentiford et al. 2022).

Aquaculture has played a fundamental role in bringing about important socioeconomic changes, especially in Low Income, Food Deficit countries (LIFDCs) such as Malawi, Uganda, Uzbekistan and Bangladesh (FAO 2020). It is a crucial source of protein and plays a key role in poverty alleviation, acting as a catalyst for social change. In the case of Bangladesh, aquaculture feeds over 20 million people (FAO 2022) and forms a major part of the country's economic stability (Belton et al. 2012, Bunting et al. 2023). Bangladesh is now in the top five aquaculture producers in the world (FAO 2022) and is expected to remain one of the main suppliers. As the industry expands globally, Bangladesh provides a good case study for seeking how to balance production goals with societal needs and resource sustainability. Bangladesh has ambitious national targets for the growth of the aquaculture sector, yet as a lower-middle-income country (LMIC), it also faces major infrastructure development challenges. Furthermore, as is the case for many other major aquaculture-producing countries, some of the past aquaculture practices in Bangladesh have caused well-recognised damage to its natural environment, particularly to freshwater and land resources (Ahmed 2003, Islam and Yasmin 2017).

Here, we assess the impacts of inland (fresh- and brackish water) aquaculture on the natural environment in Bangladesh, identifying the known, evolving, and potential effects on land, water, and biodiversity, and considering ways in which future development may be achieved sustainably. Assessing the extent of potential environmental impacts of future development plans is challenging due to the complexities involved in fully quantifying these often interdependent effects. The limited availability of comprehensive data, particularly concerning water quality, usage and ecosystem-wide impacts, affect the depth of the analysis possible and the precision on the conclusions that can be drawn. Throughout our paper we acknowledge these limitations as we seek to evaluate the potential sustainability of proposed inland aquaculture. In this review we: (i) synthesises available information on the challenges and innovation opportunities, and (ii) offers a perspective on possible strategies to develop a more sustainable future inland aquaculture industry in Bangladesh while minimising the environmental impacts.

2. Review methods

This review evaluates the environmental impacts of inland aquaculture in Bangladesh through drawing on studies published in academic journals, government reports, and industry publications over the past three decades. To identify key studies on the impact of aquaculture on freshwater quality, biodiversity, and resource use, a semi-structured search of relevant literature was conducted using the Web of Science database. Keywords used in the data base search, included variations and combinations of "freshwater aquaculture", "impact assessment", "aquaculture footprint", "salinisation", "natural resources exploitation", "habitat degradation", and "water quality impacts". Only papers focusing on inland freshwater and brackish aquaculture were considered. After reviewing these primary sources, additional literature was identified by examining references cited in the initial studies, as well as through subsequent non-systematic searches on Google Scholar, Web of Science, and ScienceDirect.

The approach we have employed is to provide a broad and exploratory overview of the subjects discussed, rather than systematic review. It also lends itself to summarising current knowledge across a wide range of aspects, considering both negative and positive impacts of aquaculture in Bangladesh. This strategy allows for the incorporation of diverse sources and practical insights from in-country experts, which have yet to be recognised in academic sources. This search strategy may not fully eliminate potential gaps in data and present some bias, however, the review has been complied in partnership with in-country experts helping to verify the accuracy of the overview presented.

3. Current land-based aquaculture in Bangladesh

In Bangladesh, 60% of human daily animal protein intake comes from fish (67.8 g day^{-1}) and over 98% of this comes from domestic production (DoF 2023) - highlighting a reliance on capture fisheries and aquaculture for food and nutritional security in the country. Bangladesh has the third-biggest inland capture fishery globally, supporting the livelihoods of over 20 million people (FAO 2022). Aquaculture production in Bangladesh increased by approximately 3.5-fold between 2001/2 to 2022, from 786.6 thousand tonnes to nearly 2.9 million tonnes (DoF 2003, 2023), and now makes up over 58% of total fish production (DoF 2023). Major hubs of production are located in the South of the Khulna Division, and in the Mymensingh and Cumilla Districts (Fig. 1). The export of fish and fish products from Bangladesh was estimated to be worth $451 million (ca. £320 million or BDT 47.90 billion) for 2022/23 (DoF 2023), with the growth of aquaculture linked directly to the country's economic and social development (Shamsuzzaman et al. 2020). In its 8th Five Year Plan (2020–25; 8FYP), the Government of Bangladesh (GOB) has set the goal of increasing overall aquaculture production by nearly 14% and the export of aquatic foods by 16%, within the same expanse of water - 7972 km^2 (GED 2020; Table 1; Supplementary Material 1).

The environmental impacts of various aquaculture systems will differ based on the characteristics of farm operation methods, the species cultivated and the scale of production. Aquaculture in Bangladesh has been focused mainly on semi-intensive production, with some supplementary feeding and limited overall environmental control, but more recently intensification has occurred with comparatively higher levels of environmental control, and with subsequent higher yields (Belton et al. 2011, Hernandez et al. 2018, DoF 2022). There has also been a diversification in the number of species cultured. Pond aquaculture (homestead and commercial) is the predominant type of land-based aquaculture (Fig. 2; GED 2020, DoF 2023) providing year-round production. Commercial production is characterised by higher stocking intensity and yields, requiring intensive labour and significant capital investment compared to cage or floodplain farming (Belton et al. 2011). Pond aquaculture has also been associated with risk of eutrophication and habitat changes (Diana 2009, Henriksson et al. 2018a).

Cultivation of shrimp and prawns has been regarded historically as more lucrative than agriculture, leading to the conversion of rice fields into shrimp/prawn ponds or the implementation of integrated rice-prawn-fish aquaculture (gher aquaculture). These systems have also been associated with significant mangrove deforestation (Edwards 2015) and can lead to increased levels of nutrients and higher eutrophication risk in the area (Bull et al. 2021). Integrated Agri-aquaculture (IAAS) is a variation on pond aquaculture offering increased productivity, reduced waste through nutrient recycling and lower water and land use (Ahmed et al. 2014, Yifan et al. 2023) through concurrent or consecutive cultivation of vegetation and fish or crustaceans (Karim et al. 2011, Billah et al. 2020). Although IAAS might be preferential for poorer households, it has not been as popular as other aquaculture

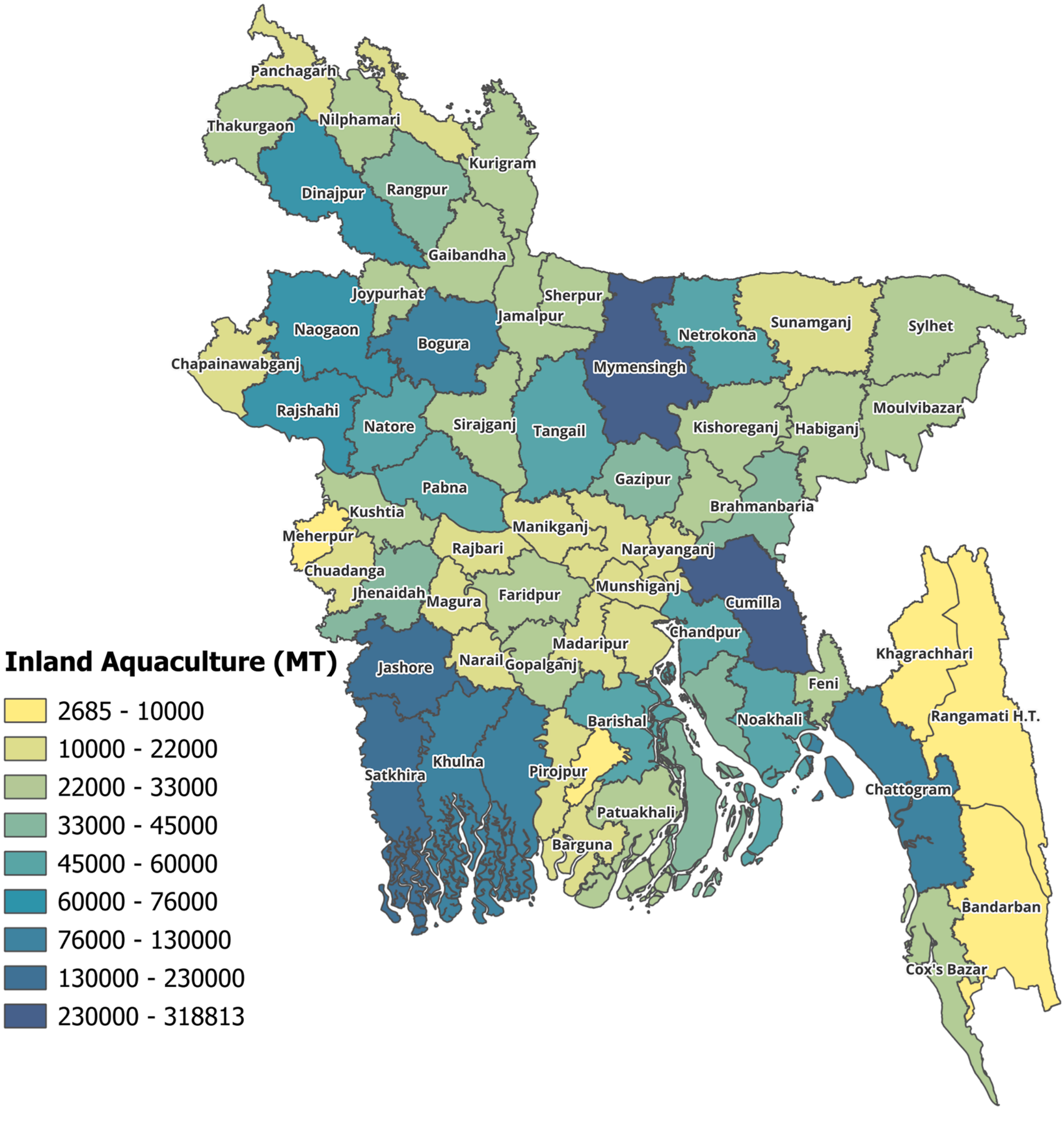

Fig 1. District-wise aquaculture production for inland waterbodies recorded for 2022/23. Data sourced from the Yearbook Of Fisheries Statistics Of Bangladesh 2022–2023 (DoF, 2023).

