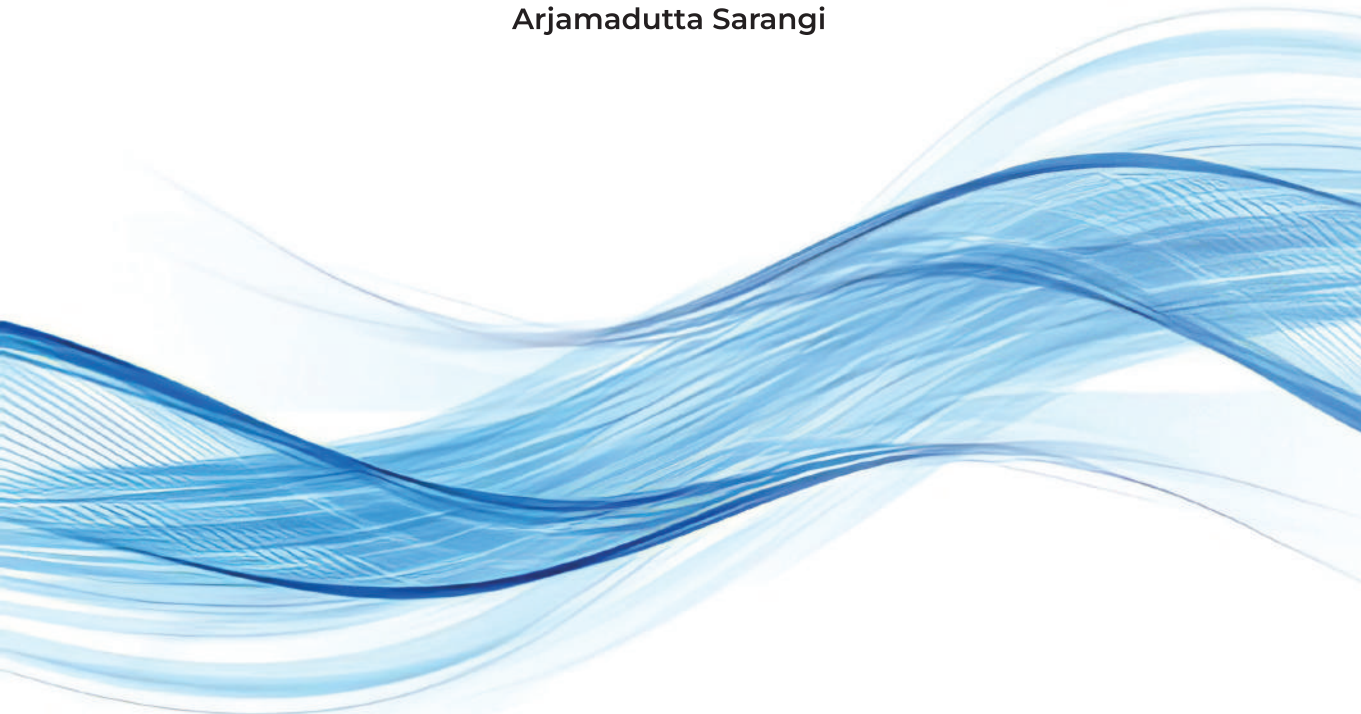
POLICY PAPER: 001

Attaining Sustainability in Water Management and Nutrition-Sensitive Aquaculture

Rajeeb Kumar Mohanty
Arjamadutta Sarangi



ICAR-Indian Institute of Water Management
Bhubaneswar, Odisha-751023
2024

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MESSAGE

The significance that water plays in ecosystem sustainability and human existence makes it intrinsically linked to various Sustainable Development Goals (SDGs). Despite its inherent nature to recycle and replenish, water availability is very much limited and the gap between demand and supply is widening over time due to unabated anthropogenic factors besides changing climate. Thus, the conservation and management of water resources are crucial for both the food and nutritional security of the Country's burgeoning population. Particularly, aquaculture, which needs a huge volume of water, warrants a focused attention. Recent technological innovations and user-friendly water budgeting protocols can certainly pave the way for long-term sustainable aquaculture production. As aquaculture production needs to be increased in the backdrop of limited water supply besides changing climate, there is a need to implement a water budgeting approach leading to increased water use efficiency. Application of best management practices (BMP) emphasizing water management protocols, intensification of existing aquaculture systems, crop diversification, nutrition-sensitive aquaculture and estimation of water and carbon footprint are required to sustain aquaculture productivity and nutritional security.

