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Evaluating the potential of innovations across aquaculture product value chains for poverty alleviation in Bangladesh and India

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Evidence is presented that innovation across aquaculture value chains can contribute to poverty reduction through income generation and increased consumption of nutritious aquatic foods. Innovation is defined and contextualized in relation to aquaculture development. Opportunities for aquaculture innovation across value chains for poverty reduction and sustainable production are described. Contemporary trends in aquaculture development in Bangladesh and India, with a focus on 2011-2020, are reviewed, as understanding transformative change to aquatic food systems during this period could benefit millions of poor and marginal consumers. Market-led commercial production, instigated by private sector entrepreneurs for domestic markets, has underpinned the surge in freshwater fish culture in key geographical locations. In contrast booms in shrimp production have been associated with export opportunities and related cycles of boom-and-bust have been described, with busts attributed to falling market prices and disease outbreaks. Innovation could safeguard supplies of affordable fish to poorer groups (especially young children and pregnant and breastfeeding women) and enable better health management of aquatic animals including coordination of surveillance and disease control measures. Innovation to effectively promote better management practices and integrated services provision to large numbers of small- and medium-scale producers could contribute to poverty reduction. Opportunities for future innovation to ensure that aquaculture development is sustainable are critically reviewed. Innovative strategies to add value to by-products and utilize waste resources could avoid negative environmental impacts, recycle nutrients and create income generating opportunities. A new paradigm for development assistance that identifies and supports promising innovation trajectories across jurisdictions, product value chains, institutional regimes and food systems is needed. Government agencies must be responsive to the needs of businesses throughout aquatic food systems and devise policies and regulatory regimes that support transformative and sustained growth of the aquaculture sector. Investment in capacity-building, education, research and training and action to promote an enabling institutional environment must be regarded as essential elements to maximize and share equitably the benefits arising and avoid potential negative impacts of inappropriate innovations.

KEYWORDS

food security, food systems, nutrition security, promising innovation trajectories, radical innovation, systems architecture innovation, technological innovation, transformative change

1 Introduction

1.1 Aims of this review

The purpose of this review was to contextualize and evaluate opportunities for innovation across aquaculture value chains to alleviate poverty in Bangladesh and India. In this regard, poverty alleviation was defined here as achieving improved food and nutrition security, income or socioeconomic development for people in rural communities engaged in aquaculture and living on less than the national average income in 2020 of US$ 5.6 and US$ 4.6 per day in Bangladesh and India, respectively (World Bank, 2022a)[1]. Specifically, we formulated two questions to guide this review. What are the most promising aquaculture production systems and geographical locations where development funding to stimulate innovation could enhance poverty reduction? What are the most promising innovations across aquaculture product value chains that could enhance poverty reduction? The approach to answering these questions is outlined below.

We commence by defining innovation in the context of aquaculture development. Evidence that aquaculture innovation can contribute to poverty reduction is presented. Mechanisms by which aquaculture innovation could be stimulated to reduce poverty through enhanced income generation and human nutrition are reviewed. Opportunities for innovation to contribute to sustainable aquaculture development[2] are discussed. Analysis of the status and recent significant growth in aquaculture in both Bangladesh and India is presented. The assessment of the location and scale of innovations provides evidence of the geographical settings in which aquaculture development has contributed to poverty reduction and how many people have benefited. Medium- and large-scale producers are included within the scope of this review as increased production on such farms can result in employment and make fish more affordable for poor consumers.

A systematic assessment is then presented of examples of aquaculture production systems (and associated value chains) that have had a significant and sustained impact in terms of poverty alleviation. Opportunities and constraints for poverty alleviation across value chains are reviewed, as is the role that innovation has played. Prospects for innovations to have unintended negative impacts on poor groups without the means to innovate or associated with other value chain stages are considered.

1.2 Innovation in the context of aquaculture development for poverty alleviation

Aquaculture in Bangladesh and India makes a significant contribution to fish supplies and provides employment and income for millions of people (Toufique and Belton, 2014; Belton et al., 2016; Belton et al., 2017; Belton et al., 2018). Considerable development investment was targeted in the past at interventionist project-based innovation to bolster production from homestead ponds to benefit poor people directly (Belton and Little, 2011). In certain cases, such as the Adivasi project in north and northwest Bangladesh targeting very marginalized communities from 2007 to 2009, significant improvements were possible as the focus was on livelihoods diversification and interventions were 'tailored to the needs and capabilities of target households' (Pant et al., 2014, p. 1). Frequently, however, poor households engaged in agriculture do not have access to sufficient water, labor or good quality inputs, notably seed, to successfully adopt aquaculture. The uptake of aquaculture can lead to a conflict of interests and competition for resources with existing uses. External support (e.g. training and subsidized inputs) for smallholder-oriented aquaculture promotion can however result in encouraging uptake rates and reasonable production levels. Farming households will also invest (money, on-farm resources, time and energy) differently in aquaculture related activities resulting in a range of outcomes. The overall contribution to diversified 'household farm enterprises' may, however, be small (Belton and Azad, 2012, p. 197) and gains can be short-lived when farmers decide not to invest further after support is withdrawn (Belton and Little, 2011).

Integrated agriculture-aquaculture (IAA) systems that combine terrestrial and aquatic crops within farming systems to optimize resource use efficiency and minimize dependence on external inputs can be important for promoting social-ecological resilience (Bunting et al., 2017). Notable examples such as tilapia seed production in rice fields (Barman and Little, 2006) have been cited as evidence that interventionist innovations can work. Even when innovations result in minimal financial gains, adoption and continued use can be attributed to synergistic effects across agroecosystems or broader social considerations

1 .The World Bank (2022c) revised global poverty lines in September 2022 with US$ 2.15 per day taken to indicate extreme poverty in low-income

2 Sustainable aquaculture development is defined here as the process of promoting and achieving medium- to long-term economic development and social development, whilst ensuring environmental protection.

(Haque et al., 2010; Belton and Little, 2011). Production and sale of fruit and vegetables from IAA systems can be important both for income generation and food and nutrition security for producer household members and local communities (Karim et al., 2011; Pounds et al., 2022). A follow up study on the status of rice field juvenile fish production in northwest Bangladesh identified some major changes (Pounds et al., 2023). Some producers that had stopped producing fish seed in rice fields attributed this to fragmentation of landholdings owing to inheritance dynamics and limited time availability due to increased off-farm activities. On-growing of hatchery-sourced riverine carp species to produce large fingerlings is now the prevailing business strategy, and these are either sold on or used by the farmers for restocking their own ponds and rice fields.

Immanent development, defined as 'a broad process of change in human societies driven by a host of factors including advances in science, medicine, the arts, communication, governance and markets etc' (Morse, 2008, p. 341) occurs alongside interventionist actions. It has been noted that access to infrastructure (e.g. electricity, rail services, roads, sewerage and docks or piers for cage-based operations), functioning markets (e.g. auction markets in shrimp/fish growing areas so prices are transparent), input suppliers, service providers and credit, for example, can be prerequisites for successful aquaculture development (Beveridge, 2004; WorldFish, 2007; Hernandez et al., 2018). Recent evidence has demonstrated that large-scale production from immanent commercial freshwater aquaculture in Bangladesh and India has had a transformative effect, making fish more affordable for poorer consumers nationally (Little et al., 2012; Belton et al., 2016; Béné et al., 2016; Hernandez et al., 2018). Income generating opportunities across product value chains benefit large numbers of poor people. In 2014 the number of fish farmers and rural fish traders in major clusters across Bangladesh stood at 1.76 million and 31,300, respectively (Hernandez et al., 2018). These authors noted that compared to a baseline in 2004, the number of feed dealers (n = 15,483), hatcheries (n = 761) and feed mills (n = 255) in 2014 had increased by 201%, 207% and 268%, respectively. Changes observed were attributed to investments by several hundred thousand mostly small-scale actors across aquatic food systems in the country.

Commercial aquaculture meeting domestic demand in Asia is subject to cycles of boom and bust observed in other commodity markets (Belton et al., 2017). Such cycles are driven by serial and parallel innovation by early adopters as margins decline in various activities stimulating further innovation (e.g. the transition from carp species to pangasius (*Pangasianodon hypophthalmus*) (also commonly referred to as striped catfish) and pangasius to a range of alternatives in Bangladesh). Whilst the aquaculture sectors continue to grow and intensify in both Bangladesh and India, outputs could be negatively affected by fish disease outbreaks and deteriorating water quality in poorly managed ponds. Consequently, innovation across value chains (e.g. seed and feed quality improvement, better biosecurity, enhanced post-harvest handling and processing to avoid spoilage and preserve quality) and aquatic food systems more generally, must be supported to avoid barriers to growth and enhance and safeguard the contribution of aquaculture development to poverty reduction.

2 Aquaculture innovation and poverty reduction

2.1 Aquaculture innovation for food and nutrition security

Fish and other aquatic foods are key parts of human diets but supplies from wild sources (fisheries) have limited scope for expansion, just as demand is accelerating through population growth and rising per capita consumption (Pauly and Zeller, 2016; Edwards et al., 2019). World marine capture fisheries landings declined from an average of 81.9 million tons per year in the 1990s to 78.8 million tons in 2020 (FAO, 2022b) and this equates to a reduction of 4.27 kg per year in global per capita fish supplies from this source. Sustainable aquaculture development could help maintain and extend per capita fish consumption (Gephart et al., 2021a), but it is uncertain if recent growth rates can be maintained (aggregate global growth of 8% per year between 2000 and 2015) and calls are growing to secure future aquatic food supplies.

Innovation across aquatic food value chains has been critical to food and nutrition security needs being met more broadly, but commentators have questioned if the aquaculture sector is innovating fast enough and in the right way to ensure sustainable fish supplies into the future (Edwards et al., 2019; Tigchelaar et al., 2022). Processes of innovation are defined here as combining technological and systems architecture innovation (Henderson and Clark, 1990). The first refers to the refining of existing production systems and practices, inventing new technologies and products or generating and applying new knowledge, techniques and processes. Systems architecture innovation is the reconfiguring or relocating of production systems, implementing new management procedures or entering into collaborative relationships and consolidated business arrangements.

Aquaculture, in historical terms a novel food production system, has itself been an innovation (Beveridge and Little, 2002). In places where it has become established and benefitted those involved, whether coastal Norway or peri-urban Asia it has changed resource use and led to a new range of human activity (Little and Bunting, 2005; Tiller et al., 2017). Aquaculture development as a duality is a common view i.e. 'modern' technologically advanced and corporate as distinct from traditional, small-scale and household managed. However, this simplification has been challenged (Bush et al., 2019) by evidence that it has been small and medium sized enterprises (SMEs) and associated value chains that have driven rapid growth in selected Asian countries (e.g. Bangladesh and Myanmar) where aquaculture is now important in supplying aquatic foods nationally. This highlights the importance of understanding how innovation differs across aquatic food systems and particularly if the innovation processes in technologically advanced aquaculture have relevance to support innovation in countries with many poor and vulnerable people such as Bangladesh and India.