systems (Ahmed and Garnett 2010, Ahmed et al. 2014) in the absence of a sustainable value chain and its resource-intensive nature, requiring close monitoring.

Seasonal floodplain aquaculture (FPA) involves the enclosure of areas for water management and harvesting during monsoon seasons, whilst, during the dry season, the area is used for rice cultivation, (Belton et al. 2011). The management of FPA areas involves stocking, feeding the stock and fertilising the area, and the products used can freely enter non-farmed areas of the waterbody and contribute to contamination, eutrophication, and threaten biosecurity (Gregory et al. 2007). Similarly, the direct use of feeds and fertilisers in open waterbodies for pen and cage culture can affect surrounding aquatic habitats. Despite several national projects aimed at popularising the pen and cage culture practice (Hambrey et al. 2008, Naser and Barman 2009, Gupta et al. 2011), there has been limited expansion over the past decade (DoF 2022). While FPA, pen and cage culture are sometimes perceived as more resource-efficient, they may introduce invasive species through escapees that in turn may disrupt the surrounding ecosystem.

Finfish and shellfish aquaculture in Bangladesh involves cultivation of introduced and indigenous species, each with its environmental risks and benefits. Indian major carps (*Labeo rohita, Cirrhinus cirrhosis, Catla catla*), pangasius (*Pangasianodon hypophthalmus, Pangasius sanitwongsei*), tilapia (*Oreochromis niloticus, Oreochromis mossambicus*) and koi (*Anabas testudineus*) dominate pond aquaculture in Bangladesh (Fig. 2) (Hoque et al. 2021). Carps, pangasius, and tilapia have a high protein conversion efficiency (Stentiford et al. 2020) and can be produced under high stocking densities. Pangasius is primarily marketed to low-income domestic consumers (Hoque et al. 2021). Aside from these, farmers are increasingly focusing on cultivating other indigenous species that are nutrient-rich and have a high market value (Shingi, *Heteropneustes fossilis*; Magur, *Clarias batrachus*; Pabda, *Ompok pabda*; Gulsha, *Mystus cavasius*). Black tiger shrimp (bagda, *Panaeus monodon*) and giant freshwater prawn (golda, *Macrobrachium rosenbergii*) are the most valuable aquaculture products in Bangladesh, although recently white-leg shrimp (*Penaeus vannamei*) was introduced for commercial culture.

Table 1
Sector-wise annual aquaculture production of inland closed waterbodies based on Yearbook of Fisheries Statistics of Bangladesh (2022/23) and projected production under the 8th Five-year Plan (2020/21 Baseline, 2024/25 Targeted). For further information on the baseline and projections, see Supplementary Material 1.

Sectors of Aquaculture	2020/21 (Baseline 8FYP)			2022/23 (Reported)			2024/25 (Targets under 8FYP)			Production increase 2020–25 (%)
	Water Area (Ha)	Production (MT)	Productivity (Kg/Ha)	Water Area (Ha)	Production (MT)	Productivity (Kg/Ha)	Water Area (Ha)	Production (MT)	Productivity (Kg/Ha)	
Pond	371,000.00	2,032,200.00	5477.63	415,872.00	2,272,667.00	5464.82	371,000.00	2,333,300.00	6289.22	14.82
Seasonal Cultured Waterbody	131,000.00	230,900.00	1762.60	144,513.00	231,582.00	1602.50	131,000.00	252,260.00	1925.65	9.25
Baor	5000.00	8500.00	1700.00	5671.00	12,158.00	2143.89	5000.00	8840.00	1768.00	4.00
Shrimp/ Prawn Farm	275,000.00	271,400.00	986.91	261,833.00	301,103.00	1149.98	275,000.00	295,600.00	1074.91	8.92
Crab	9854.00	12,800.00	1298.96	9372.00	12,881.00	1374.41	9854.00	14,000.00	1420.74	9.38
Pen Culture	5290.00	10,600.00	2003.78	9080.00	16,402.00	1806.39	5290.00	11,080.00	2094.52	4.53
Cage Culture	13.00	4300.00	330,769.23	19.3	5254.00	272,227.98	13.00	4600.00	353,846.15	6.98
Total	**797,157.00**	**2,570,700.00**	**3224.84**	**846,360.30**	**2,852,047.00**	**3369.86**	**797,157.00**	**2,919,680.00**	**3662.62**	**13.58**

4. Challenges and potential solutions for sustainable aquaculture in Bangladesh

4.1. Freshwater requirements

The Challenge: Demands for freshwater in Bangladesh are intense and influenced by economic, physical and institutional factors (see: Chan et al. 2016, Khan and Paul 2023). Capital constraints, ineffective governance, and regulations result in over-extraction and pollution, further diminishing clean water availability and contributing to the competition between aquaculture, agriculture, provisions of potable water and natural freshwater habitats. Changes in precipitation patterns, prolonged droughts and reduced water availability further compound the issue.

For aquaculture, the freshwater footprint comprises water used for artificial waterbody creation (rainwater, surface water and groundwater) and maintenance (including losses from evaporation and infiltration), water used for aquafeed production, which is anticipated to increase with aquaculture expansion and water lost for human consumption due to contamination (Pahlow et al. 2015, Yuan et al. 2017, Guzmán-Luna et al. 2021). However, Bangladesh lacks comprehensive data on its water footprint, making it challenging to assess the true impact of water use across different sectors, including aquaculture, although in-country experts co-authoring this review provided invaluable insights into this issue. Water needs also depend on the species cultivated and the type of farm. Shrimp and pangasius ponds, for example, require daily fresh water exchange of between 5- 40% depending on the cultured animal life stage and culture intensity (Wahab et al. 2003, Anh and Mai 2009, Anh et al. 2010). Furthermore, the lack of water reuse practices exacerbates freshwater depletion. High water demand for aquaculture is particularly problematic for Bangladesh's northwest seasonal ponds, where it is difficult to retain water during the summer due to sandy soils, and high dry season temperatures cause elevated evaporation. In Mymensingh, one of the most important areas for finfish production, drought in dry seasons has been recognised as a major limiting factor for the future development of finfish aquaculture (Ahmed and Diana 2016). During dry seasons, groundwaters (which are often at low levels), are frequently used for irrigating ponds (Ahmed and Diana 2016), which in turn hinders the natural replenishment of waterbodies (Malay 2011, Schmidt 2015, Dey et al. 2017). Excessive exploitation of groundwater can also exacerbate the threat of arsenic pollution (Hossain 2006, Chakraborti et al. 2010), already problematic for groundwater and surface freshwaters in the Mymensingh area and the southwest of the country (Shahid 2010, Alam et al. 2011, Islam et al. 2015, Ayers et al. 2017). However, small-scale aquaculture farmers lack the capital to implement technologies for efficient water use.

Flooding, common in Bangladesh, not only disrupts aquaculture operations but also affects the surrounding ecosystems. As it damages infrastructure, washes away stocks and releases water treated with chemicals, it creates another link between water quality degradation and aquaculture (Islam and Hoq 2018). Loss of water necessitates frequent replenishment, which further strains freshwater resources in the country.