I take this opportunity to congratulate the authors for bringing out this policy paper on "*Attaining Sustainability in Water Management and Nutrition-Sensitive Aquaculture*" based on research and on-farm evaluation. This Policy Paper would assist planners, policymakers, academicians and other stakeholders involved in aquaculture activities for enhancing water productivity in aquaculture.

Dated the 2nd May, 2024
New Delhi

(Himanshu Pathak)

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MESSAGE

Despite being one of the most dynamic industries in the world food chain, aquaculture is still remarkably under-represented in the majority of food policy literature. New aquaculture production techniques hold great promise for reducing the world's food security and achieving sustainability while meeting human nutritional demands. With the largest share of water resources and the largest labor force, India's agriculture and aquaculture industries guarantee the Nation's food and nutritional security. It is important to look at ways to enhance the utility of water, as shortage looms big in different parts of the country due to changing climate. In light of the restricted water supply, aquaculture productivity needs to be raised. Such situation warrants for the implementation of a water budgeting strategy that will increase water use efficiency. Application of smart aquaculture practices emphasizing water management protocols, water productivity, water and carbon footprint in nutrition-sensitive aquaculture is required to sustain aquaculture productivity and nutritional security.

I hope that the policy paper on "Attaining Sustainability in Water Management and Nutrition-Sensitive Aquaculture" brought out by the ICAR- IIWM will be helpful to stakeholders associated with aquaculture. The document will also serve as a source of information to farmers, policymakers, entrepreneurs, researchers and extension workers for judicious water management in aquaculture for enhancing aquaculture water productivity.

Dated the 2nd May, 2024
New Delhi

(Suresh Kumar Chaudhari)

1.0 Introduction

Despite being one of the most dynamic industries in the world food chain, aquaculture is still remarkably under-represented in the majority of food policy literature. New aquaculture production techniques hold great promise for reducing the world's food security and achieving sustainability while meeting human nutritional demands. Over the past 25 years, aquaculture output has increased more than most other food commodities (nearly tripling in live weight), and the business has developed into a mature global one (Garlock et al., 2022). Over the past 50 years, the amount of fish consumed globally per person has almost doubled, and on an edible weight basis, it is currently comparable to that of poultry and pork (FAO, 2022). Asia is by far the greatest aquaculture producer, accounting for 92% of global live-weight production. Inland freshwater aquaculture dominates the sector, producing 62% of global live-weight volume and 75% of global edible weight volume (FAO, 2022). India is currently the world's third-largest fish-producing nation, contributing 7.96% of the total production and ranking second in aquaculture followed by China.

Aquaculture presents multiple opportunities to lessen poverty by sustaining economic growth through better use of natural resources by supplementing nutritional requirement and reducing hunger. Compared to the agriculture sector, modern sustainable aquaculture methods produce less waste and carbon-nitrogen footprints. Essentially, fish is a healthy super food, rich in quality animal proteins, polyunsaturated fatty acids especially the (ω)-3 eicosapentaenoic, docosahexaenoic acid and micronutrients (Mohanty et al., 2019), thus helps in achieving sustainable development goals (SDGs) 2 and 3. Furthermore, in tropical nations, fish are more readily available and reasonably priced than other animal protein sources. It has been demonstrated how important fish is to a healthy diet and how it helps fight under nutrition and micronutrient deficiencies in underdeveloped nations besides, promoting food security. It is commonly known that aquaculture and food and nutritional security are linked (Fig. 1). However, a comprehensive set of practices encompassing water conservation and management practice-which primarily addresses SDGs 2, 3, 6, 14, and 17-which are oriented towards aquaculture development.

Water, which is essential for aquaculture, is also vital for ensuring advancement in the modern food and energy industries. Recognizing this significance and the role that water plays in supporting daily living is an important aspect of the systems thinking paradigm. The broader function of water in enabling society, as seen through a nexus lens, will be increasingly recognized and accounted for policy formulations and resource management decisions. Furthermore, climate change, particularly extreme weather, necessitates integrated management of the water, energy, and food systems. Enhancing water productivity and efficiency enhances food and nutrition security while supporting socioeconomic growth. Water, the most significant resource required in a broader water-energy-food (WEF) nexus setting, is influenced by a variety of factors, including rapid population expansion, climate change, policy implementation, and socioeconomic development (Bleischwitz et al., 2018). Understanding the WEF nexus is therefore critical for water management in aquaculture.