Concerning the future of food security and human nutrition, a 'perfect storm' of global population growth, resource competition, increased energy and input costs, water scarcity and climate change impacts is forecast (Beddington, 2010). Driving forces for chronic food insecurity globally were reviewed by The Royal Society (The Royal Society, 2009). Drivers of change for the aquaculture sector reflect those for food production generally and include: consumption patterns; economic development; international trade; market demand; rural-urban migration; standards assurance and certification; urbanization (Béné et al., 2016). Conscious of the global challenges facing humanity, the Sustainable Development Goals (SDGs) ratified by signatories to the United Nations' 2030 Agenda for Sustainable Development call for urgent action (United Nations, 2015). Sustainable aquaculture development has potential to contribute to each of the seventeen SDGs (ASC, 2022; Bunting et al., 2022). Aquaculture development can result in greater availability and access to affordable aquatic foods, create income generating opportunities and contribute to enhanced socioeconomic development and wellbeing for people in poor and marginal communities. Improved sustainability of food production systems requires food losses across value chains to be drastically reduced and waste generation eliminated through prevention, reduction, recycling and reuse (United Nations, 2015).

Aquatic production has often been side-lined from food systems research and policy (Thilsted et al., 2016; Tlusty et al., 2018) but is critical in human nutrition systems, especially in food-insecure contexts. Globally, diets are tending toward higher levels of meat (including aquatic animal source foods) and dairy products, but this can culminate in excess consumption with negative human health and environmental impacts. Sustainably cultured fish are a critical constituent of future diets to supply essential nutrients and maintain food production within the carrying capacity of supporting ecosystems locally and globally (Gephart et al., 2021b; Shepon et al., 2021). Transition from eating wild caught fish to cultured species could affect the nutritional intake of consumers (Little et al., 2016; Bogard et al., 2017) and dietary advice could adapt accordingly to optimize health outcomes, especially for pregnant women and children prior to their second birthday (1000 Days).

The populations of both India and Bangladesh are increasing at 1% annually (World Bank, 2022d) and in 2021 reached 1.39 billion and 166.3 million, respectively (World Bank, 2022b). Aquaculture production in India and Bangladesh was 8.64 and 2.58 million tons in 2020 and accounted for 11.2% and 3.3% of Asian output, respectively (FAO, 2022b). This equates to a national annual average of 6.2 kg per person in India and 15.5 kg per person in Bangladesh. Markedly different per capita production levels reflect demand from domestic markets and the incredibly heterogenous diets in these neighboring countries. National average values mask variation in consumption patterns within countries and between households and individuals; for example, owing to geographical differences, religious beliefs and socio-economic status (Naylor et al., 2021). Poor households in Bangladesh typically depend on rice as a staple food source and have low levels of dietary diversity making them vulnerable to malnutrition and external shocks (Ali et al., 2021). Meat and fish were found by these authors to make a significant contribution to daily energy intake amongst rich households in Bangladesh that tend to consume wheat and have a high dietary diversity. Marked geographical differences in diets in India are apparent when it comes to deficits in the consumption of animal source proteins, fruits, legumes and vegetables (Sharma et al., 2020). These authors noted that in the central, north and west regions, daily per capita caloric intake from fish was only 1-4 calories per day and increased to 16 calories in the east and south and 22 calories in the northeast, as compared to a recommended intake of 40 calories in the EAT-Lancet reference diet for healthy and sustainable food systems globally (Willett et al., 2019). Consequently, assessments of demand and supply must account for such variations to better guide investment and support to promising innovation trajectories with potential to alleviate poverty.

Recent intensification and commercialization of aquaculture in Bangladesh resulted in production increasing rapidly from 0.54 to 1.27 million tons in 2004 and 2014, respectively, with a concomitant increase in employment opportunities (Hernandez et al., 2018). Aquaculture production destined for domestic markets in 2010 was more than 90% of the total national output (Belton et al., 2018) and accounted for over 50% of the 18.1 kg y^{-1} average per capita fish consumption in Bangladesh (Toufique and Belton, 2014). Production from aquaculture here has resulted in more affordable fish, thus increasing consumption amongst both the moderate and extreme poor. Similarly, the recent and rapid expansion in striped catfish culture in Andhra Pradesh (AP), India to 0.5 million tons in 2018 (Mohan et al., 2019) has benefited domestic consumers with most being sold to 'lower income' groups in other states (Belton et al., 2017, p. 203). Aquatic food consumption in India during the period 2017-2019 was estimated at 5-10 kg per capita per year (FAO, 2022b) but is generally well below recommended levels for heathy and sustainable diets (Sharma et al., 2020).

To achieve food and nutrition security, production strategies, aquatic product value chains and associated regional food systems must be sustainable (HLPE, 2020; Cohen et al., 2021; Pounds et al., 2022). Conventional aquaculture production is characterized by innovation to produce faster growing strains, fed increasingly on plant-based ingredients, that compete with terrestrial livestock in expanding urban markets. Comparable innovation trajectories have made chicken probably the least impactful terrestrial animal source food available based on most Life Cycle Assessment (LCA) studies (Pelletier and Tyedmers, 2007; Tlusty et al., 2018). Enhanced environmental management systems irrespective of the production scale or management intensity (i.e. formal schemes for firms e.g. ISO14001 or better management practices [BMPs] by small-scale operators) (Bunting, 2013) and adoption of integrated cultivation practices (e.g. combining aquatic food production with crop and livestock farming or polyculture and rotational cropping practices) can bolster agrobiodiversity on farms, contribute to climate change adaptation and mitigation and enhance social-ecological resilience (Bunting and Pretty, 2007; Ahmed et al., 2014; Bunting et al., 2015; Bunting et al., 2017; IPCC, 2019).

2.2 Identification and support for innovation to enhance poor incomes

Aquaculture innovation theoretically can contribute to poverty alleviation either incrementally, making poverty less severe through enhanced income and consumption of nutrient-dense aquatic foods, or be a transformative change agent when large-scale culture rapidly develops and makes fish more affordable and expands employment opportunities (Little et al., 2012; Costello et al., 2020). Large-scale development can generate a cluster effect and associated economic spill-overs have been modelled for aquaculture development in Myanmar (Filipski and Belton, 2018) and described more broadly in Asia (Belton and Little, 2011). Devising more effective and efficient means of supporting innovation for sustainable aquaculture development is of rapidly growing importance.

Establishment of successful private sector hatcheries for riverine carp species and the emergence of informal local markets for trading live fingerlings have been key factors stimulating commercialization in northwest Bangladesh (Pounds et al., 2023). In general, positive outcomes depend on enabling environments, such as market development, non-cumbersome regulatory regimes and value chain actors that are willing to innovate, pivot and specialize (Pounds et al., 2023), to support the uptake and retention of aquaculture by farming households. Crucial to this may be the inclusion of women, who, across Bangladesh and India are largely excluded from key nodes of aquaculture value chains and/or their roles undervalued in contrast to other areas of rapid aquaculture development in Southeast Asia and West Africa.

Aquaculture development projects targeting lower income groups (e.g. seed traders, producers and consumers) can be effective at problem identification and formulating and testing practical solutions (Joffre et al., 2017). Issues with carp seed supplies and on-growing in Bangladesh were identified and addressed through investments in improving seed quality combined with farmer training targeting the poor and women (Karim et al., 2016). Opportunities for poor ethnic minority groups in Bangladesh to engage in aquaculture and associated product value chain income generating activities were identified and capacity-building provided to realize increases in fish consumption, incomes, and savings amongst participants (Pant et al., 2014). Concerns have been raised, however, that claims made for change achieved by project-based actions are often excessive as the overall impacts on diversified livelihoods of participants are modest (Belton and Little, 2011).

Development assistance to achieve the cost effective and efficient uptake of improved or BMPs could ensure that modest benefits are replicated and captured by millions of poor people, and this could help 'reduce the severity of poverty' (Belton and Azad, 2012, p. 200). Immanent development processes proceed in tandem with interventionist actions. Immanent developments in terms of striped catfish and tilapia (*Oreochromis niloticus*) culture in Mymensingh District, Bangladesh, and carp, tilapia and striped catfish culture in AP, India, over the past decade have resulted in a marked increase in the supply of affordable fish to domestic markets (Belton et al., 2016). Targeting support at 'promising innovation trajectories' (Sulaiman et al., 2011, p. 36) across value chains to mitigate and adapt to cycles of boom and bust inherent in farming commodities could safeguard and increase supplies of affordable fish to lower income groups (Barman and Little, 2011; Belton et al., 2017). Challenge prizes designed to initiate and accelerate innovation to achieve a specific goal have been used to tackle major problems, including antimicrobial resistance (Nesta, 2019). Recently, challenge prizes have been used to stimulate innovation in replacing fish oils in feed and bolstering production globally with enhanced technology and data use (F3; Global Aquaculture Challenge, 2020). Using challenge prizes for poverty reduction though innovation in the aquaculture sector would be new and require the formulation of appropriate monitoring and evaluation strategies (Gould et al., 2020).

Better handling, cold chain management and storage facilitates could reduce food losses, and innovative processing and packaging solutions could extend the shelf-life of products (Gustavsson et al., 2011; Belton et al., 2017). Making better use of processing by-products could reduce waste and add value to aquaculture production (Yan and Chen, 2015; de la Caba et al., 2019). Crucially these innovations may have relevance to, and impacts on, poorer people. Maintaining integrated production practices may be more labor intensive but they create employment and enable people to eat nutritionally balanced diets that are healthy and sustainable (Newton et al., 2021). Furthermore, by-products may be priced at levels that are affordable to poorer people (e.g. giant freshwater prawn (*Macrobrachium rosenbergii*) heads are poor peoples' food in Bangladesh).

2.3 Innovation for enhanced socioeconomic development

Aquaculture development can result in an array of economic, environmental and social impacts, both positive and negative (Edwards, 2015). Various factors, however, can stifle innovation thus constraining development of the sector in promising locations that could otherwise contribute to poverty reduction. Innovation across product value chains can create income generating opportunities for poor people, reduce waste and capitalize on opportunities for upgrading (product, process, functional and inter-chain) (Ponte et al., 2014). Adverse environmental and social impacts of poorly planned and managed aquaculture can stimulate innovation, both technical and institutional. Farm area management agreements have been developed in the Scottish salmon farming sector to counter recurring disease outbreaks and waste dispersion models are used by regulators to support decision-making on new cage site lease applications (Ross et al., 2013; Salmon Scotland, 2022). Lessons learned here could help the emerging cage sectors in Bangladesh and India avoid problems of conflict and exceeding the carrying capacity of supporting ecosystems witnessed in Indonesia (Taskov et al., 2021).

Responsibly planned and managed aquaculture development can: help achieve habitat restoration (Muir, 2005); sequester nutrients and carbon (Wahab et al., 2003; Ahmed et al., 2017); contribute to productive multiple-use of urban water bodies (Evans et al., 2014); facilitate wastewater management when combined with appropriate policies to safeguard public health and the rights of producers (Bunting and Edwards, 2018); bolster agrobiodiversity that sustains social-ecological resilience (Amilhat et al., 2009; Bunting et al., 2015). We now summarize past innovations in the aquaculture sectors of Bangladesh and India that contributed to aquaculture development, reduced dependence on wild seed, avoided waste across value chains and mitigated disease risks, although they sometimes had negative environmental impacts locally.