Addressing the challenge: A comprehensive approach that blends climate-resilient infrastructure, nature-based solutions, effective water management, policy support, and ongoing research are crucial for developing a sustainable future inland aquaculture sector in Bangladesh. Further research into the water footprint of the sector is necessary to inform these changes. Appropriate future site selection is a vital step, to ensure the best use of natural features such as topography, soil type and water holding capacity to minimise water loss and impacts from flooding. Moreover, climate-adaptive measures including elevated ponds and recirculating aquaculture systems (RAS) can help improve water retention and system resilience to hazardous events (Wongbusarakum et al. 2017). Reinforcing pond embankments and improving drainage

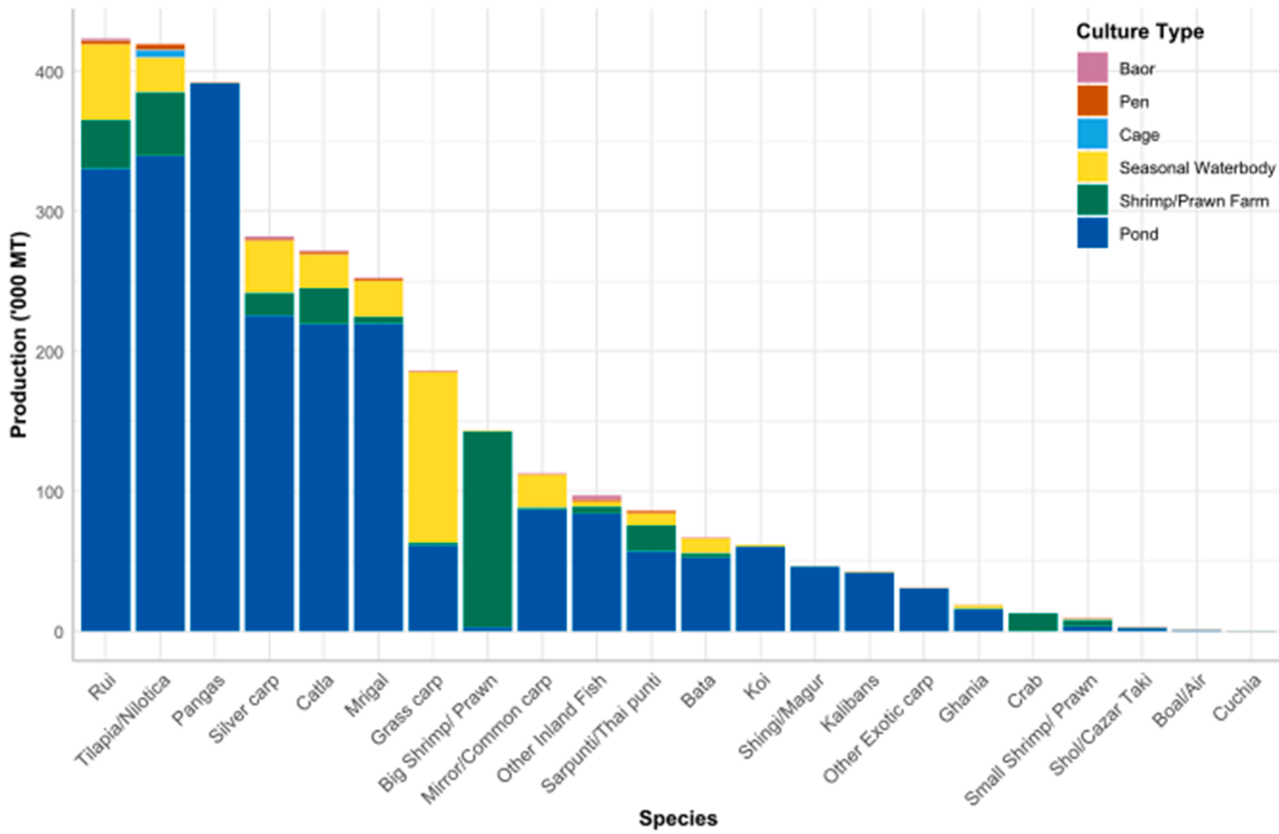

Fig 2. Species-wise annual aquaculture production for inland waterbodies in 2022/23 in Bangladesh. Data sourced from DoF (2023).

systems could reduce contamination risk of surrounding ecosystems from influx of treated water. Flood protection can also be improved through nature-based solutions, such as the restoration of wetlands and mangroves, that offer additional ecosystem services for water quality and ecosystem resilience (Gijsman et al. 2021).

For established pond systems, water loss reduction, prevention of ground contaminants, and the salinisation of pondwater or soil in the case of brackish aquaculture, can be improved on a local scale, where practicable, by sealing the base of ponds or ghers using liners, including with natural materials such as clay (Ashton 2008, Tal et al. 2017). Trials in northwest Bangladesh (Rajshahi district) have shown that clay-coated polyethene beds improved water retention and lengthened water holding leading to more than a two-fold greater water depth in coated ponds (Nahar et al. 2023). In turn, this improved fish growth and yields during the dry season by nearly five-fold (Nahar et al. 2023). It is accepted that the application of such systems may not be accessible to many subsistence farmers, however, due to the associated material cost outlays. Further water-saving measures involve improvement of water quality in the systems and better effluent management, which can allow for the re-circulation of water back into aquaculture ponds or reuse for crop irrigation (discussed below).

4.2. Water quality

The Challenge: Safe and sustainable aquaculture production requires access to water where hazards that impact the health of farmed stock, and consumers, are minimised (Stentiford et al. 2022). Whilst data on water quality and loadings of contaminants in Bangladesh are limited, there is evidence of health and food production impacts, with natural freshwaters experiencing progressive degradation (Ghose 2014, Hasan et al. 2019, Ranjan 2020, Uddin and Jeong 2021, Parvin et al. 2022). Detailed analyses of the specific pollution hazards and the monitoring schemes in Bangladesh have been compiled (for example Parvin et al. (2022), and Bilal et al. (2023)). Other sources of water contaminants in Bangladesh include textiles, tannery, mining and mineral processing industries, pharmaceutical plants, as well as landfill sites and agriculture (Gulfam-E-Jannat et al. 2023) with pollutant types spanning heavy metals, organic chemicals, pharmaceuticals and agrochemicals. Some of these contaminants, notably heavy metals, can exceed recommended limits set by the Department of Environment of Bangladesh and, the recommendations of the WHO (Sarkar et al. 2019). Natural disasters such as floods and cyclones also have a profound impact on water quality in Bangladesh and their effects can be long-term. Moreover, extensive river and seasonal floodplain systems across the country mean that transmission of inputs can occur across large distances and impact areas far from the source (Ranjan 2020, Uddin and Jeong 2021). The utilisation and management practices of shared rivers by India and Myanmar also affect water availability and quality in Bangladesh. Upstream damming such as the Farakka Barrage, irrigation, and industrial discharge reduce water flow and increase pollutant concentrations, impacting agriculture, fisheries, and public health in the country (Mirza 2004).

Whilst the impact of aquaculture on overall water quality can be difficult to quantify, excess feed, waste products, antibiotics, probiotics, and pesticides are known to cause elevated concentrations of nutrients, chemicals as well as organic matter. Semi-intensive and intensive production systems have been shown to be sources of nutrient-rich effluents (Henriksson et al. 2018a, Boyd et al. 2020, Goto et al. 2023) and intensification of these systems positively correlated with eutrophication in local freshwaters (Henriksson et al. 2018a). Water quality in highly biodiverse areas in Bangladesh, such as Tanguar Hoar or Sundarbans wetlands, is already adversely impacted by major industries (Kibria and Yousuf Haroon 2017), and the growth and intensification of aquaculture could increase the risks from water contamination, and negatively impact further on the wild biota in these areas (Alam et al. 2012). Moreover, aquaculture pollutants can have interactive effects with other anthropogenic and climate change stressors, resulting in both acute and long-term cumulative effects, thus exacerbating negative effects on the environment (Reid et al. 2019).

The overall use of chemical products in Bangladesh aquaculture is relatively low compared to many other nations (Ali et al. 2016), however use of antibiotics, fertilizers, and hormones, contributes significantly to water and soil contamination and the growing disease burden is tackled with increasing chemical use (Heal et al. 2021). Heavy use of disinfectants and antibiotics occurs with pangas and koi production, and the use of pesticides and fertilisers is particularly associated with shrimp/prawn farms and with IAAS (Ali et al. 2016, Hasanuzzaman et al. 2017, Parvin et al. 2022). In tilapia and pangasius tissues, levels of lead have been measured at between five and seven times higher, and for chromium at between 20 and 54 times higher than that recommended for human consumption (Alam and Haque 2021, Sultana et al. 2022b), with similar levels observed in wild fish (Sapkota et al. 2008, Uddin and Jeong 2021). Levels of lead and copper in shrimp have also exceeded recommended levels for human consumption (35.5 times higher and 1.9 times higher, respectively; Alam and Haque 2021, Sultana et al. 2022b). Heavy metals can also be introduced to farmed stock through fish feeds, which have been found to contain lead, cadmium, copper, zinc and chromium (Kundu et al. 2017, Sarkar et al. 2022). Hatcheries and nursery preparations use known poisons (e.g. Rotenone, Phostoxin, Endrin) to remove unwanted fish with a survey in Mymensingh revealing that 33% of hatcheries applied poisons to their ponds (Chowdhury et al. 2012, Das et al. 2022).