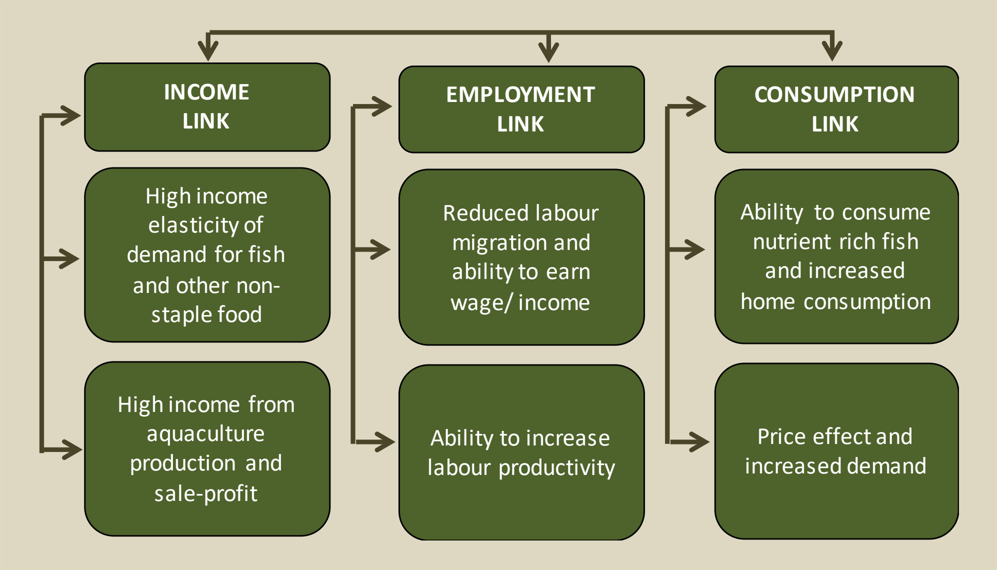


Fig. 1: Linkages of aquaculture with food and nutritional security

The water–energy–food nexus (WEF nexus)

Although the effective functioning and sustainability of nexus resources are critical for human well-being and development, approximately 1 billion people lack access to clean water, 2.5 billion lack basic sanitation, 1.4 billion lack electricity, and over 850 million are chronically malnourished, with global food waste estimated at 30% of production (World Bank, 2013). Simultaneously, demands for water, food (*viz.* land), and energy (*viz.* fossil fuel supplies) are predicted to rise during the next century. Overexploitation of WEF resources is a key global issue that is receiving policy attention (World Bank, 2013; European Economic Association, 2015; Carmona-Morena et al., 2019; Sood et al., 2019). Despite the life-sustaining nature of WEF resources, there are clear indicators of stress. Aquifers are overexploited over the world (Gleeson et al. 2012). Water is rapidly being transferred across basins and trans-boundaries of Countries, either physically or through the 'virtual water trade' (Chen et al. 2018). Moreover, fossil fuel and land resources are limited. Due to the interconnectivity of WEF resources, a shortage or failure in the operation of any WEF sector has the potential to cause drastic changes in the availability of key resources, production and distribution of goods, social and geopolitical disruption, and irreversible environmental situations. Therefore, water plays a central and key role in the wider functioning of the WEF nexus, and in the ability to provide other services to humanity.

Role of water in nutrient-sensitive aquaculture

Water is essential for food production (Rodell et al., 2018), and is primarily used in irrigated agriculture, aquaculture, and animal husbandry. Different crop production practices consume around 7,100 km^3 of water globally each year, which is expected to increase to