Carp culture in Bangladesh and India during the first half of the 20th century was largely dependent on wild caught seed of native Indian major carp species [catla (*Catla catla*); mrigal (*Cirrhinus* *cirrhosus*); rohu (*Labeo rohita*)] from rivers (Jhingran, 1991). Fish hatcheries appear to have developed in West Bengal as it was an established center for seed trade and wild stocks were in decline (Jhingran, 1991); the private sector would have been keen to exploit new technologies to maintain seed supplies and meet increasing demand. Capitalizing on a government initiative to establish commercial hatchery techniques at the Barrackpore research station, clusters of hatcheries such as those in Naihati, West Bengal, innovated through adopting the Chinese system for carp rearing and nursing and subsequently expanded to meet the growing demand for dependable seed supplies (Milwain et al., 2002). Production of introduced Chinese species [common carp (*Cyprinus carpio*); grass carp (*Ctenopharyngodon idella*); silver carp (*Hypophthalmichthys molitrix*)] became an established practice.

Seed from West Bengal were widely distributed to other states, notably AP, where carp grow-out developed rapidly owing to favorable environmental and social characteristics (Belton et al., 2017). The boom in fish culture in AP was fueled by domestic demand in other states, establishment of commercial practices by entrepreneurs and subsequent investment in the sector from an 'urban business class' that 'maintained close ties with their natal villages' (Belton et al., 2017, p. 8). AP has emerged as a crucible for agribusiness innovation owing to: ease of doing business; active entrepreneurs; effective communications; functioning financial services; adaptable governance; favorable climate (Business Standard, 2016; Government of Andhra Pradesh; Borpuzari, 2015). On-growing in West Bengal may have been constrained as land reforms in the 1950s led to the acquisition and redistribution of larger holdings as small parcels of land to poor people, whilst in the 1970s a land ceiling was introduced, and political parties and labor unions were agitating for the rights of workers. In concert, these factors may have discouraged investment in commercial grow-out production in the state. State-wise, time-series data for India are not accessible preventing a comprehensive review of aquaculture development in the country; publications covering developments in Bangladesh are apparently more numerous and available to contribute to policy formulation, management planning and resource allocation. Development of transparent and collaborative processes for tracking innovation in aquaculture value chains through time series data could be a critical function for governments, enabling the identification and support of promising innovation trajectories.

Belton et al. (2017) described how a favorable regulatory environment, combined with local innovation (private hatcheries, nursing hubs, 1000 liter plastic (high-density polyethylene, HDPE) tanks supplied with oxygen from gas cylinders, stunted yearlings, zero-point fingerlings, culture species diversification, increased pond depths, floating feed, mechanization and vertical integration) across a range of value chain nodes and actors led to a massive increase in aquaculture in AP (Belton et al., 2017). A similar sequence of developments was observed previously in Jessore, Bangladesh, where hatcheries switched to buying in broodstock, nursery clusters expanded and innovated to produce fingerlings and stunted yearlings and grow-out farmers were able to dispense with ponds for nursing (ADB, 2005). Analyzing the aquaculture crop booms witnessed in AP, it was concluded that they were a result of 'interlinked technical and institutional innovation and transformations' throughout value chains (Belton et al., 2017, p. 197). This constitutes a prime example of radical innovation resulting in a dramatic boom in food fish production. These authors describe how interspecies technology transfers (e.g. plastic trays used initially for shrimp were adopted for finfish to reduce spoilage) and feed sector innovation, diversifying from producing livestock and shrimp feeds to formulations suited to pangasius, enabled the boom in production and domestic sales.

In AP, fish ponds were constructed in suitable sites around Lake Kolleru, however, owing to a lack of effective governance the rapid development of the sector caused conflicts with other users and wildlife (Nageswara Rao et al., 2010). Although the average size of farms registering with the Department of Fisheries was 2.5 ha these farms were capital intensive and fully commercial, with operating costs per crop of $US 7000 to 12,000 and $US 15,000 to 24,000 ha^{-1} y^{-1}, for carp and pangasius culture, respectively (Padiyar et al., 2014; Belton et al., 2017). Larger fish farms (100-1000 ha) are in operation and account for a 'significant share of total pond area and fish production' (Belton et al., 2017, p. 198). Aquaculture was estimated to occur on 37,750 land holdings, although many leased out their land at $US 2600 to 3300 ha^{-1} y^{-1} (Padiyar et al., 2014). Institutional innovation resulting in a lease market was critical in systems becoming more competitive and efficient.

Building on 'foundations laid by the state's predominantly "traditional" carp and "modern" export-oriented shrimp sectors' farmers in coastal areas of AP affected by shrimp disease problems converted to striped catfish and tilapia production (Belton et al., 2017, p. 203) and other lower value species that were adaptable to saline conditions and not prone to the same diseases as shrimp. This suggests an inherent capacity for innovation concerning both production and marketing and mirrors developments in central Thailand where cycles of boom-and-bust were accompanied by innovations to diversify into novel species (Belton and Little, 2008). Some farmers now rotate between shrimp and finfish to mitigate against disease problems or switch pre-emptively to pangasius and tilapia following successive shrimp harvests if productivity is declining. The affordability of striped catfish to poorer consumers and improvements in reducing spoilage across product value chains meant the fish was sent to other fish-eating Indian states, including Bihar, Jharkhand, Madhya Pradesh and Uttar Pradesh. Rapid expansion of the sector to over half a million tons in 2010 caused prices to collapse and many producers to go out of business. This was followed by diversification into whiteleg shrimp (*Litopenaeus vannamei*) culture which has become a driver for intensification. Species diversification and the consolidation of production in larger, vertically integrated operations constitute pertinent examples of technical and architectural innovation.

Pacu (*Piaractus brachypomus*) culture has emerged as a promising new venture with 18,000 t produced in 2012 (Belton et al., 2017), however, seed supplies for both striped catfish and pacu still originate from West Bengal. There is an apparent lag in technical innovation and capacity-building in support of local seed production. Statistics compiled by FAO (2022a) do not report any pacu farming in India and this may be to do with legality (Sudhi, 2018; Seshagiri et al., 2022) and production could potentially be recorded under 'Freshwater fishes nei' (see Table 1 and accompanying text). Specialization in specific geographical areas owing to environmental and social factors may have stimulated innovation, and commercial operators in centers for seed production in West

TABLE 1 Top twenty aquaculture species produced in Bangladesh and India in 2020 as compared to 2011[†].

Bangladesh: top 20 species	Production volume (t)		India: top 20 species	Production volume (t)	
	2011	2020		2011	2020
1. Striped catfish	156,375	395,131	1. Catla	1,697,977	3,286,134
2. *Roho labeo*	276,813	355,942	2. *Roho labeo*	645,300	1,371,590
3. Tilapias nei[¶]	104,716	328,318	3. Freshwater fishes nei	177,578	1,223,417
4. Silver carp	138,930	246,985	4. Whiteleg shrimp[‡]	125,000	894,772
5. Mrigal carp	158,066	218,783	5. Striped catfish	450,000	613,600
6. Catla	215,328	206,488	6. Silver carp	103,331	549,460
7. Marine fishes nei[‡]	60,290	142,513	7. Mrigal carp	131,793	289,619
8. Freshwater fishes nei	70,118	109,709	8. Torpedo-shaped catfishes nei	0	143,457
9. Common carp	61,637	104,410	9. Marine fishes nei[‡]	52,808	118,724
10. Giant tiger prawn[‡]	56,569	64,688	10. Giant tiger prawn[‡]	125,000	31,032
11. Grass carp (White amur)	21,296	63,481	11. Grass carp (White amur)	103,330	29,072
12. *Labeo bata*	0	54,710	12. Common carp	0	26,070
13. Climbing perch	13,406	54,645	13. Orangefin labeo	7901	15,647
14. Giant river prawn	39,868	51,096	14. Giant river prawn	0	9128
15. Silver barb	47,096	45,961	15. Green mussel[§]	9956	9000
16. Orangefin labeo	36,563	37,161	16. Orange mud crab[‡]	0	7900
17. Philippine catfish	4156	18,654	17. Manipur osteobrama	10,567	5665
18. Kuria labeo	0	18,113	18. Barramundi (Giant seaperch) [‡]	0	5311
19. Stinging catfish	2913	17,220	19. Red seaweeds[§]	4500	5300
20. Orange mud crab[‡]	0	12,562	20. Indian backwater oyster[§]	4058	4000
Total	1,464,140	2,546,570	Total	3,649,099	8,638,898

[†]data source was FAO FishStatJ (FAO, 2022a); cultured in freshwater environments unless otherwise indicated thus - [‡]brackishwater, [§]marine; [¶]'Tilapia nei' is an abbreviation for Tilapia species (grouped together) that are not elsewhere included as individual species e.g. Nile tilapia (*Oreochromis niloticus*) in the FAO database (FAO, 2022a).

Bengal and grow-out in AP continue to innovate in response to market opportunities. Geographical lengthening of value chains has been possible owing to better transport infrastructure and technology and through processing pangasius fillets to supply domestic urban markets in India and for export in the case of Bangladesh (Belton et al., 2017).

Aquaculture has been subjected to blanket criticism for both poor environmental and social impacts (Naylor et al., 1998), and food system impacts at local and global levels are under increasing scrutiny (United Nations, 2015; Willett et al., 2019). Shrimp aquaculture development in Bangladesh and India during the 1980s sometimes involved the conversion of agricultural land to ponds and localized mangrove loss. The areas lost owing to aquaculture in Bangladesh and India amount to approximately 7% and 4% of total original mangrove cover; significantly less than in many other shrimp producing countries (Hamilton, 2013). Timely conservation measures by the governments of the two countries have protected much of their mangrove, notably in the trans-boundary Sundarbans (UNESCO, 2022). Mangrove loss has a direct negative impact on poor people as it provides alternative sources of revenue and employment either directly through the harvest of mangrove wood or non-timber products including aquatic animals for food and aquaculture seed. It also has an indirect effect as it provides a nursery ground and source of food and clean water for productive fisheries and aquaculture. Innovative strategies to re-establish mangroves in conjunction with modifications to aquaculture systems have been developed and can bolster stocks and flows of ecosystem services (Clough et al., 2002; Fitzgerald, 2007; Bosma et al., 2012; Bunting et al., 2013). In Thailand and Vietnam sustainable intensification of shrimp culture has been credited with alleviating pressure on coastal ecosystems and increasing natural resource use efficiency and economic benefits for producers (WWF, 2017).

Rapid development of shrimp farming in coastal areas resulted in periods of social unrest (Deb, 1998), but subsequently the introduction of coastal aquaculture has been credited with promoting economic development and generating income for poor and marginal groups (Milstein et al., 2005). Over the past decade, a proportion of shrimp farming in West Bengal has migrated further inland to intermediate salinity areas where disease problems are less pronounced and switched to stocking whiteleg shrimp as opposed to tiger shrimp (*Penaeus monodon*). Shrimp farmers in Bangladesh were prevented from transitioning to producing whiteleg shrimp owing to a government ban, however, extensive tiger shrimp cultivation continued with significant livelihoods impacts associated with the recruitment of marine species and establishment of free breeding populations (e.g. tilapia). Although yields of shrimp are comparatively low in such ponds, income and yield of other species of fish and aquatic animals combined with rice and vegetable crops is considerable and contributes to enhanced revenues and food and nutrition security for local communities (Bunting et al., 2013; Mamun, 2016; Bunting et al., 2017). Ponds remaining in high salinity areas still produce cultured finfish and shrimp and a modest harvest of wild quality shrimp (Chowdhury et al., 2010) but salinization promoted in part by shrimp culture precludes rice and vegetable cultivation (Faruque et al., 2017). Innovation across the salinity gradient was initiated by a small number of pioneers that tested novel production strategies (e.g. gher farming, dike-cropping, crab fattening and using snails for feed) and these techniques were adopted more widely through inter-household learning, made possible by pre-existing 'strong social networks' (Faruque et al., 2017, p. 14).