Addressing the challenge: Addressing surface freshwater pollution from Bangladesh's major industries, including landfills and agriculture, is a significant challenge and will require a highly integrated approach and substantial investments in waste management to resolve. Key concerns that need to be addressed are the lack of water quality data and insufficient quantification of both the impacts of aquaculture effluents on the surrounding environment and water consumption for different types of aquaculture. While there is abundant evidence of aquaculture impacts on water quality, quantification of these impacts in Bangladesh is lacking and this hinders the sustainable expansion of the inland aquaculture sector. These data are needed to guide the most appropriate, efficient and actionable Best Management Practices (BMP). In turn, national policies for protecting and enhancing water quality need to be developed with those focused on aquatic food production (Stentiford et al. 2022), together with other stakeholders to deliver more effective water management strategies. Technological advancements, investment in infrastructure, and bridging the skills gap will contribute considerably to meeting this challenge (Chatla et al. 2020), and although beyond the scope of this review, this is crucial in order to meet the requirements for the growth of sustainable inland aquaculture systems in Bangladesh.

Effective implementation of wastewater treatment and BMP can go a long way toward reducing the waste contamination impact of aquaculture. Effluent waste treatment systems do not have to be high-tech, as illustrated below, and can be relatively easy and low-cost to implement. However, currently, the guidelines for good practices are often not adhered to, in part due to a lack of training (Mondal et al. 2013). Moreover, aquaculture practices in Bangladesh are largely aimed at increasing production (Haque et al. 2021) rather than minimising the environmental impacts of aquaculture practice. Implementing limits on pollutant discharges is needed, but enforcing and monitoring this will be extremely difficult and require political will, nationally agreed targets, and resources to implement both the systems and monitoring. Alongside basic water analysis kits, simple daily observation of water conditions by farmers can help with early detection of water quality issues (Rajts and Shelley 2020). Ammonia contamination from aquaculture systems can be effectively controlled by the use of biodegradable aluminium phosphate or yucca extract, which also minimises hazards to aquatic wildlife (Boyd and Massaut 1999). However, cheaper and more broad-spectrum chemicals that have negative impacts on the ecosystem currently tend to be favoured in the removal of ammonia (Boyd and Massaut 1999, Ali et al. 2016). Regular removal of the nutrient-rich sediment that builds up on the bottom of ponds (which can be used as fertiliser) minimises subsequent sediment discharges during periods of high rainfall or pond disturbance (Hossain et al. 2013). Pelleted feed can add significantly to pondwater and discharge pollution but refinement of feed management, including the use of high-quality, highly digestible feed, helps significantly in reducing the amount of waste produced and in turn, reduce nutrient accumulation (Zlaugotne et al. 2022). Increasing the proportion of small, indigenous fish species (SIS), in pond systems can also help to ensure a reduction in the amount of uneaten food by the primary production species and reduce the subsequent food and nutrient waste (Karim et al. 2011, Shepon et al. 2020). However, SIS are obtained mostly through fishing rather than aquaculture, and their populations have been much reduced, in turn limiting natural broodstock availability.

A highly accessible strategy that can increase system productivity, whilst minimising waste and nutrient build-up and reducing the need for chemical fertilisers, is IAAS, or Integrated Multi-Trophic Aquaculture (IMTA), where fish and shellfish and/or algae cultures are combined and which can also provide alternative sources of income, food and animal feed (Azad et al. 2016, Ibrahim et al. 2023). Numerous variations of the IAAS approach are currently practised in Bangladesh, although these methods would greatly benefit from further propagation (Ahmed et al. 2007, Ignowski et al. 2023). IAAS has been successfully applied with tilapia and floating rice nurseries (Sharma and Mitra 2008), as well as in tilapia, catfish, cabbage and salad systems in coastal farms in Thailand. Floating gardens have also been used traditionally, particularly in the southwest of Bangladesh, and show a positive impact on water quality (Neazi 2022). However, those approaches are not widely adopted in the country (Kibria & Haque 2018, Selim et al. 2021) perhaps as they require knowledge and adequate space for cultivation, which has limited their application. High efficiency in the removal of nitrogen compounds from aquaculture wastewater has also been shown by constructed treatment wetlands (CTW), which are a variation of RAS (Tom et al. 2021, Goto et al. 2023). While the use of natural wetland habitats, including mangrove forests, can have negative repercussions, CTW offer a low-cost solution with some of the ecosystem services of their natural counterparts (Tom et al. 2021, Goto et al. 2023). On the negative side, CTW can become reservoirs of antibiotic-resistant genes and thus they require a relatively extensive area and further research is needed to understand full remediation potential and optimal setups of the systems (Oscar Omondi and Caren Navalia 2021). Nevertheless, a combination of improved farming practices, which reduce the amount of effluent, with the re-circulation of the water through IAAS or CTW can offer a balanced solution, with considerable economic and environmental benefits.

Seaweed and algae cultivation has recently begun in Bangladesh, and although it is currently focused mainly on coastal regions (Al et al. 2019, Chowdhury et al. 2022, Akhtar et al. 2022, Sobuj et al. 2023), it offers several ecosystem services including absorbing excess nutrients and carbon dioxide (Buschmann et al. 2008, García-Poza et al. 2020). In locations where heavy metal contamination is a concern, and algae cannot be used for human consumption due to their high bioaccumulation potential, the biomass can be burnt for energy or disposed of as part of remediation efforts (Nnaji et al. 2023). Implementing seaweed into shrimp/prawn ponds could act similarly to the beneficial effects of mangroves and boost the growth and survival of shrimp (Fourooghifard et al. 2017). Trials in Vietnam, with shrimp-tilapia-seaweed cultivation, have brought improvements in cost efficiency and a reduction of contamination (both chemical and natural) (Tran et al. 2020), and with more governmental and NGO support, this approach could be adopted by Bangladeshi farmers.

4.3. Salinisation of soil and water

The Challenge: Salinisation is a process that can be driven by rising sea levels, cyclones, storm surges and reduced rainfall (Brammer 2014) Improper irrigation techniques, dominance of irrigation-based cultivation practices, poor drainage systems, and excessive use of chemical fertilisers also contribute to the accumulation of salts in the soil (Salehin et al. 2018, Feist et al. 2023). However, coastal aquaculture has contributed significantly to the salinisation of both soil and water (groundwater and flowing water), which has led to altered hydrological balance and to increased competition over freshwater supply (Deb 1998, Chowdhury 2010, Hou et al. 2022).

In the context of aquaculture, salinisation has been associated mostly with the removal of mangrove forests for the expansion of shrimp aquaculture (Mizanur Rahman et al. 2013, Bryan-Brown et al. 2020). In the Khulna region, for example, saline water intrusion has penetrated over 150 km inland as a consequence of the development of the coastal shrimp industry (Miah et al. 2020). The problem is exacerbated by pumping groundwater into coastal ponds, which lowers groundwater levels and increases saltwater intrusion into the remaining supply (Ahmed et al. 2008, Chowdhury 2010). The long-term influx of saline water into Bangladesh's land base and release of saline effluent has resulted in further penetration of contiguous soils, altering their chemistry with consequences for wild biota and agriculture (Islam and Yasmin 2017, Morshed et al. 2020). As a result, freshwater species are experiencing diminished growth and survival rates with increased disease susceptibility due to exposure to conditions outside of their normal physiological tolerance spectra (Dasgupta et al. 2017, Alam et al. 2020). Moreover, high salinity has contributed to the disappearance of 12% of marine finfish and 25% of shrimp species in the Kalapara Coastal Belt (Alam et al. 2017). Saltwater intrusion has furthermore caused declines in local agrodiversity, including indigenous rice varieties and various vegetable species across southern Bangladesh (Rahman et al. 2011). As a consequence, major land tracts in southern regions have become increasingly uncultivable, with croplands further converted into aquaculture ponds or salt fields, which are more profitable (Paul and Røskaft 2013).

Addressing the challenges: Since the 1970s, when the transformation of coastal, southwest croplands to ghers began, aquaculture systems have been improved to minimise the associated salinity risks (Bhowmik et al. 2023) and the expansion of the shrimp sector has also lost its original intensity. Restricting saltwater and brackish aquaculture in favour of sustainably managed freshwater species will help further reduce salinisation, although this process requires changes in traditional practices, and updating of policy and legislation. In the short term and on a localised scale, improving the drainage systems of ponds and the use of clay layers, algae sealants or synthetic liners in ponds can reduce the salinisation of underlying aquifers (Tal et al. 2017). However, lack of technical expertise and high costs limiting their current implementation needs addressing, and perhaps more adaptive measures should be considered.

In areas where soils and surface waters have become salinised, a range of adaptive measures for enabling freshwater aquaculture have been applied, such as harvesting rainwater in ponds to alleviate the pressure on groundwater in post-monsoon seasons (Chowdhury et al. 2023). This, however, depends on precipitation patterns and incurs costs related to the installation and maintenance of harvesting systems that can meet the demand of extensive aquaculture. Suggestions for future freshwater supply strategies include diverting river flow for sedimentation and constructing barriers against climate-related saltwater intrusion, which aggravates the salinisation from aquaculture (Brammer 2014). Other mitigation and adaptation measures implemented by coastal farmers, particularly in Khulna and Bagerhat, include the introduction of salt-tolerant crops, improved irrigation, raised vegetation beds and floodplain management to help limit the susceptibility of crops to water quality degradation (Brammer 2014, Lam et al. 2022, Bhowmik et al. 2023). New practices are gaining traction in the country through the dissemination of salt-tolerant crop seeds and saline testing kits, and training of small-scale farmers in coastal Bangladesh (Cordaid 2021). However, further support is required for farmers to access resilient seeds, and greater coordination is needed between the government and private sector within and outside the country to increase seed quality and yields (Shrestha et al. 2020).