13,500 km^3 by 2050. It is thus implicitly linked to land use and land cover, with water demand and water quality issues influenced by how land is used, notably for agricultural and aquaculture production. The amount of water utilized in aquaculture production is determined by supply and demand factors. The amount of water needed for aquaculture varies greatly in terms of supply, dependent upon various factors such as farming practices, species and varieties, water budgeting, water use efficiency, local climate, cropping patterns, soil conditions, water quality besides on-farm water management practices (Mohanty and Sarangi, 2023; Masia et al., 2021). It has been demonstrated that implementing water budgeting, managing water quality, and enhancing on-farm management practices would result in notable water savings (Mohanty and Sarangi, 2023; Jägermeyer et al., 2015, 2016). Moreover, aquaculture requires effective water quality management since farmed fish are extremely sensitive to changes in factors such as harmful chemicals, pH, temperature, and presences of gaseous substances. To ensure the optimal fish health, production, and quality, water quality must be monitored and regulated periodically. Fish use water for a variety of purposes, including temperature regulation, oxygenation, and waste elimination. Water quality characteristics *viz.* pH, hardness, and dissolved oxygen levels all have a substantial impact on fish growth, survival, reproduction, and embryology. Water quality in aquaculture is an important scientific tool for understanding the dynamics of the fish pond. Therefore, water should be suitable for fish growth and survival to make aquaculture profitable.

2.0 Water resource and its use in aquaculture: Indian scenario

India's fisheries resources are rich and diversified (Fig. 2), accounting for more than 11% of global fish and shellfish variety. At present, 2.41 million ha are under ponds and tanks, while 1.24 million ha are suitable for brackish water aquaculture. More than 8,752,000 ha of freshwater ponds are in use worldwide (Verdegem & Bosma 2009), with around 850,000 ha under carp culture in India (Ayyappan, 2006). According to DAHDF (2017), approximately 0.895 million hectares of water area have been converted to freshwater aquaculture, with an average production of 3 tonnes per hectare. During the first census of water bodies in India, 24,24,540 water bodies were counted, with 59.9% (14,42,993) being ponds, 15.7% (3,81,805) being tanks, 12.1% (2,92,280) being reservoirs, and the remaining 12.7% (3,07,462) being other water bodies (MoJS, 2023). According to a recent estimate, around 151,815 ponds/tanks in India are being used for both freshwater and brackish water aquaculture (Gupta et al., 2021). India is currently the world's third largest fish producer, accounting for 7.96% of total production, and the world's second largest aquaculture producer, trailing only China. The total fish production in 2020-21 FY was 14.73MMT (million metric tonnes), including 11.25 MMT from the inland sector and 3.48 MMT from the marine sector (DoF, 2022). Inland fish production accounts for approximately 76% of the total fish production of the Country. India's projected fisheries potential is 22.31 MMT, which includes both marine and inland fisheries potentials of 5.31 and 17.0 MMT, respectively. During 2020-21 FY, 66% of marine fisheries potential and 51% of inland fisheries potential were realized (DoF, 2022). Latest available data revealed that fish production has reached all-time high of 16.18 MMT during 2021-22 FY (Fig.

3) as well as all-time high exports of 13.64 lakh tonnes valuing INR 57,587 crore mainly dominated by exports of shrimps (PIB, 2022).

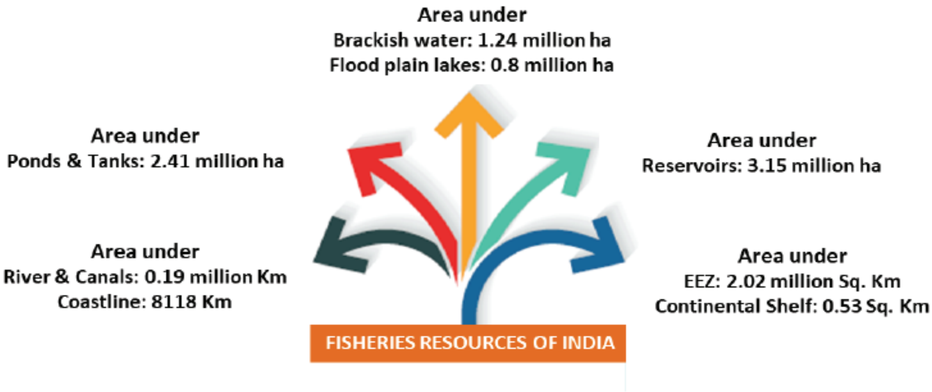


Fig. 2: A glimpse of fisheries resources of India. (*Source: DoF, 2022*)