Nascent prawn farming capitalized on local feedstuffs, and consequently populations of wild snails were exploited with implications for both their sustained availability, freshwater ecology and livelihoods employed in their collection and transformation for feed (Nahid et al., 2013). Harvesting and processing snails for aquaculture created diverse and extensive employment opportunities for some of the poorest people and snail meat continued to be preferred over formulated diets. Greater dependence on specially formulated feeds may have alleviated pressure on local resources, but sourcing feed constituents from poorly managed capture fisheries merely shifts impacts to other ecosystems and communities (Naylor et al., 1998; Thiao and Bunting, 2022). Collection of prawn and shrimp post-larvae for the aquaculture sector resulted in a significant by-catch of other juvenile marine species (Hoq et al., 2001). Shrimp post-larvae now originate from hatcheries, but for *M. rosenbergii* this remains problematic almost everywhere (including China and Vietnam).

3 Analytical frameworks and findings

3.1 Analytical approach

Analysis concerning the potential of aquaculture innovations to alleviate poverty in Bangladesh and India was conducted by reviewing the scale and geographical distribution of production systems using published accounts and data collated by the Food and Agriculture Organization of the United Nations (FAO, 2022a). The potential of technologies and initiatives and associated challenges, barriers to adoption and benefits were assessed for their relative importance for poverty alleviation in different geographical locations. A systematic evaluation of promising production strategies was conducted against innovation quality criteria formulated as part of this review (see Table 2). The range and scope of technologies, initiatives and promising production strategies to be assessed were agreed jointly by the authors. Opportunities and constraints across product value chains were identified and scored by the authors in terms of their perceived importance for poverty alleviation. To carry out these assessments a single author first scored each of the items and this was reviewed by the others and modified to reflect the consensus. The intention was to provide a national level assessment to help in targeting more detailed studies. At different scales and over time the relative importance of the items assessed will change and it is proposed that future assessments could be enhanced through the interactive participation of multiple-stakeholder groups (Rossignoli et al., 2023) representing the full range of aquatic food system stakeholders, including consumers disaggregated by age, gender and wealth (Sharma et al., 2020; de Bruyn et al., 2021). Guidelines for carrying out effective, equitable, representative, transparent and trustworthy interactive assessments are provided elsewhere (Bunting et al., 2016).

3.2 Aquaculture sector and policy development in Bangladesh and India

Aquaculture development in Bangladesh and India has been significant over the past decade (Table 1). Growth of freshwater aquaculture has accounted for most of the increase pointing to a 'green' rather than 'blue' revolution in aquatic farming systems. Output of the top twenty species in India in 2020 totaled 8.64 million tons. Culture of a single freshwater species (*C. catla*) yielded over a third of the total amount at 3.29 million tons; production of this species nearly doubled as compared with 2011 and had a value of US$ 4.8 billion in 2020 (FAO, 2022a). Over 1.2 million tons of production in 2020 was attributed to the generic groupings of 'Freshwater fishes nei' and this may include indigenous species and introduced pacu and tilapia. It is impossible to discern the relative importance of these species owing to a lack of differentiation. Whiteleg shrimp are the highest non-finfish species and production was 0.9 million tons in 2020. Owing to the relative value of shrimp this was the second most important species by value at US$ 4.5 billion in 2020 (FAO, 2022a). 'Marine fishes nei' are grouped together and accounted for 0.12 million tons of production in 2020. Only two bivalve species appear in the top twenty, namely green mussel and Indian backwater oysters and accounted for 9 and 4 thousand tons of production; red seaweed production was only 5.3 thousand tons in 2020 (Table 1).

Striped catfish (*P. hypophthalmus*) often referred to as 'pangasius' and 'Tilapia nei' culture in Bangladesh has expanded rapidly, from no reported output in 2008, to rank first and third, respectively for biomass produced at 0.4 and 0.33 million tons in 2020 (Table 1). Production of these introduced fish has rapidly surpassed that of traditional carp species. Four carp species complete the top six places with production in 2020 accounting for 40% of production at 1 million tons. Data compiled by the UN FAO (FAO, 2022a) indicate that values for several species with significant production volumes were first reported in 2009 and this suggests that previously these species may have been aggregated within a generic reporting category. No striped catfish production was reported for Bangladesh in 2008 but in 2009 a production level of 59,487 t was noted (FAO, 2022a). By 2020 a total of sixteen species groups had an annual production level of above 37 thousand tons. This may reflect a more detailed approach to collating and reporting production statistics.

Producers engaging in 'entrepreneurial pond culture' defined as 'semi-intensive or intensive culture entered into as a productive investment with moderate or high capital costs and frequently employing labor' (Belton and Azad, 2012, p. 358) are principally concerned with profit margins and financial viability. It is critical however, to balance the level of management intensification with the carrying capacity of supporting ecosystems (Berg et al., 1996; Bunting, 2001; Bunting et al., 2013). In China, producers opted for high-value species but owing to pollution problems, fish ponds in Hunan Province were closed and cages removed from Dongting Lake as the authorities outlawed agricultural activities causing nutrient enrichment (SeafoodSource, 2016) and policies have been enacted more broadly to encourage the low environmental impact growth of aquaculture (Zou and Huang, 2015). Producers utilizing extensively managed systems, with lower overheads and associated financial risks, are motivated more by modest returns that can constitute a valuable contribution to a portfolio of livelihoods activities (Newton et al., 2021). The 'equilibrium of survival' can be crucial in such cases as more valuable fish may be sold by households to purchase greater amounts of cheaper staple food items (Sen, 1999). Producers can also switch between various levels of management intensity and species combinations depending on market opportunities and other factors that influence their decision-making. Households and producer groups engaged in aquaculture are not homogenous and intra-household and intra-group dynamics and issues influencing decision-making and management of resources must be considered including: gender and age; hierarchy; wealth; ethnicity; politics; social dynamics; exclusion; illicit, illegal and unethical practices (Bunting, 2010; Punch and Sugden, 2013; Lund et al., 2014).

3.3 Location and scale of innovations

The scale of selected production systems where accessible data permit analysis and innovation could contribute to poverty reduction is summarized in Table 3.

3.3.1 Bangladesh

There are an estimated 4.27 million homestead ponds in Bangladesh and on average they contribute 2.8-15% to the total household income (Belton and Azad, 2012). Households consume 26-47% of the fish they produce which based on mean average values from Table 3 equates to 98.6 kg per year and a significant nutritional benefit. The fact that poorer households tended to have smaller than average ponds and use more traditional practices were cited as a reason as to why poor people benefited less from homestead ponds than other groups. Striped catfish production involves far fewer producers concentrated in a small number of districts. Excepting striped catfish production, it was noted that 'no-information on the socio-economic characteristics of producers of other intensively farmed species was available' (Belton and Azad, 2012, p. 202). The large volume of semi-intensive commercial carp culture in Bangladesh was highlighted as significant yet often overlooked. Compared with homestead pond culture, commercial production has developed rapidly over the past decade (Hernandez et al., 2018). Gher-based farms in Bangladesh occupy nearly a quarter of a million hectares and owing to their relatively modest average size of below one hectare are estimated to involve a comparable number of operators. Owners of land suited to gher farming in Bangladesh can lease their land out through an auction-based system (Faruque et al., 2017). Institutional innovation has led to an effectively functioning leasehold market that can increase financial returns to poorer people.

3.3.2 India

Carp production in AP was estimated at 1.3 million tons in 2012 and owing to the small average size of ponds used involves 37,750 landholdings, but it was noted that the majority (65%) of these holdings were leased out to others for the purposes of aquaculture. Consequently, smallholders can benefit financially from leasing out their land in return for a rent of US$ 3000 ha^{-1} y^{-1} (Belton et al., 2017). In common with Bangladesh, rapid growth of the sector has created opportunities for poorer people to lease out land suited to aquaculture development. It was noted however, that members of fisheries cooperatives in Chilika Lake, Odisha were encouraged to lease out their share in the lake area for 'gheri' farming as the cooperatives did not have the 'financial capital required for gheri cultivation' (Vivekananda et al., 2014, p. 1151). Consequently, this 'reduced the economic base of the fishermen by restricting their access to those parts of the lake under gheri use'. Most ponds in India are privately owned and those on government land are often used for research purposes or allocated to groups of fishermen and cooperative bodies for fish culture. Reviewing the status of government owned tanks (ponds) in Erode District, Tamil Nadu, it was noted that the proportion stocked with seed ranged from 0-86% across seven sub-Districts (Little et al., 2007). Only 10 tanks out of 69 were stocked in Sathyamangalam sub-District but previously 40 of these had been stocked, indicating a degree of underutilization (Table 3).

3.4 Options for aquaculture innovation in different geographical locations

Options for aquaculture innovation across different geographical locations (open marine, coastal (marine), coastal (brackish), inland (freshwater), highlands) are summarized in Table 4. Ongoing initiatives for each location are identified, challenges to implementation and barriers to uptake are critically reviewed and potential benefits are detailed. A scoring system ranging from minor (+), to moderate (++), to major (+++) is used to indicate the perceived importance of each issue (Table 4).

3.5 Systematic criteria assessment

Building on the assessment of how aquaculture development can be pro-poor (Toufique and Belton, 2014) other desirable attributes of aquaculture innovation to benefit poor people are summarized in Table 2. For each thematic area criteria are specified to differentiate the perceived importance of an innovation (Table 2).

Criteria presented in Table 2 were used to assess a range of aquaculture production systems in selected geographical locations (Table 5). The perceived importance of production systems in benefiting poor people was scored using the individual criteria and then ranked according to the cumulative score across all categories.

TABLE 2 Innovation quality criteria across key thematic areas to generate sustained economic and nutritional benefits.