4.4. Habitat impacts

The Challenge: Habitats most compatible with aquaculture development are often characterised by high biodiversity that also support important fisheries and fish nurseries. Wetlands and floodplains are particularly at risk from land conversion for aquaculture purposes (Diana 2009, Ramsar 2015, Sultana and Thompson 2017). Mangrove loss in the coastal regions of Bangladesh and wetland conversion into shrimp and fish ponds are well-documented negative consequences of aquaculture expansion, impacting wildlife diversity and abundance (Ahmed 2003, Bala and Hossain, 2010a, 2010b, Edwards 2015). Mangrove loss in the Sundarbans and Chakaria Sundarbans (approximately 97 km^2, Ahmed 2013; and 80 km^2, EJF, 2004 loss, respectively), has reduced tree density and increased forest fragmentation (Hossain et al. 2016), and resulted in the endangerment of species due to movement restriction, changes in reproductive behaviour and separation of populations (Jacquemyn et al. 2012, Haddad et al. 2015, Rybicki et al. 2020). Clearance of these rich, productive wetlands has led to substantial declines in Bangladesh's native fish, birds (resident and migratory), amphibians and reptiles, many of which are endangered or vulnerable (Hussain 2022, Sultana et al. 2022a). In particular, bird species, including the masked finfoot (*Heliopais personatus*; IUCN endangered) and small lesser adjutant stork (*Leptoptilos javanicus*; IUCN vulnerable), depend upon wetland habitats like the Sundarbans and are facing a rapid population decline due to habitat loss and changes in hydrology (Chowdhury and Sourav 2012, BirdLife International 2022). Other bird species, for example, the Asian openbill, have now been lost as a breeding species in Bangladesh due to the destruction of these mangrove areas (Elliott et al. 2020).

Mangrove deforestation has also left the country more prone to the effects of tidal waves and cyclones (Mizanur Rahman et al. 2013, Bryan-Brown et al. 2020) and reduced the capacity for carbon sequestration and storage (Islam et al. 2017, Majumder et al. 2019). Sea-level rise, as a consequence of climate change, will further exacerbate the loss of wetland habitats (Nevermann et al. 2023). Other anthropogenic interventions including the construction of dams, roads and embankments constrain the natural occurrence and functioning of floodplain wetlands (Pal and Singha 2023) and restrict the movement of aquatic species, such as migratory fish. This, in turn, increases the pressure on populations outside of areas affected by aquaculture (Gregory et al. 2007). A study of the Daudkandi floodplains showed that in farmed areas (versus more natural areas) there was a lower planktonic diversity, lower abundance of indigenous species and the community composition differed with invasive carps and tilapia dominating the fish-farmed areas as opposed to minnows and barbs in the areas with the absence of fish farming practices (Alam et al. 2010).

Addressing the challenge: Silvo-aquaculture, which reintegrates mangroves into the landscape, and afforestation offers an effective way to support wild fisheries and improve general biodiversity, conserve land resources and limit salinisation (Islam and Wahab 2005, Terwisscha Van Scheltinga et al. 2023). Silvo-aquaculture, where mangrove trees are grown in the aquaculture ponds, has been shown to improve shrimp production while preserving pond banks, lowering the necessary food input, and providing water cleaning services and shade for shrimp growth (Alam et al. 2021, 2022, Ahmed et al. 2023). Silvo-aquaculture has been successfully implemented in Indonesia (Fitzgerald 2000, Basyuni et al. 2018), Thailand, and Vietnam (Primavera et al. 2000, McIlveen and Hung 2019), however, it requires greater propagation (including training in the practice) in Bangladesh. Adoption of this culture method also requires a greater understanding of mangrove-shrimp interactions in Bangladesh and the optimal mangrove coverage needs to be verified (Bosma et al. 2016, Ahmed et al. 2023). Care has to be taken to avoid the conversion of intact mangrove forests and the following loss of ecosystem function (McSherry et al. 2023), but rather implement Silvio-aquaculture as part of afforestation efforts. Afforestation will improve coastal protection, carbon sequestration and provide habitat for many important wildlife species (Ali Reza and Kamrul Hasan 2020, Uddin et al. 2023). The Community-Based Adaptation to Climate Change through Coastal Afforestation (CBACC-CF) initiative has been successfully introduced through the National Adaptation Programme of Action (NAPA), planting 61 km^2 of new mangrove forests and introducing 10 species to existing monocultures (Ahammad et al. 2013).

Improving management strategies is necessary to protect land space and habitat quality, including balancing stocking density levels, pond sizes, water needs and input costs. Implementing IAAS is more land-effective and thus helps to limit the expansion of food production systems into natural habitats (Jahan et al. 2015). This practice is now slowly spreading across the country with great potential for water quality improvement (Neazi 2022). Future expansion of aquaculture urgently needs to have more spatial awareness and prioritise less ecologically sensitive areas (Henriksson et al. 2018a).

The establishment of protected areas (PAs) that promote biodiversity conservation in natural mangrove forests and wetlands needs to be a top priority in Bangladesh, although historically, PA governance in Bangladesh has been ineffective due to prolonged delays in designation, insufficient area coverage, lack of ecosystem representation and low numbers of remaining wild fauna (Mukul et al. 2008). Biodiversity also needs to be more effectively protected in areas immediately surrounding PAs, as these can act as important buffer zones. Here, limiting destructive practices while still allowing low-intensity multifunction use of the landscape, can provide a vital means of increasing PA performance will also providing some benefits to people. Implementing a more participatory approach and switching to alternative economic activities such as eco-tourism could increase community engagement and compliance with PA exploitation guidelines. Moving the entire PA community towards alternative income sources requires substantial funding and engagement from all of the members and transparency in progress and plans (Rashid et al. 2016, Mollick et al. 2023). Moreover, care needs to be taken to work with, rather than supersede, customary institutions to avoid negative social outcomes (Dawson et al. 2021). A sustainable PA system would need to strike a balance between reducing the pressures exerted on the ecosystem from unsustainable usage practices, creating opportunities to improve the socio-economic well-being of local communities and empowering their environmental stewardship.

4.5. Exploitation of natural resources

The Challenge: Aquaculture can reduce the pressure on wild fisheries population and thus contribute to their conservation, although this is not true for all aquaculture practices (Naylor et al. 2000, Ahmed et al. 2019). In floodplain aquaculture, for example, wild fish may enter the farming areas and become part of the harvest (Alam et al. 2010). More importantly, the demand for seed- and broodstock in Bangladesh aquaculture has been largely met through wild capture. Indiscriminate fishing and high harvest discard, including post-larvae of shrimp, finfish and other macro-zooplankton have led to major declines in wild prawn populations and other species (Ahmed 2003, Ahmed et al. 2008, AftabUddin et al. 2021). The collection of prawn post-larvae has resulted in restrictions being placed on post-larvae fishing, but the ban has not been strictly enforced largely due to the limited availability of hatchery seed and lack of alternative livelihoods in coastal communities (DoF 2002, Ahmed et al. 2008, 2010). The intensity and scale of shrimp/prawn aquaculture in Bangladesh, associated with habitat degradation, and harvesting of wild post-larvae has a high likelihood of leading to reduced biodiversity, genetic diversity and population decline of targeted (and bycatch) species (Ahmed and Troell 2010), and is very likely to have done so already.

Wild fisheries populations and other aquatic organisms are also under pressure from harvest for the production of fish meal and fish oils (FMFO) and raw feed. As FMFO production increases in Bangladesh to meet the growing demand from aquaculture, it will further strain wild fisheries (Mamun-Ur-Rashid et al. 2013). On land, overharvesting of snails (*Pila globosa*) used as feed for expanding prawn aquaculture has led to their localised extinction in parts of the country, while discarded shells have caused blockages to canals and open water bodies (Ahmed et al. 1997, 2008).

Small-scale finfish farmers facing capital constraints have begun adding different Azolla species to their polyculture, which enhances pond water quality (Zakarya et al. 2023). This floating fern is rich in protein, minerals, chlorophyll, carotenoids, amino acids, and vitamins and provides supplemental nutrition to fish through its ability to fix atmospheric nitrogen (Korsa et al. 2024). However, widespread overharvesting of Azolla has led to uncontrolled toxic algal blooms, exacerbated by industrial runoff and disrupted nitrogen balance, potentially causing nutrient deficiencies and negatively impacting the aquatic food web.