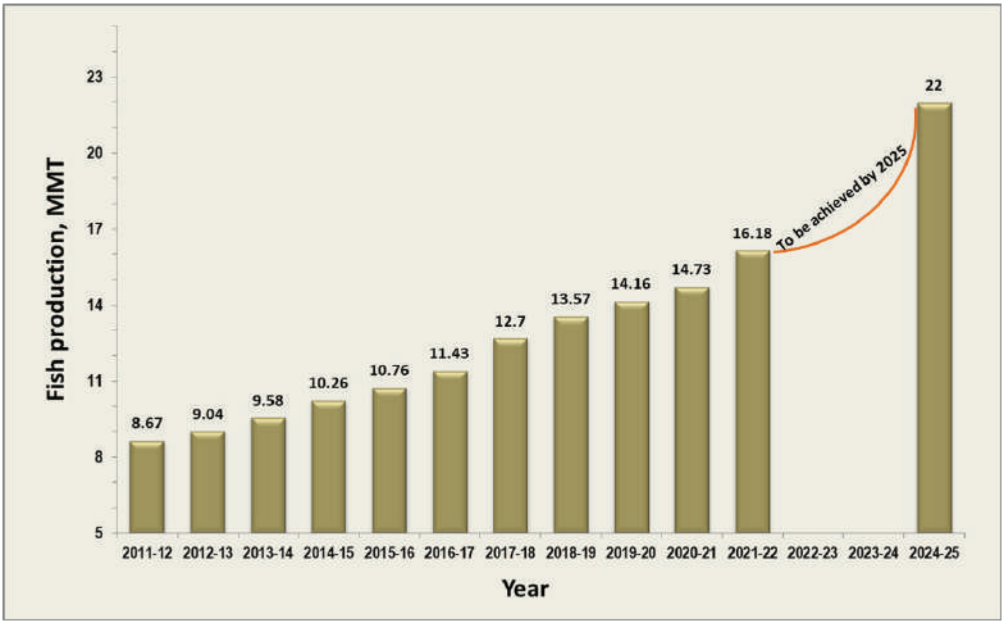


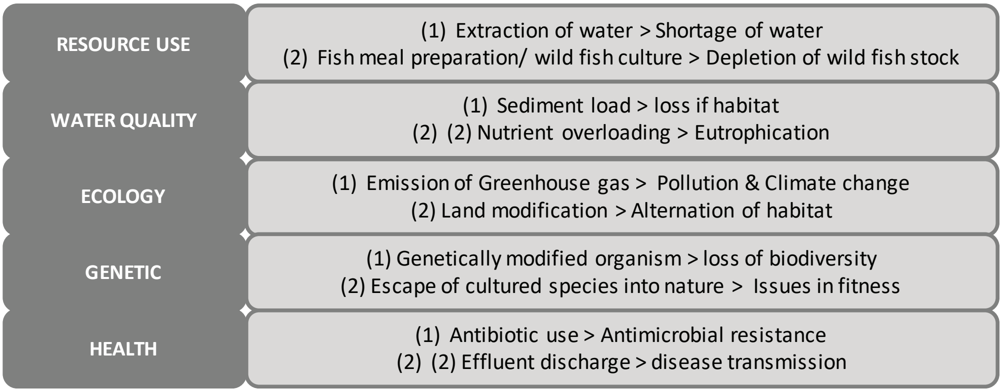
Fig. 3: Trend of fish production in India and target to be achieved by 2025. (*Source: DoF, 2022*)

Basically, two types of aquaculture that are most commonly used in India are freshwater and brackishwater. The breeding and culture of freshwater fish, such as major and minor carps, catfish, SIFs, murrels, prawns, pearl culture, and ornamental fish farming, is known as freshwater aquaculture. Fish like sea bass, mullet, milk fish, grouper, etroplus, shrimp, and crabs are raised in brackish water aquaculture. About three times as much aquaculture is produced in this inland sector than in the capture sector. In order to fill the gap between deficit of capture fisheries and demand of seafood, the viable option left behind is the brackish water and freshwater aquaculture as among the global food resources, 31.4% of assessed fish stocks are overfished and 58.1% are fully fished (FAO, 2018). In India, brackish water aquaculture, almost exclusively dominated by shrimp, has been the most dynamic and socially emotive food production system. Exotic species *L.vannamei* account for about 90% of farmed shrimp production. Until 2010, the tiger shrimp, *P. monodon*, constituted over 100% of cultivated shrimp in India. However, it has been gradually supplanted by exotic *L. vannamei* since 2010. Currently, farmed shrimp production (*L. vannamei* + *P. monodon* + Scampi) has reached an all-time high of 843633MT utilizing 166722 ha area during 2020-21 FY (MPEDA, 2023), which can primarily be attributed to improvements in seed production, feed, genetically improved fast growing stock, specific pathogen-free stock, adoption of better management practices, and adherence to bio-security principles.