Thematic areas	Innovation quality criteria				
	--	-	-/+	+	++
They help prove feasibility, identify pathways to scale and support growth for innovations in aquaculture	- Proposed innovations are impractical - No pathways to scale are identifiable - Could entrench unsustainable practices	- Social, Technical, Environmental, Political, Sustainability (STEPS) barriers constrain innovation and pathways to scale	- Barriers to feasibility not adequately assessed with value chain stakeholders - Pathways to scale remain unclear and poorly defined	- Conditions (STEPS) required for successful innovation are fully assessed & achievable - Pathways to scale are clearly elaborated	- Benefits of innovation are clearly demonstrated and examples of good practices are widely shared using appropriate mechanisms
They would bring economic benefits to significant numbers of people currently living under $4.6-5.6 per day	- Mechanisation and value chain efficiency gains significantly reduce employment for people living on under $4.6-5.6 per day	- Economic benefits could be limited for those living on under $4.6-5.6 per day - Small number of individuals stand to gain disproportionately	- Increased incomes from entry into aquaculture or higher returns from existing production† - Economic benefits from interventions modest in terms of overall activity	- Employment on fish farms† - Marked contribution to GDP could support infrastructure & services for the poor‡	- Employment in up and downstream product and by-product value chains† - Consumption linkages in the rural/peri-urban non-farm economy†
They would bring broader nutritional benefits to significant numbers of people currently living under $4.6-5.6 per day	- Amount of fish reaching people living on $4.6-5.6 per day could be reduced - Modified practices induce changes in diets or consumption patterns that negatively impact poor girls and women	- Price or species or size of fish produced not accessible to or favoured by poor consumers - People living on under $4.6-5.6 per day fail to benefit from falling fish prices as cold chain/ preservation methods are inadequate	- Increased consumption of fish from own production† - Combined aquaculture with/not excluding other crops could enhance diets of local people	- Increased availability of fish in markets† - By-catch from extensive and semi-intensive systems bolstered and accessible to people living on under $4.6-5.6 per day	- Increased accessibility of fish due to reduced prices† - Purposeful culture of small and indigenous fish and other aquatic animals to benefit people living on $4.6-5.6 per day
They would protect ecosystems on which people currently living under $4.6-5.6 per day depend	- Ecosystems on which people living on under $4.6-5.6 per day depend could be degraded and provisioning services yielding food items lost	- Access to ecosystems by people living on $4.6-5.6 per day could be curtailed or modified and stocks and flows of ecosystem services diminished	- Measures to protect the environment and associated ecosystem services are planned and appropriate	- Wise-use of ecosystems and sustainable intensification are guiding principles	- Innovation would enhance ecosystems on which people living on $4.6-5.6 per day depend - Reuse of nutrients in water and sediments can increase overall income and production
They would help develop technological or social innovations that would not otherwise be developed in this timescale	- Innovation would stifle investment in aquaculture development that could benefit people living on under $4.6-5.6 per day or outcompete poorer farmers	- Assistance to target producers could disadvantage others and promote inequality	- Progress with developing technological and social innovations would not be significantly enhanced	- Innovation is imminent but could be accelerated and spread more widely (geographically and socially)	- Impact of overcoming technological or social barriers to innovation is clear and could have a transformative effect on the livelihoods of people living on under $4.6-5.6 per day

†source (Toufique and Belton, 2014); ‡source (Ahmed and Flaherty, 2014).

An indication of the range of individual scoring is included to further classify the alternative systems (Table 5).

3.6 Product value chain analysis

Systematic product value chain analysis has been specified for carbon footprint assessments for food production (BSI, 2011). A standardized approach is required to permit comparison of the impacts of assorted products and to identify value chain phases where disproportionate greenhouse gas (GHG) emissions occur. To guide the assessment high-level process mapping is conducted for raw materials, manufacture, distribution/retail, consumer use and disposal/recycling. This framework is adapted here to assess potential opportunities and constraints to aquaculture innovation with the objective of poverty reduction (Table 6). Production of aquaculture crops is included as a distinct phase and manufacture is termed processing. Separation of the value chain into discrete processes allows the materials and activities to include in the analysis to be systematically identified. Raw materials analysis covers inputs required 'at any stage in the life cycle' and accounts for 'processes related to raw materials' (e.g. mining, farming, packaging, storage and transport) and 'impacts of raw materials' (e.g. fertilizer production, transport and application and land-use change) (BSI, 2011, p. 14) (Table 6).

When assessing potential innovations for poverty reduction it is necessary to consider constraints and opportunities associated with stakeholder participation, poverty, vulnerability, risk and inequality

TABLE 3 Scale of selected production systems in Bangladesh and India.

Production systems	Characteristics				
	Mean pond size (ha)	Typical production (t ha^{-1} y^{-1})	Cumulative area (ha)	Cumulative number of producers	Cumulative production (t y^{-1})
Homestead ponds, Bangladesh (BD)	0.08-0.1[†]	1.5[†]	266,259[†]	2,958,433[$]	399,389[†]
Commercial striped catfish ponds, BD	1.26-7.33[†]	20-36.9[†]	10,000[†]	7600[†]	284,500**
Commercial tilapia* ponds, BD	–	10[†]	5000[†]	–	50,000**
Commercial carp ponds, BD	–	3.5[†]	111,905[†]	–	391,668**
Integrated ghers***, BD	<1[‡]	0.6[†]	244,294[†]	244,294[$]	145,585[†]
Carp farming in ponds, Andhra Pradesh	2.5[¶]	<20[¶]	126,400[¶]	37,750[¶,****]	1,300,000[¶]
Carp farming in ponds, Bihar	–	2.2[††]	67,440[††]	–	148,368**

[†]source (Belton and Azad, 2012).
[‡]source (Faruque et al., 2017); [¶]source (Belton et al., 2017).
[††]source (Indian Council of Agricultural Research).
*'comprised largely of tilapia and minor commercial species' (Belton and Azad, 2012, p. 201).
**mean average typical production x cumulative area = cumulative production.
[$]cumulative area/mean typical size.
***ghers typically produce 0.4 t ha^{-1} y^{-1} of prawns or shrimp and 0.2 t ha^{-1} y^{-1} of fish (Faruque et al., 2017, p. 203).
****35% owner operated, 65% leasing out land (Belton et al., 2017, p. 198).

TABLE 4 Specific technologies, initiatives, challenges, barriers and benefits related to aquaculture systems in different geographical locations and perceived importance for poverty alleviation[†].

Thematic areas	Geographical location				
	Open marine	Coastal (marine)	Coastal (brackish)	Inland (freshwater)	Highlands
Technologies	Small-scale seaweed and invertebrate cultivation (++); long-lines and rafts for shellfish (++); cage-culture (+)	Shrimp and fish culture (++); mangrove-shrimp culture (++); crab culture (+); shrimp monoculture (+)	Prawn or shrimp culture with fish in ponds (++); prawn-fish-rice and shrimp-fish-rice culture in ghers (++)	Mixed species in ponds fed supplementary feed (+++); monoculture in ponds with complete feed (++)	Culture-based fisheries (++); multi-purpose ponds (+); cage and pen culture in hydropower and irrigation reservoirs (+)
Initiatives	Seaweed drying and value addition (+); small-scale depuration (+); cage culture trials (NFDB, 2015) (+)	Biomarkers showing nutritional benefits of fish in shrimp ponds for girls and women (++); value added by-products (++)	Ghers identified to mitigate climate change risks in vulnerable coastal areas (++); value added by-products (++)	'Stunted yearlings' to shorten culture cycle (++); hapa fry nursing for on-growing (++); 80:20% high value service species (++)	Fish culture in multi-purpose ponds (++); stock enhancement with carp/snow trout (+); cage trials in highland lakes (+)
Challenges*	Physical conditions (++); management for multiple uses (++); pollution and contamination (+)	Storms and flooding (++); shrimp disease (+); continued dependence of wild shrimp post-larvae (+)	Surface water flooding (++); regulating water levels in ponds and flooded fields to optimise production (++)	Pest and disease transfers (+++); feed formulation dependent of fish oil and meal (++); surface water pollution (+)	Temperature regime sub-optimal (++); soils and topography (++); establishing ownership of stocked fish (++)
Barriers*	Investment cost (++); securing access to suitable sites (++); lack of infrastructure and support services (++)	Uncoordinated pond construction has restricted water management options (+); lack of specific pathogen free post-larvae (+)	Expansion of marine shrimp farming inland can cause salinization (++); resistance to converting agricultural land to aquaculture (+)	Capital and operating costs (+++); access to quality seed of optimal strains for specific grow-out conditions (++)	Logistical constraints in supplying seed (++); limited markets locally (+); impacts on endemic/endangered fish (+)
Benefits*	Income for small-scale operators and employees (+); stimulate economic activity in coastal areas (+); increased seafood production (+)	Employment in input supply chains and processing sector (++); nutritional benefits of fish and shrimp by-products (+)	Income and nutrition from aquaculture and staple crop production (++); employment in input supply chains and processing sector (++)	Large production volumes make fish more affordable in domestic markets (+++); income generating opportunities (++)	Enhanced fish production for highland communities (++); increased benefits from hydroelectric and irrigation reservoirs (+)

[†]relative importance of topics is indicated thus: (+) minor; (++) moderate; (+++) major.
*challenges, barriers and potential benefits will vary given the type of technology or initiative, precise geographical location, social-economic setting and proposed scale of development and therefore more refined assessments would be needed to test the feasibility and sustainability of a specific production unit, management strategy or initiative.

TABLE 5 Characterisation of production strategies in specified geographical locations against innovation quality criteria.

Production systems	Systematic area†					
	They help prove feasibility, identify pathways to scale and support growth for innovations in aquaculture	They would bring economic benefits to significant numbers of people currently living under $4.6-5.6 per day	They would bring broader nutritional benefits to significant numbers of people currently living under $4.6-5.6 per day	They would protect ecosystems on which people currently living under $4.6-5.6 per day depend	They would help develop technological or social innovations that would not otherwise be developed in this timescale	Cumulative score‡ and range (lower: upper)
Combined feed-fertiliser carp culture in ponds in eastern India (Edwards, 2015)	++	++	++	+	+	8 (+: ++)
Integrated gher-based farming systems in Bangladesh (at different salinities)	+	+	++	+	+	6 (+/++)
Pangasius culture in ponds in central Bangladesh	+	++	++	-/+	+	6 (-/+: ++)
Tilapia nursing in hapas in rice fields and on-growing in ponds in Bangladesh	+	++	++	-/+	+	6 (-/+: ++)
High value and service species polycultures (e.g. cage-pond)	-/+	+	++	+	+	5 (-/+: ++)
Major carp and indigenous species combinations	-/+	+	++	+	+	5 (-/+: ++)
Shellfish, seaweed or invertebrate culture in accessible coastal areas of both countries	+	+	+	+	+	5 (+: +)
Shrimp culture with other aquatic animals in Bangladesh and coastal states in India	+	+	+	–	++	5 (-: ++)
Culture-based fisheries in upland lakes and reservoirs (north Bengal, Assam) and common-property aquatic resources (e.g. Bangladesh floodplains)	-/+	-/+	++	-/+	+	3 (-/+: ++)
Carp-based integrated agriculture-aquaculture (IAA) systems	-/+	-/+	+	+	-/+	2 (-/+: +)
Urban and peri-urban culture in and around cities and towns in Bangladesh and India	-/+	+	+	-/+	-/+	2 (-/+: +)
Wastewater-fed aquaculture using intermediaries and biorefinery strategies along the Ganges in India	-/+	-/+	+	+	-/+	2 (-/+: +)

†criteria quality scores: –– very negative; - negative; -/+ neutral; + promising; ++ very promising; ‡cumulative scores summed across rows with (+) add one and (-) subtract one.

TABLE 6 Product value chain phases and opportunities and constraints regarding innovation for poverty reduction[†].