Addressing the challenge: In the first instance, stricter enforcement of seed and broodstock collection bans are urgently needed to help mitigate pressures on stocks of wild shrimp and prawn populations, and the bycatch species. A major requirement is investment, in infrastructure, technology and skilled manpower to establish broodstock hatcheries and avoid using wild-caught broodstock for hatchery operations as is currently done for bagda (*P. monodon*) (Debnath et al. 2016). The demand for a supply of specific pathogen-free post-larvae (SPF PL) in the country through certified hatcheries is slowly being addressed, for example through the SAFETI project funded by the USDA (Consiglieri Private Limited 2017) and the recent GOB initiative to convert hatcheries into SPF PL hatcheries across the country. Promotion of organic shrimp and prawn farming, which does not allow the use of wild-caught larvae (Paul and Vogl 2012), could also help to improve the situation. However, currently, the local organic market is extremely limited and reliance on exporting brings many further challenges not least a limited choice of exporters (Paul and Vogl 2012). Support from NGOs and the GOB, in combination with enforcement of the ban on wild seed/-broodstock collection, would help significantly in transitioning towards more sustainable cultivation practices through the use of hatchery post larvae (Paul and Vogl 2012).

The use of more sustainable and economically viable alternatives to FMFO, including earthworms, soldier fly larvae, as well as plant products (rice polish, mustard oil, linseed oil) have been tested on tilapia with promising results in terms of nutritional potential, digestibility and accessibility (Khan et al. 2013, Rana et al. 2015, Zlaugotne et al. 2022). Promoting non-fed aquaculture species such as bivalves and algae will also help to alleviate some of the pressures placed on wild fish and other animals and plants currently used as feed sources in aquaculture as well as the further benefits of the water purification services they provide. Alternative feeds have yet to gain traction in Bangladesh as insect-based technology is still in its infancy, and the cultural preferences in farming techniques favour known and tested feeds. However, with the right support through training and incentives for sustainable aquafeed production, alternatives to FMFO can become more widespread across the country. In the case of algae and bivalve products, the limited local market and water pollution are hindering the development of seaweed and bivalve farms.

4.6. Disease spread and AMR

The Challenge: Diseases are a fact of life for wild and farmed animal populations (Stentiford et al. 2017), and although there is little evidence of farm-to-wild population transmissions in inland aquaculture systems currently (Arechavala-Lopez et al. 2013, Teixeira Alves & Taylor 2020), the results of disease management can impact upon wild populations.

Improper identification or failure to respond to outbreaks constitutes a prime opportunity for pathogens to spread to other aquaculture systems or wild populations and affect biodiversity. Disease transmission between farmed and wild populations is becoming an emerging issue in Bangladesh. As aquaculture ponds often discharge untreated effluents into surrounding water bodies, they facilitate the exchange of parasites between farmed and wild organisms, and alter parasite transmission dynamics among wild species (Bouwmeester et al. 2021). The introduction of new, external pathogens creates another risk to biodiversity. The recent introduction of *P. vannamei* for commercial farming in Bangladesh could impact disease transmission dynamics, potentially spreading White Spot Syndrome Virus and Taura Syndrome Virus between native cultured and wild shrimp populations (Overstreet et al. 1997, Ramírez et al. 2021, Intriago et al. 2024). Moreover, the extensive shrimp farming practices in Bangladesh often combine shrimp farming with poultry and other livestock, and they use livestock manures to fertilise ponds (Boyd 2018, Hasan et al. 2020). This leads to poor bio-security and cross-contamination between animal excretions and shrimp ponds, potentially increasing disease transmission within both aquatic and terrestrial ecosystems. Even the involvement of shrimp farmers in secondary occupations, like honey collection from mangrove forests, can lead to the introduction of microsporidians into shrimp farms, which can cause disease (Han et al. 2016).

Another key issue related to aquaculture disease management is the emergence of antimicrobial resistance (AMR). Insufficient control of antibiotics and antimicrobials, and their liberal use in Bangladesh aquaculture poses a great risk to the industry, the environment and human health. Prolonged use of antibiotics can lead to antibiotic resistance of both, fish and bacteria, in both farmed and wild populations (Cabello et al. 2016, Preena et al. 2020, Munni et al. 2023), for example, the transmission of antibiotic-resistant bacteria from shrimp farms through *Vibrio* plasmids (Molina-Aja et al. 2002, Kitiyodom et al. 2010). The proliferation of antibiotic-resistant pathogens can lead to the emergence of new resistant strains, while changes to microbial communities have the potential to disrupt the functioning of ecosystems (Derome 2019, Pepi and Focardi 2021, Singh et al. 2022). Exacerbating this issue is a surge in imports of foreign goods and non-native species, which might introduce new parasites and diseases, increase the presence of invasive species, and lead to genetic depletion, thereby heightening the risk of disease outbreaks and susceptibility of native species to pathogens.

Addressing the challenge: As aquaculture production expands and intensifies, effective disease prevention and management will become crucial for maintaining high production of quality fish and shrimp and export to high-value markets. Fish health management faces constraints due to a lack of knowledge of diseases and proper treatment and a lack of advisory services from NGOs and GOB on surveillance and biosecurity (Bagum et al. 2013). Farmers need to be supported through educational campaigns that highlight the risks and pathways for disease transmission, especially involving cross-contamination from other activities. Training programs should emphasise the importance of proper disinfection regimes and maintaining sanitary environments. As the diseases spread more rapidly in high stocking densities, when water quality deteriorates, and when untreated water effluent contaminates natural waterbodies (Wiyoto et al. 2017, Buchmann 2022), the management methods should align with the solution outlined in the previous section for water quality control and improvement in operation methods. Upgrading pond conditions, regular monitoring and reporting, and early outbreak detection and control are crucial (Alam and Guttormsen 2019, Deb et al. 2021). Utilising systems-based (syndemic) approaches to understanding and controlling diseases in aquaculture is increasingly recommended (Stentiford et al. 2023). Improving the infrastructure for disease identification, choosing the right course of treatment for disease management, and training for farmers sanctioned by the government or facilitated through NGOs are crucial entities for addressing the problems in disease management in aquaculture in Bangladesh (as they are globally).

Liberal use of antimicrobials in Bangladesh has become a vicious cycle as the occurrence of AMR further fuels the use of antimicrobials (Henriksson et al. 2018b). Insufficient control of antibiotics and antimicrobials poses a great threat to biosecurity (Thornber et al. 2022) and needs to be addressed urgently by the GOB through clear policies and monitoring, especially at the field level. The primary goal should be to minimise the demand for antimicrobials use through improved husbandry that combats the invasion and proliferation of pathogens (Kawsar et al. 2022). Accessible education regarding disease identification, management and proper use of antimicrobials is crucial (Debnath et al. 2023). As the implementation of necessary training is time- and resource-demanding, cooperation of GOB, NGOs and the private sector is necessary for the situation to improve. Popularising the knowledge on threats posed by AMR and improper use of antimicrobials through media outlets would also spread awareness and exert social pressure on the farmers, as has happened in the case of farming salmon in Chile and pangasius in Vietnam (Leith et al. 2014, Henriksson et al. 2018b).

4.7. Invasive species

The Challenge: Introduction of new non-native species for aquaculture can improve production capacity and disease resistance, increasing yields, but a lack of adherence to safety rules can result in their introduction as invasive species into the wider environment through release and escape or from non-native live feed sources. The extensive borders with Myanmar and India, both prominent aquatic food producers, mean that Bangladesh is also vulnerable to the introduction of alien species via cross-border communal waterways (Islam et al. 2003). Invasive species can cause significant ecological and economic damage (Singh and Lakra 2011, Nghiem et al. 2013, Mukul et al. 2020) and their presence in natural waterbodies can be the first indicator of declining ecosystem health (Kennard et al. 2005).

The number of invasive fish species (IFS) in Bangladesh is hard to define, and whilst a recent review (Mukul et al. 2020) placed the number at 16, other publications have suggested as many as 150 (Constantine et al. 2022) fish species have been introduced over the years. A list of verified introduced and invasive species is provided in Table 2. Notable examples are Nile tilapia (*Oreochromis niloticus*) and Mozambique tilapia (*Oreochromis mossambicus*), which currently underpin a major part of the local finfish industry (Rahman et al. 2021). These species can be highly invasive, are often predatory (Mukul et al. 2020), and characterised by high adaptability that enables them to outcompete many native fish groups (Khan et al. 2021).

Invasive tilapia, pangasius, carps and catfish can lead directly to reductions of aquatic vegetation, invertebrates and native fish through predation and competition and they can also alter the algae community composition (Figueredo & Giani 2005, Mamun et al. 2023). The invasive African sharptooth catfish (*Clarias gariepinus*) has reduced populations of native fish species significantly through predation (Mukul et al. 2020, Khan et al. 2021). Moreover, with breeding populations established in at least 17 rivers across Bangladesh, the vermiculated sailfin catfish (*Pterygoplichthys disjunctivus*) has adversely impacted populations of native cyprinids (Parvez et al. 2023) and native minnows (Hossain et al. 2018). At least five of the introduced carp species have become invasive species and had a detrimental effect on native flora and fauna in Bangladesh (Mukul et al. 2020). They contribute to the erosion of banksides, increase turbidity and the re-introduction of nutrients into the water column through uprooting vegetation while grazing (Lougheed et al. 1998, Mukul et al. 2020).