Product value chain phase	Opportunities	Constraints
Raw materials	- Promote development investment and support to enhance carp seed quality for homestead aquaculture in Bangladesh as research has demonstrated this could increase production by 52% as compared with a control groups, but only when this was accompanied by training (Karim et al., 2016) (++) - When the natural productivity of ponds is supplemented with feed inputs it can optimise production, maximise resource-use efficiency and minimise production and financial risks (+++); cages can be used to hold the fed fish and the nutrients released can stimulate primary production in the pond (++) - Formulated feed can be manufactured with minimal fish meal and oil inputs to reduce pressure on wild fish stocks and avoid broader environmental impacts of fishing (+++)	- Innovation to deliver improved fish seed has less impact when a complementary training component is not included (++); could be a tendency to focus on high value/volume species (+); improved seed may be more expensive and hence less accessible to poor groups (+) - Management of fed-fertilised and mixed species systems could be more demanding (+); access to appropriate and timely seed, feed and fertiliser inputs could be difficult (+); partial dependence on feed inputs will have negative environmental impacts (++) - Depending on the species of fish cultured feeds with higher plant-based meal and oil may not be efficiently digested or converted to harvestable biomass (++); land-use change to produce oilseed crops can impact biodiversity, release greenhouse gases (GHGs) and reduce the production of staple crops for direct human consumption (++)
Production	- Innovation by producers can result in an array of locally appropriate aquaculture production systems (e.g. polycultures of complementary species, ideally including small indigenous fish species), management procedures (e.g. disease surveillance and digital monitoring of critical parameters) and business strategies (e.g. integrated crop production, inclusive business models and horizontal and vertical integration) that could be successfully integrated into prevailing hydrological, geographical, agricultural and socio-economic settings to supply diverse and nutritious products to regional food systems, create income generating opportunities across value chains, contribute to food and nutrition security and help enhance wellbeing amongst poor and vulnerable communities (+++) - Modest improvements in the management of existing aquaculture systems can significantly reduce environmental impacts, minimise disease risks to stock and financial risks to producers and enhance production levels (++)	- Financial costs and scales at which innovations are viable may prevent equitable access amongst poorer producers and adoption of technological innovations can be constrained by the need for skilled labour (++) - When aquaculture is demonstrated to be successful there is a tendency for the number of producers to increase rapidly (++); collectively the impact of culture practices can exceed the carrying capacity of the supporting ecosystem area e.g. cages in rivers and reservoirs (Hart et al., 2002; The Fish Site, 2011) (++) - Usefulness of Better Management Practice (BMP) guidelines to improve the management of small-scale aquaculture operations has been demonstrated, but these must be targeted at specific systems and implemented by groups or clusters of famers to achieve mutually-supporting benefits (++)
Processing	- Processing fish into nutritious food stuffs targeted at pregnant women and young children could result in long-term human health and developmental outcomes (+++) - Adding value to by-products could create significant income generating opportunities for people living on under $4.6-5.6 per day (+++); emerging technologies such as those embodied in the 'shell biorefinery' described by Yan and Chen (2015) have potential to create employment opportunities within poor and marginal communities (++)	- Value-added products may be too expensive for poorer consumers (++) and distrust of processed food targeted at mothers and infants may present a barrier to innovative products (++) - There is a degree of risk that introducing novel biorefinery practices may divert by-products away from small-scale and local businesses employing poor people and make alternative food products (fish paste, sauce, soups) more expensive (++); unethical practices have been uncovered in the seafood processing sector in South and Southeast Asia (++)
Distribution/Retail	- Innovation to extend the shelf-life of fish and eliminate spoilage could maximise the amounts of fish available for consumption, avoid public health problems and reduce waste and add value across product value chains (+++) - Establishment of small-scale enterprises selling modest portions of ready-to-eat fish products can employ poor people and the products sold are affordable and convenient (++)	- Costs associated with such measures may mean that they are only financially viable for high value products that would be beyond the means of poor consumers (++) - Investment costs in establishing such a venture can be high and therefore a suitable support mechanism may be required in terms of cooperative formation to spread the cost and risks and enable access to credit (+)
Consumer use	- Innovation to combine the production of high-value species with the size and types of aquaculture products favoured by poor people would help secure appropriate supplies for poor consumers (++) - Encourage innovation to develop and promote adoption of effective, transparent and trustworthy hazard analysis and critical control point (HACCP) principles and procedures to safeguard public health (++) and support the deployment and use of innovative and locally appropriate safe water supplies and sanitation provision across product value chains to ensure sanitary conditions and hygienic processes (++)	- Value chains for low and high value species are generally very different and this may complicate marketing arrangements for producers (+) - Vendors selling in poor neighbourhoods are often itinerant and selling very modest quantities that would not generate enough income to pay for expensive market infrastructure (++)
Disposal/recycling	- Eating small cooked fish whole avoids food waste (+)	- Economics of farming small fish and issues of combining production with other species (+)

[†]relative importance of opportunities and constraints is indicated thus: (+) minor; (++) moderate; (+++) major.

across different value chain nodes and horizontal elements and vertical linkages (Bolwig et al., 2010; de la Caba et al., 2019). Co-products that result from the preparation of raw materials or processing phase must be accounted for and this will necessitate the allocation of impacts across outputs, usually on an economic basis. Transport between each process must be included and all steps in the disposal or recycling of waste must be considered.

4 Discussion

4.1 Sector and species focused reviews identify specific constraints

Aquaculture value chain assessments routinely identify a range of technical limitations that result in suboptimal production or food waste (Gustavsson et al., 2011). Declines in fish seed quality in Bangladesh were attributed to 'inbreeding, inter-specific hybridization, negative selection, and improper broodstock management' (Karim et al., 2016, p. 20) and consequently this results in 'a low growth rate, high mortality, disease susceptibility and deformations'. Reviewing aquatic agricultural systems across the salinity gradient in southwest Bangladesh it was noted that salinization had been exacerbated by shrimp culture in the high salinity zone excluding the cultivation of rice and vegetables (Faruque et al., 2017). Consequently, a need for community-based adaptation strategies to facilitate continued transformation and adaptation to change was identified.

The relative success and wealth of experience (established capabilities) concerning innovative institutional development, notably co-management in Bangladesh (Toufique and Gregory, 2008; Dey et al., 2013; Haque and Dey, 2016; Haque and Dey, 2017) contrasts with a lack of development across India and a tendency towards formal top-down government led comprehensive planning (Bunting et al., 2016). Preparing an action plan for aquaculture development in Bihar, India, it was noted that production enhancement in 50,000 ha of ponds and 5000 ha of oxbow lakes could lead to yields of 194,800 t y^{-1} (Indian Council of Agricultural Research). Steps specified included: leasing and renovation; desilting and weed clearance; pen construction; subsidized seed stocking; brood bank and seed production unit establishment; community feed unit and private sector feed mills; post-harvest infrastructure; laboratory facilities; capacity-building. As a plan developed by a government agency this constitutes an example of a top-down approach that is unlikely to be successful. Interventions to address specific constraints will result in moderate productivity or efficiency gains or risk reductions. Innovation and transformation in governance at a state level is required in India to encourage private sector investment and enable significant increases in aquatic food production in promising locations such as Bihar and Tamil Nadu. Recruiting people with commercial private sector experience, conducting consultations and establishing effective communication channels with the business community could help ensure policy-making and regulatory regimes can support rapid and sustained aquaculture sector growth. Continuous improvements across all aspects of production or value chains are needed for significant and sustained performance gains.

4.2 Current initiatives to overcome constraints to aquaculture development

Private sector innovation (by both high- and mid-level entrepreneurs) over the past decade has been one of the key driving forces responsible for the establishment of large-scale commercial tilapia and pangasius catfish production in Bangladesh. Similarly, commercial operators in AP have responded to disease outbreaks and market price fluctuations by diversifying into new species and business consolidation. Further innovation and policy-support is warranted, however, to mitigate against patterns of boom and bust that can affect aquaculture production for domestic markets in Asia (Belton et al., 2017). Government research centers are active in both Bangladesh and India but there is limited evidence that they have made a substantive contribution to recent progress with commercial aquaculture development of new species. Concerning India, it was noted that 'government departments due to their organizational, manpower, technical and budgetary constraints' have restricted 'their role mostly towards regulation of aquaculture by registration and monitoring the compliance of guidelines' (Alagappan and Kumaran, 2016, p. 118). Consequently, it was observed that 'the information link between research and extension subsystems is missing'.

Several bilateral research and development programs and projects concerning the monitoring and control of diseases of aquatic farmed species are active in Bangladesh and the need for such initiatives highlights deficiencies with public and private sector service provision. Studies conducted by WorldFish researchers have addressed a range of issues concerning both the freshwater and marine aquaculture sectors in Bangladesh (WorldFish, 2021). Additional studies have focused on the important aquaculture sector in AP, India (Belton et al., 2017). Research findings could potentially inform the development of BMPs guidelines covering issues from pond preparation, broodstock selection and management, seed production and quality testing to biosecurity and feeding regimes (ADB et al., 2007; Mehar et al., 2022). Given the diversity of production systems and geographical locations where aquaculture has become established, however, this makes the formulation of generic solutions difficult. Examples of entrepreneurs being the main innovators in a specific location are apparent and this was exemplified by the case of a fish seed and fingerling producer in Bihar (The Hindu, 2014) but the challenge is how best to identify and support individuals and clusters of proactive producers.

4.3 Immanent aquaculture innovations

Recent growth of striped catfish and tilapia production in Bangladesh has highlighted a willingness to import and adapt outside technologies and created opportunities for people to enter value chains. Rapid aquaculture sector development can, however, exceed the capacity of the supporting ecosystem area to sustain the goods and services needed for production. In the case of striped catfish farming in ponds in Bangladesh, producers have had to manage their ponds with limited water exchange. Consequently, nutrient rich sediments tend to accumulate in these fed ponds over

2-5 years, which can negatively affect pond water quality. Trials have been conducted, using these sediments to grow vegetables and this could be a feasible way to extract more value per unit of nutrient input (Haque et al., 2016). Innovations to reduce the labor requirement to remove sediments for pond-side cropping and to make the process more efficient are needed (Hossain et al., 2016).

Culture of novel species, including smaller fish such as climbing perch and spiny eel, has broken through based on the blueprint of striped catfish and tilapia. Established sectors in certain locations are in transition with prawn and shrimp farming developing in areas inland from mangroves. IAA gher farming systems constitute an established technology that has potential to aid this transition by efficiently transforming low-lying areas to combined pond-field systems that can produce cash and staple food crops using water with a range of salinities (Ahmed et al., 2014; Faruque et al., 2017). Fundamentally, the success of such a strategy may depend on being open to innovative ideas and having the capacity to translate or adapt technologies to local conditions.