The recent introduction of *Penaeus vannamei* for commercial culture in Bangladesh may pose significant ecological risks by disrupting local food webs. The species' nonselective feeding behaviour and potential successful reproduction could lead to it becoming an invasive population and out-competing native shrimp species – already experienced in

Table 2
Introduced and invasive fish species reported in Bangladesh with the origin country of introduction and year. F – Food, O – ornamental.

Family	Scientific name	Common name	Use	Native range	Origin Country	Year
Chanidae	Chanos chanos	Milkfish	F	Indo-Pacific	Philippines	1996
Cichlidae	*Clarias gariepinus*	African sharp tooth catfish	F	Africa	Thailand	1989
	Oreochromis mossambicus	Common tilapia	F	Africa	Thailand	1954
	Oreochromis niloticus	Nilotica	F	Africa	Thailand	1975
Cyprinidae	*Barbonymus gonionotus*	Thai Sarpunti	F, O	Southeast Asia	Thailand	1986
	Carassius auratus	Goldfish	O	China	Pakistan	1953
	Ctenopharyngodon idella	Grass carp	F	China, Russia	China, Japan, Nepal	1966, 1970, 1979
	Cyprinus carpio	Common/Mirror carp	F, O	Central Eurasia	India, Nepal	1960, 1979
	Hypophthalmichthys molitrix	Silver carp	F	China, Russia	Hongkong, Japan	1969/70
	Hypophthalmichthys nobilis	Bighead carp	F	China	Nepal; China	1981
	Mylopharyngodon piceus	Black carp	F	China	China	1983
Loricariidae	*Pterygoplichthys multiradiatus*	Orinoco sailfin catfish	O	South America	South America	1980
	Pterygoplichthys disjunctivus	Vermiculated sailfin catfish	O	South America	South America	1980
	Pterygoplichthys pardalis	Amazon sailfin catfish	O	South America	South America	1980
Osphronemidae	*Trichopodus pectoralis*	Snakeskin gourami	F, O	Southeast Asia	Singapore	1952
Pangasiidae	*Pangasianodon hypophthalmus*	Iridescent shark	F, O	Thailand, Indochina	Thailand	1990
	Pangasius sanitwongsei	Giant pangasius	F	Thailand, Indochina	Thailand	1990
Poeciliidae	*Gambusia affinis*	Western mosquitofish	O	Mexico, USA	North America	1930/40; 1972/73
	Gambusia holbrooki	Eastern mosquitofish	O	Mexico, USA	North America	1930/40; 1972/73
Poeciliidae	*Poecilia reticulatus*	Guppy	O	South America	Thailand	1957
Serrasalmidae	Pygocentrus nattereri	Red-bellied piranha	F, O	South America	Thailand	2000

Sources: Barua et al. 2001, Pallewatta et al. 2003, Ahasan et al. 2003, DoF 2011, ISSG 2011, Sarkar et al. 2011, Mukul et al. 2021, Froese & Pauly 2022, CABI 2023

Thailand (Senanan et al. 2007, 2010, Panutrakul et al. 2010).This highlights the need for thorough investigation and understanding of the ecological consequences of this emerging invasive species in Bangladesh.

Declines in native species as a consequence of IFS can affect biodiversity and result in genetic depletion (Canonico et al. 2005, Arthur et al. 2010), in turn, contributing to disease susceptibility. This also increases their susceptibility to pathogens associated with the invasive species. Examples of impact include heavy mortalities of native finfish species across Bangladesh between the 1980s and 2000s as a consequence of Epizootic Ulcerative Syndrome disease, likely introduced by the silver barb (*Puntius gonionotus*) (Islam et al. 2003).

Addressing the challenge: As Bangladesh continues to expand its aquatic food production, the contribution and introduction of alien species is steadily increasing (De Silva et al. 2006) as is the case more generally across South Asia (Constantine et al. 2022). Implementation of improved and more strict biosecurity measures to prevent escapees and minimise disease spread is urgently needed. Under the United Nations Convention on Biological Diversity (CBD), the National Biodiversity Strategies and Action Plans (NBSAPs) and the Sustainable Development Goal 15.8, Bangladesh has committed to preventing the introduction and controlling or eradicating invasive alien species (IAS). However, Bangladesh faces significant challenges in enacting those targets, such as limited data availability and resources, competing demands and a lack of an efficient invasive species system (ISS) with a central coordinating body that brings together relevant institutions and ensures the implementation of policies backed by the GOB (Williams et al. 2021, Constantine et al. 2022).

Bangladesh has yet to implement a National Invasive Species Strategy and Action Plan (NISSAP) and understanding of the current functioning of the invasive species system within the country requires further investigation. Adopting a theoretical framework proposed by Williams et al. (2021), where key actors of the ISS are engaged through a participatory approach, could help to assess the effectiveness of Bangladesh's ISS and improve collaboration between research and governmental bodies for the management of invasive species. On a regional scale, facilitating training on advanced aquaculture techniques and access to expert advice is crucial to implementing conservation and IAS management measures. For example, propagating the use of monosex or sterile fish, such as tilapia, reduces the risk of escapees outcompeting or hybridising with native species (Rahman et al. 2018, Kunda et al. 2021, Das et al. 2022).

5. Future prospects for aquaculture in Bangladesh

The GOB aims to increase inland aquaculture production by nearly 14% within the surface area of 7972 km^2 of inland waterbodies (Table 1; Supplementary Materials 1), which equates to a production increase of 4377,800 kg/km^2 by 2025. For this to occur sustainably, industry management will need to be more closely aligned with minimising environmental impacts and ensuring natural resource protection. Some of the changes required for greater sustainability of large-scale intensive systems include the need for advancements in culturing and post-harvesting technologies and significant investment in infrastructure. For the smaller, more common individual and farmstead productions, there is the need for facilitation of training and more modest resourcing to optimise traditional production systems, with an emphasis on water conservation, water quality maintenance and improvement, waste control, and minimising natural resource exploitation. Examples of where trials have taken place and/or the methods to achieve elements of the above in Bangladesh can be seen in Table S2 (Supplementary Material 2).

In exploring the environmental sustainability issues for aquaculture in Bangladesh in this review it is important to acknowledge that quantifying the direct impact of current aquaculture practices on many environmental features from a country-wide perspective is difficult, albeit for many effects on the environment these are negative impacts. Additional research is crucial to better quantify aquaculture impacts, such as those on biodiversity, and to help guide future policy and regulation efforts supporting best practices and technological solutions. The approaches identified (Fig. 3) have great potential for supporting improvements to the environmental sustainability of fresh and brackish-water aquaculture in Bangladesh. However, their effectiveness relies heavily on active drivers for their implementation and enforcement (as well as management understanding). Effective policies are needed to advance sustainable aquaculture, regulate use of natural resources and ensure adherence to environmental standards. In Bangladesh aquaculture policy, which belongs to the National Fisheries Policy, has not been updated since its development in 1998, although recent workshops have been organised to revise the policy (Hossain 2022) and with support from FAO, in 2014 GOB released a national aquaculture development strategy and action plan for 2013–2020 (GOB & FAO 2014). With the action plan timeline having expired (2020) and considering the rapid growth of the industry, as well as the evidence base of its effects on the environment, a new government strategy is warranted. The solutions

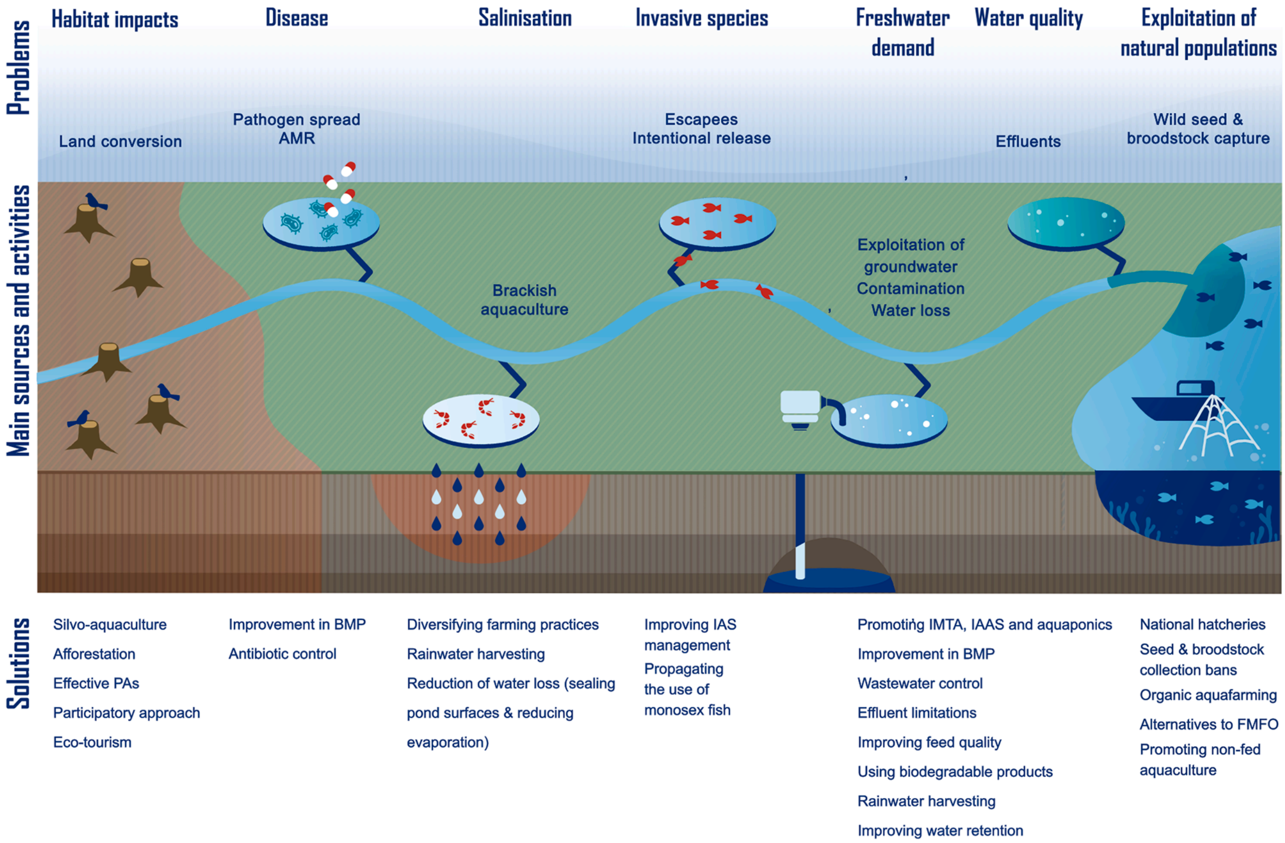

Fig 3. Summary of measures and methods with the potential to mitigate or limit the environmental impacts of inland aquaculture in Bangladesh.

supporting greater environmental protection in this review will require a collaborative, multi-sectoral and trans-disciplinary approach, with an action plan following the principles of One Health to achieve benefits for the health of citizens, non-human organisms and the environment they share (Stentiford et al. 2020). To enable, and direct this, discrete units within Government departments responsible for overseeing the nation's aquaculture production aspirations are needed, and ideally working in conjunction with the support from the GOB and NOGs at local and national levels (FAO 2022). However, it is crucial to keep the farmers at the heart of these collaborative activities. Government-supported training programs and incentives would help to encourage farmers to adopt resource-efficient cultivation methods. Moreover, peer-to-peer learning has been vital for the success of aquaculture in Bangladesh and remains a powerful method for disseminating beneficial practices. While both negative and positive approaches may be replicated, directing social learning towards sustainable farming practices and leveraging the influence of lead farmers, could amplify the impact of training.

Implementation of BMP, designed for Bangladesh and promoting the principles of sustainability, including through technological advancements, would help mitigate the negative environmental effects of aquaculture, particularly in the case of shrimp/prawn farms, that historically have arisen from poor planning and ineffective enforced management (Paul and Vogl 2011). Programs of improved shrimp BMPs have been applied in India, Ghana, Honduras and Nicaragua, reducing environmental impacts, empowering small-scale fishers and improving yields (Engle and Valderrama 2006, Umesh et al. 2010, Ansah and Frimpong 2015, Sivaraman et al. 2019), and may serve as useful guides for action in Bangladesh. Improving the management practices would also support Bangladesh's aquaculture on its journey to comply with the requirements of aquaculture certifications and expand its export market. Modern consumers are increasingly aware of animal welfare and environmental standards for food production, relying on certifications such as Aquaculture Stewardship Council (ASC) or Global Good Agricultural Practice (Global G.A.P), to guide their choices and are willing to pay more for products with environmental certifications (Smetana et al. 2022). Implementing certifications for finfish would increase the profits of farmers and the environmental integrity of the industry, ensuring long-term viability and improving reputation (Haque et al. 2021).

The establishment of PAs and education on property rights can be used to motivate communities to protect surrounding natural habitats and the ecosystem services they offer. Such common pool resource system has been applied in other LIMCs, for example by the Zanjera irrigation community in the Philippines where it has helped avoid overexploitation of water resources (Yabes and Goldstein 2015). The concept of community management has also been applied in Bangladesh, in the Daudkandi FPA, which has now become a model adopted by over 90 similar FPAs, although the relative success of the system has been debated (Toufique and Gregory 2008, Bayazid 2016). The FPA clearly defined boundaries and use of common pool resources, with the help of a lease and shares system helps manage engagement with the area, while the shareholders are directly involved in establishing and making changes to the operational rules of the FPA (Bayazid 2016). Another key to the success of the model is accountability, ensured by monitoring through salaried employees who oversee compliance with the operational rules and enforce sanctions when the rules are breached (Bayazid 2016). The challenges of implementing this model more widely relate to ensuring compliance with the rules at the "field level" and establishing a new property rights regime which can be a complex process (Bayazid 2016).

Zonation of land for specified activities, based on for example GIS-supported spatial planning (Hossain et al. 2007, Gimpel et al. 2018), could help diversify land use and help buffer the negative environmental impacts of aquaculture. Improving spatial planning and the use of less ecologically sensitive lands as means for habitat and biodiversity conservation is essential in balancing the need for growth with the protection of natural ecosystems. Implementing an objective index which takes into consideration multiple parameters of ecosystem health, such as the aquatic health index proposed by Barua and Rahman (2020), could also help guide the expansion and choice of optimal habitats for aquaculture and conservation.

More work is needed to understand how different aquaculture activities impact biodiversity and ecosystem health, as these data are severely lacking. Moreover, these analyses have to consider habitat modification and freshwater use in the context of localised climate change impacts, such as floods, drought and rainfall variation in north-central Mymensingh (Ahmed and Diana 2016) and sea-level rise in southern regions (Pethick and Orford 2013) and how these changes will impact on the environmental sustainability of aquaculture.

Finally, in considering Bangladesh's future need for aquaculture production, the country's coastline, extending nearly 710 km, includes some prime areas for expanding aquaculture into the sea and easing the pressure of farms on land (Islam and Shamsuddoha 2018). Blue growth can help to alleviate freshwater pollution and eutrophication as well as land usage changes and habitat modification associated with freshwater aquaculture (Amon et al. 2022), minimising on-land impacts (Gulam Hussain et al. 2017, Sarker et al. 2018). However, the promotion of sustainable mariculture would have to occur with great consideration for potential challenges and risks to the coastal and offshore environment, which have been extensively covered in recent literature (Taylor and Kluger 2018, Brown et al. 2020, Bujas et al. 2023, Narwal et al. 2024).

6. Conclusions

Aquaculture is vital for feeding the growing global population, including in Bangladesh, with major contributions to the quality of human livelihoods and the country's economy. However, to date, for some aquaculture sectors this has incurred significant environmental costs in terms of water usage, contamination impacts, natural habitat degradation and biodiversity loss. Without changes in some of the cultivation practices, the proposed projections for aquaculture growth will result in further divergence from environmental sustainability. To achieve benefits for the health of humans and animals, a well-defined government strategy following One Health Aquaculture principles and an action plan for the development of more sustainable approaches in aquaculture in Bangladesh are vital. Actively promoting sustainable practices, such as IAAS and IMTA, improved feeds, altering water use patterns, offsetting contamination, and conserving and rebuilding natural habitats are all key elements for the implementation of an environmentally sustainable future for the aquaculture industry. Application of these solutions nationally however will require significant coordination and financial commitments to invest in farmer support and training, modifications of the current culture systems, and infrastructure development, most notably for the more intensive commercial production systems. NGOs and governing bodies will need to support these activities at local and national levels. Against this backdrop, more transdisciplinary studies are needed to better quantify how different aquaculture species and forms impact biodiversity and ecosystem health in Bangladesh, and how habitat modification and freshwater use are affected by these aquaculture practices and their proposed expansion. Educational and training programs are necessary to disseminate research-led innovations and information among the farmers and ensure the widespread application of practice improvements. Embracing science-based decision-making and adaptive management on a regional scale will be instrumental to achieving a profitable, but importantly, sustainable expansion of Bangladesh's aquaculture sector, as it will for the aquaculture sector globally.

CRediT authorship contribution statement

Konstancja Woźniacka: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Lisa K. Bickley:** Writing – review & editing, Writing – original draft. **Richard D. Heal:** Writing – review & editing. **Ilya M.D. Maclean:** Writing – review & editing, Project administration. **Neaz A. Hasan:** Writing – review & editing. **Mohammad Mahfujul Haque:** Writing – review & editing. **Grant D. Stentiford:** Writing – review & editing. **Regan Early:** Writing – review & editing, Project administration. **Michelle Devlin:** Writing – review & editing. **Charles R. Tyler:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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