Reviewing promising technological developments for aquaculture globally, several were identified including: rapid pond-side disease detection kits and spatial mapping of pathogen spread; improved strains and techniques to produce mono-sex seed; crop plant breeding to aid the formulation of more digestible and high yielding diets (Little and Bunting, 2016). These authors noted, however, that to minimize unnecessary production risks it is advisable to avoid instilling dependence on externalizing technology i.e. technology that requires ongoing energy or technical support that makes the user more vulnerable. Additionally, some technologies are 'unlikely to be scale-neutral and could exacerbate inequalities and potentially exclude poorer producers' (Little and Bunting, 2016, p. 106). The cost of technological innovations will dictate what poorer people can afford and adopt. Access to ethical finance or credit facilities could help promote equitable innovation across the full range of aquaculture production systems. Support to entrepreneurs attempting to enhance and up-scale production can be critical for the successful adoption and adaptation of existing technologies in harmony with prevailing local conditions. Devising appropriate business models (e.g. contract farming, franchise type arrangements, inclusive approaches and optimized supply chain logistics) could be key to enabling poor people to benefit (Kaminski et al., 2020; IntraFish, 2021). A joint venture between Mega feed and Nam Sai is providing support services as part of a package supplying seed and feed for tilapia producers in Bangladesh. Enabling the private sector to establish hatcheries with effective broodstock management and selective breeding programs and seed distribution networks can stimulate development of the aquaculture sector more widely and in new geographical areas.

Tilapia culture in India was previously banned by the government in 1959 (Department of Fisheries, 2020) but it continued covertly and illicit introductions apparently occurred (Mongabay, 2020). Such fish movements will have been associated with risks of introducing a non-native (and potentially invasive species) and associated pests and diseases. Reflecting on this situation, responsible authorities must innovate to avoid illicit introductions and movements of aquatic animals and plants that can be biosecurity risks and invasive. When possible, authorities could usefully support the production of improved strains of established species or native species that are novel candidates for aquaculture where there is promising commercial potential or opportunities to promote food and nutrition security. The Government of India approved the culture of *O. niloticus* in 2012 and published revised guidelines in 2020 to govern biosecurity, hatchery establishment, breeding, on-growing, post-harvest practices and marketing (Department of Fisheries, 2020).

Affordable Information and Communication Technology (ICT) and simple digital monitoring of farms could be key areas for innovation, for example water quality could be checked, feed delivery automated and regulated and farm records maintained and analyzed (Aquaconnect, 2017; Dhenuvakonda and Sharma, 2020; XpertSea; eFishery, 2022). CARE International are supporting the development of applications and feed tables for use by the private sector to ensure feed is used more efficiently, creating less pollution and generating more profit. Spreadsheet based cost-benefit analysis was used to evaluate the potential of integrating small-scale fish production in 0.1 ha ponds dug for irrigation purposes in Buxa, West Bengal, India, and demonstrated that this could contribute an additional Rs 20,000 (US$ 358) per year or 28.5% to the net benefit realized by producers (Bunting et al., 2015). Reviewing ICT applications in support of aquaculture extension services in India it was noted that 'ICT aided tools are one of the means to enhance the capacity of the end users and have the potential to bridge the research-extension-farmer-inputs-market linkage gap' (Alagappan and Kumaran, 2016, p. 122). Considering climate change and the role for ICT in aquaculture the need to 'bridge the gap between those who are trying to develop "systems" and those who could use them' was highlighted (Jain, 2010, p. 25). Addressing the specific role for ICT in improving the efficiency of freshwater aquaculture it was noted that innovations should respect four key criteria and be: 'clear and focused services'; 'simple and user-friendly'; 'accurate information'; 'well organized and easy to find' (Kaushal, 2010, p. 1). A promising strategy might be to challenge people that have developed successful (i.e. with proven benefits and strategies around inclusion) ICT solutions for poor people in allied sectors (e.g. agriculture, livestock, value chains or financial services) to devise appropriate innovations for the aquaculture sector.

The Livestock Guru, 'an interactive multimedia program for poor livestock keepers in India and Bolivia' has been cited as useful for poor farmers (Heffernan and Nielsen, 2007, p. 113) but these authors noted that 'ICTs had a greater effect in transferring instructional versus descriptive information to the poor' (p. 119). ICT-based systems and training materials tailored to the needs and capacity of aquaculture producers could be one mechanism to facilitate knowledge sharing and support services [see for example AgroMarketDay (2022)]. Disease diagnosis in aquatic animals based on visual inspection or symptoms is problematic and may demand a different approach. Ideally animal health management practices must aim to minimize any risk from pests and diseases through good animal husbandry and appropriate biosecurity. Drawing on evidence from the UK trout farming sector, linking data from many farms can enable 'real-time epidemiological modelling' leading to 'early warning of disease outbreaks in the industry and allow precautionary actions to be put in place' (Bostock et al., 2010, p. 2910). Responsible authorities could establish effective surveillance and reporting procedures to identify emerging disease risks and to instigate appropriate infection control measures (Bunting and Stentiford, 2014) and when there are large numbers of potential users this could make using the new capabilities of big data analysis, machine learning and internet of things (IoT) technologies, affordable in low- and middle-income country contexts (The Fish Site, 2020).

4.4 Examples of good practices being adopted across product value chains

Opportunities for innovations for poverty reduction are apparent throughout the life cycle of aquaculture products. Innovations to enhance the operations of poorer producers and value chain actors and to benefit poorer consumers are considered here in this context. Seed production, nursing and trading can generate employment for poor people and stimulate the spread and growth of the aquaculture sector (Barman and Little, 2006; Barman and Little, 2011; The Hindu, 2014; Short et al., 2021). Innovations to improve broodstock management, trait selection and the quality of seed reaching producers could help optimize the conversion of raw materials to harvestable biomass, avoid waste, increase production and enhance the appeal to consumers (Mehar et al., 2022). Introduction of 1000 l oxygenated HDPE fish tanks was cited as an important innovation permitting the transport and stocking of larger 'stunted yearlings' in AP (Belton et al., 2017). Growth restriction is induced through feed and stocking density manipulation and when environmental conditions permit, some fish species can exhibit a compensatory growth phase that can yield better results for producers (Hossain et al., 2003). Furthermore, the production cycle can be shortened generating more regular cash-flows, producers can dispense with nursing ponds and broodstock do not have to be maintained by farmers. Avoiding dependence on wild broodstock and juveniles and establishing supplies of certified disease-free seed can make a crucial contribution to minimizing disease risks on farms. Large numbers of poor people in coastal areas of both countries collect shrimp post-larvae and a fundamental shift in demand to cultured juveniles could result in widespread hardship. Action must be intensified to ensure people have alternative and reliable sources of income year-round that makes them more resilient (WWF India). Seasonal schemes established to restrict overfishing of hilsa (*Tenulosa illicia*) in Bangladesh are a prime example (Islam et al., 2016; Mohammed et al., 2018).

Initiatives to involve poor groups in adding value to aquaculture products by undertaking cooking and processing could provide direct employment and increase access to affordable and ready-to-eat fish products within local communities. Setting up retail kiosks to sell fried fish by the West Bengal State Fishermen´s Co-Operative Federation Ltd (BENFISH) provides a pertinent example of what has been achieved (BENFISH). Producing innovative nutritious products containing fish targeted at pregnant women and infants within the first 1000 days following conception (Sigh et al., 2018; Ahern et al., 2020) could result in long-term health and developmental benefits for mothers and children (1000 Days). Understanding the factors that govern the acquisition and consumption of aquatic foods, notably food environments in different settings, could be crucial to devising effective nutrition-sensitive strategies (de Bruyn et al., 2021; Pounds et al., 2022). Asian carp can be processed effectively into value added products including traditional fish paste and fillets (Bloomberg, 2017). Primary processing by-products are often more accessible to the poor (e.g. informal women's groups using fish guts to make cooking oil). Consequently, diverting processing by-products away from local added value food manufacturers to more remunerative biorefinery processes (Yan and Chen, 2015) could impact negatively on food and nutrition security and poor livelihoods. Safeguarding assessments with stakeholders disaggregated by gender and age may therefore be required to avoid negative impacts (de la Caba et al., 2019).

Systematic assessment methods to map processes and collect data on the physical characteristics of value chains have been developed for carbon footprint accounting and LCAs (BSI, 2011; Newton et al., 2014). Value chain assessments must, however, consider broader policy issues and the situation of stakeholder groups associated with different value chain nodes (Bolwig et al., 2010). Innovation in packing fish for market in AP in insulated plastic boxes with ice has significantly extended the distribution range therefore potentially benefiting poorer consumers with more affordable fish throughout India (Belton et al., 2017). Enhanced preservation reduces aquatic food loss and maintains value, but some preservation strategies used to offset shelf-life losses (e.g. canning, fermentation, salting and sun-drying) can result in health concerns and food safety issues (Ahern et al., 2021).

4.5 Effectiveness of aquaculture innovation to reduce poverty

Employment on farms and across product value chains benefits significant numbers of poor people. Technological innovations (e.g. automation or mechanization) may put such jobs at risk. Interventionist development actions to reduce poverty through expanded and enhanced aquaculture production can benefit people living in poverty but often this represents only a relatively small contribution to their overall livelihood strategy. If gains recorded amongst participants could be efficiently replicated across the 4.27 million multipurpose 'homestead ponds' in rural Bangladesh (Belton and Azad, 2012, p. 198) the aggregate benefit to poor people could be significant. Cumulative production from homestead ponds with an average yield of 1.5 t ha^{-1} y^{-1} was estimated at 399,389 t y^{-1} (Table 3) and if adopting improved management practices could raise yields above 3 t ha^{-1} y^{-1} this would equate to an additional 0.4 million tons of production annually. Considering private pond culture in India there are a limited number of published accounts, although the difference in system productivity (see Table 3) appears to reflect vast social and economic variation in India. Aquaculture development, where clusters of good practice become established, can enhance water and nutrient use efficiency, bolster agrobiodiversity, compliment other pond uses, add value to waste resources and agro-processing by-products and contribute to broader benefits for smallholders, commercial producers and society.

Most interventionist development initiatives have had modest direct effects on participants, not reaching significant numbers of producers or only generating short-term benefits. Funding to enhance carp seed quality and training resulted in an added net benefit for participants of US$ 470,000 equating to a 285% return on investment (Karim et al., 2016). It was, however, noted that this equated to only 'modest absolute increases in income and production estimated for participating households' (Karim et al., 2016, p. 20). The need to focus on capacity-building for farmers as opposed to technical innovations was highlighted if productivity and profitability were to be significantly improved. Overall, however, the aquaculture sector in both countries has developed considerably during the past decade. It is not possible to separate out the influence of interventionist and immanent aquaculture development processes. Businesses acumen and configurations, human capital and trading networks are well developed in certain locations (e.g. AP) that enabled producers to quickly transition from carp to striped catfish culture. The capacity to adopt novel aquaculture production systems in Mymensingh, Bangladesh, could be attributed to sustained interventionist development actions over several decades combined with evolving market conditions and improving infrastructure and communications (Ahmed and Toufique, 2015). Strengthening capabilities across value chains and aquatic food systems may be necessary to achieve transformative change and enhance sustainability (Short et al., 2021).

4.6 Gaps constraining aquaculture innovation

Considering the contribution of aquaculture to food security and poverty reduction, Béné et al. (2016) conducted a systematic review of the literature and identified four key gaps. The first was that 'key components' of aquaculture 'are not accounted for in national statistics, and/or the available figures are inaccurate' (p. 187). Second that 'poverty is not clearly conceptualized, articulated, or measured' in studies. The third concerned 'the causal relationship - either positive or negative - between aquaculture development and food security, economic growth, and impacts on poor people'. The fourth was around 'nutrition where problems persist in demonstrating the impact of fish availability on micronutrient status or other functional outcomes (e.g., cognition, infections, growth, and development)'.

Innovation to produce cost-effective and environmentally sound feeds, formulated to match the nutritional needs of cultured species is crucial (Muir, 2013). Subsidies to damaging agricultural, livestock, aquaculture and fishing practices must be curtailed, with support redirected to continually evaluating options and taking whatever actions possible to push choices towards the most sustainable (Pretty, 1995; Bunting, 2013; Sumaila et al., 2021). Incentives to produce species and use production systems that benefit poor and marginal groups through enhanced employment opportunities, improved food and nutrition security or environmental protection and regeneration could be instigated. Adopting a One Health approach, which aims to optimize human, animal and environmental health, could greatly benefit the development of sustainable aquaculture systems (Stentiford et al., 2020). This requires leadership from policy organizations and input from researchers to help producers meet this objective. A framework for sustainable intensification of aquaculture has been proposed where animal and human welfare are fundamental concerns but acknowledges that increased productivity is required (Little et al., 2018). Higher animal welfare standards and practices, for example, eliminating unilateral eyestalk removal from shrimp broodstock, could confer enhanced resilience (to disease and environmental stressors) to their progeny (Zacarias et al., 2021) and achieve comparable survival and growth in subsequent production phases when compared with juveniles from ablated female shrimp (Zacarias et al., 2019).

Barriers to progress concerning the global food system identified by Godfray et al. (2010) included: climate change, competition over energy, land and water, and understanding the dependence of agriculture on ecosystem services. A global review of agricultural questions of importance noted that research was needed on: understanding the environmental impacts of aquaculture; minimizing environmental impacts of aquaculture; creating carbon sinks in ponds; elaborating the best options for crop-aquaculture integration; enhancing the contribution of aquaculture in developing countries to protein production; understanding impacts of 'crop genetic improvement' on the availability of micronutrients for fish and humans (Pretty et al., 2010, p. 227). Considering options for the sustainable intensification of food crops a range of potential negative side effects of technology or practice innovation were identified (The Royal Society, 2009). Gaps in the scientific knowledgebase for aquaculture globally were identified through a recent scoping review (Béné et al., 2016). Constraints to the sustainable development of aquaculture were elaborated for Southeast Asia by stakeholders at the UK-SEA workshop (James, 2014).

Lack of institutional capabilities and policy support and incentives can be major barriers; subsidies can perpetuate unsustainable practices to the detriment of good practices; governance failures concerning pollution control, land-use planning and public investment can stifle aquaculture development; prevailing environmental conditions can constrain sector growth and this can be exacerbated by external influences. The case of aquaculture development around Lake Kolleru, AP, emphasizes that governance must be responsive to pressures exerted by an emerging aquaculture sector and ensure the needs of aquaculture development are included in land-use planning. Large-scale aquaculture development, notably in coastal zones, adjacent to large lakes and around cities and towns in both Bangladesh and India has driven migration within countries and from rural to peri-urban areas. In anticipation of such change, authorities and other key food system stakeholders must take into consideration potential implications for migrants (disaggregated by age, gender and wealth). Government departments, civil society organizations and humanitarian agencies must ensure policies and processes are conducive to migration and that individuals receive appropriate support.

Anticipated worsening climate change impacts in South Asia (Conway and Waage, 2010) are expected to increase risks from storms, flooding and tidal inundation and propagate the emergence of new animal, environmental and public health hazards. The National Adaption Plan of Bangladesh (2023-2050) (MoEFCC, 2022) calls for research and innovation in support of climate-resilient aquaculture production and value chains, notably 'post-harvest facilities and e-commerce-based marketing facilities' nationwide (p. 75). Potential opportunities for carbon-sensitive management practices and carbon sequestration through aquaculture and across value chains have been highlighted (Bunting and Pretty, 2007; Ahmed et al., 2017). Innovative production strategies and value chain configurations (e.g. integrated prawn-fish-rice culture) could be promoted in inland areas as effective strategies for community-based climate change adaptation and to avoid risks associated with operating in vulnerable coastal areas of Bangladesh and India (Ahmed et al., 2014; IPCC, 2019). Diversified shrimp-fish-rice agroecosystems and integrated mangrove-shrimp culture could be promoted in coastal zones to enhance social-ecological resilience in response to anticipated worsening of climate change impacts (Bunting et al., 2013; Bunting et al., 2017; IPCC, 2019).

Problems with untreated sewage water flowing to the Ganges River in India were highlighted in a funding call by the Government of India for innovative demonstration projects for in-stream treatment (NMCG, 2021). A series of centralized government initiatives over the past four decades costing hundreds of millions of US dollars have largely failed owing to poor project design and implementation, an absence of coordination, corruption, and a lack of public awareness and participation (Dayal, 2016). Treatment plants were constructed but owing to poor maintenance and ongoing operational costs many facilities are now not working or performing very poorly (Central Pollution Control Board, 2013). This highlights the problem of introducing technological solutions that rely on technology requiring external inputs (e.g. consumables, energy and skilled workers) and that are expensive to design, build and operate. Safe wastewater management facilitated through productive reuse, including for aquaculture, can be an attractive business proposition, prevent loss of valuable nutrients to the biosphere and produce crops to contribute to food and nutrition security (Bunting et al., 2010; Bunting and Edwards, 2018).

Opportunities to innovate for aquaculture development for poverty reduction are apparent across value chains and aquatic food systems. Appropriate innovations to improve resource use efficiency and increase productivity and income generation could enhance direct and indirect benefits accruing to poor groups. Measures to ensure that catches of small pelagic fish species are accessible for direct human consumption (de Bruyn et al., 2021; Thiao and Bunting, 2022) with corresponding substitution of promising alternative ingredients in feeds (Hua et al., 2019) could lead to enhanced human nutrition outcomes and more rational and sustainable aquaculture development. Better conversion of feed to harvestable biomass would reduce pollution, as would measures to productively utilize nutrient enriched water and sediments (Karim et al., 2011). Enhanced environmental protection would improve the state of habitats that deliver ecosystem services that sustain poor communities. Development of biorefinery processes to add value to fish processing by-products could create novel employment opportunities for poor groups. Greater knowledge on the contribution to the income and nutrition of poor people of fish and other animals cultured in conjunction with export-oriented cash crops in what are commonly mixed species systems is required. Co-culture of small indigenous fish, to be cooked and eaten whole, could disproportionately benefit poor children and women (Roos et al., 2007; Thilsted, 2012; Muir, 2013; Karim et al., 2017).

Policies to encourage sustainable intensification of aquaculture through value chains (Little et al., 2018) and support smallholders or other poorer actors in the value chain in capturing the benefits of aquaculture development are required (Kruijssen et al., 2018). Initiatives that engender and strengthen recognition of pro-poor producer innovations must be championed. Effective mechanisms to share knowledge of appropriate innovations with and between clusters and groups of poor producers should be devised and supported. Ideally, comprehensive pathways to impact, focusing on the role of value chain actors, multi-stakeholder groups, social learning and collective action, should be elaborated and followed. Opportunities to promote sustainable growth of the commercial aquaculture sector could be identified and supported when this has potential to boost economic and social development and make aquatic foods more affordable and accessible to poorer consumers (Belton and Azad, 2012; Little et al., 2012; Costello et al., 2020).

As with small-scale inland fisheries, an ecosystem approach to management could usefully be adopted (Ahmed et al., 2013a; Ahmed et al., 2013b). An ecosystem approach was defined as a 'strategy for the integration of the activity within the wider ecosystem in such a way that it promotes sustainable development, equity, and resilience of interlinked social and ecological systems' (Soto et al., 2008, p. 15). Benefits of bolstering stocks of aquatic animals in farmer-managed aquatic systems could be promoted (Amilhat et al., 2009). Innovations enabling the breeding and nursing of small-indigenous species for stock enhancement initiatives could be prioritized, both through hatcheries and in the wild (e.g. decentralized rice field-refuge system) (Barman and Little, 2006). Innovative culture-based fisheries enhancement programs could be endorsed and supported when poverty reduction is an achievable goal (Liu et al., 2019). Changes to institutional arrangements could be instigated to enable the effective management of common pool resources to permit appropriate aquaculture development including both wealthier and poor stakeholders. Mechanisms to compensate poor resource users that might be excluded should be established (Toufique and Gregory, 2008). As nutrient-use efficiency increases in aquaculture systems, this can eliminate opportunities for poor and marginal groups to make productive use of nutrient rich water and sediments, potentially diminishing local food and nutrition security (Edwards, 2015; Little et al., 2018). Trade in aquatic foods to urban and export markets can also result in the loss of nutrients from farming systems and nutrition from local communities and the consequences of this for poor and vulnerable groups, especially young children and breastfeeding women, demand serious and timely assessment and appropriate mitigation (Thiao and Bunting, 2022).

Authorities could commit appropriate resources to implement international conventions and agreements conceived to counter unsustainable aquaculture practices. Research and development funding must be accompanied by capacity-building and training. Education programs must address processes of social change to enable families to adapt more broadly (Pilgrim et al., 2007; Punch and Sugden, 2013). Existing policies and subsidies could be re-evaluated to ensure they do not disadvantage poor producers or promote unsustainable practices.

5 Conclusions

Promising innovations across aquaculture product value chains that could enhance poverty reduction have been reviewed and opportunities and constraints identified. Innovation to enhance fish seed quality and accessibility can increase yields and optimize the efficiency of input use. Furthermore, associated capacity-building for producers has been shown to increase the benefits achieved.

Innovation to enhance disease detection, management and prevention is needed, but measures must be cost effective and supported with appropriate national monitoring and surveillance programs to coordinate control actions and restrict the spread of emergent diseases. Innovation to optimize the use of formulated feed with the natural productivity of systems is needed. Combined feed-fertilizer carp culture in ponds in eastern India provides an exemplar for innovative producers. Innovation to eliminate fish spoilage and add value to by-products across aquaculture product value chains could avoid aquatic food losses and contribute to higher consumption of nutritious fish.

Innovation to stimulate the spread of promising practices amongst producers and value chain stakeholders is required. The means of knowledge or technology transfer should be tailored to meet the needs and capacity of prospective adopters. To encourage innovation for sustainable aquaculture development for poverty reduction it is important to acknowledge the roles and responsibilities of actors at various stages across value chains. Recognizing the role that the private sector has played in large-scale commercial aquaculture development benefiting poor people in Bangladesh and India is critical. In this context, external assistance and development funding could be targeted to promote private sector innovation and investment to overcome production constraints, increase yields and benefit actors across value chains. Decision- and policy-makers could make a critical contribution by encouraging private sector aquaculture development, enhancing value chain governance and regulation, strengthening capabilities across aquatic food systems and fostering enabling institutional environments to facilitate innovative access- and benefit-sharing arrangements.

Author contributions

SB: methodology, formal analysis, writing - original draft, review and editing. JB: contributions to scoping, research coordination, writing - review. WL: conceptualization, methodology, writing - review and editing. DL: funding acquisition, conceptualization, methodology, writing - review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author SB is self-employed by Bunting AAARCS. Author WL is self-employed by Casammak Aquaculture.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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