3.0 Importance of water management and nutrition-sensitive aquaculture

Need of aquaculture water management, water budgeting and water productivity

Various hazards posed by aquaculture to the environment (Fig. 4), together with water availability and quality, have become major issues around the globe, and the growing global population is putting many regions and Countries at risk of water stress. By 2050, an estimated 2.3 billion people would experience severe water stress (Hussan et al., 2019; Vishwanathan et al., 2021). Water is the prime need for any aquatic production system, thus budgeting and effective utilization are critical in water-scarce situations. Moreover, the increased demand of fish as affordable and safe protein source warrants the rationalisation of water use in every step of the fish production process. Water use in aquaculture may be classified as either total use or consumptive use. Aquaculture's total water use varies substantially, mostly according to the cultivation technique employed. According to reports, intense pond and raceway culture utilizes the majority of water, whereas cage, biofloc, and net pen cultures use the least. The total amount of water used for fish production is usually limited to 4–8 m^3/kg in embankment ponds (*i.e.* which are created without excavation by erecting one or more dikes above ground level to impound water, usually drainable and fed by gravity flow of water or by pumping) and 8–16 m^3/kg in excavated ponds. The amount of water used in ponds varies depending on the intensity of production, frequency, and quantity of water exchange used (Boyd, 2005, Boyd et al., 2007). Currently the on-farm water use in aquaculture can range from 0.5-0.7 m^3 in super-intensive re-circulation systems to 45m^3 per kilogram of production in large pond systems (Verdegem et al., 2006; Mohanty et al., 2017). Furthermore, the degree of water exchange is an important factor in determining water use efficiency in aquaculture. However, most methods of pond aquaculture do not require water exchange (Boyd and Tucker, 1998). Reducing or eliminating water exchange conserves water and lowers pumping expenses. Additionally, reduced water exchange increases the hydraulic retention time (HRT) in ponds. This permits natural processes to completely digest trash and lowers the concentration of possible contaminants in effluent (Boyd 2005). The hydraulic retention time (HRT) of static ponds is in weeks or even months, whereas HRT in ponds with water exchange is usually a week (Boyd et al., 2007).



RESOURCE USE	(1) Extraction of water > Shortage of water (2) Fish meal preparation/ wild fish culture > Depletion of wild fish stock
WATER QUALITY	(1) Sediment load > loss if habitat (2) (2) Nutrient overloading > Eutrophication
ECOLOGY	(1) Emission of Greenhouse gas > Pollution & Climate change (2) Land modification > Alternation of habitat
GENETIC	(1) Genetically modified organism > loss of biodiversity (2) Escape of cultured species into nature > Issues in fitness
HEALTH	(1) Antibiotic use > Antimicrobial resistance (2) (2) Effluent discharge > disease transmission

Fig. 4: Possible environmental threats due to aquaculture

With an aim to reduce water diversion for aquaculture and meet rising food demand of 3 billion tons by 2050, aquacultural water productivity must be improved at various levels. In its broadest sense, water productivity seeks to produce more food, revenue, better livelihoods, and ecological services with less water. Water productivity is defined as the net return per unit of water consumed, or the ratio of net benefits from crop, forestry, fisheries, animal, and mixed agricultural systems to the amount of water required to provide those advantages. Physical water productivity is defined as the ratio of aquacultural production to the amount of water consumed, and economic water productivity is defined as the value derived per unit of water used. In general, enhancing water productivity refers to the most effective way to increase the yield of an aquaculture crop using the available water in the region. Higher water productivity minimizes the demand for more water. To measure the sustainability of water use, several factors must be addressed, including water withdrawal, consumed water, and virtual water use. Water withdrawal refers to water diverted from streams or rivers or pumped from aquifers for aquaculture use. Periodic withdrawal of water from the aquaculture system can subsequently be reused or restored to the environment. The retained part represents consumed water, namely water that is evaporated or incorporated into products and organisms. The virtual water use refers to the indirect water consumption towards production of fish feed etc. Currently, 1.7 m^3 of water per kilogram of fish output is consumed indirectly by evaporation during the production of grains used in fish feeds. In the future, grain-associated water consumption will rise with greater inland aquaculture production, but will plateau at 3 m^3 water per kg production using current technology. Pond evaporation consumes an average of 5.2 m^3 of water per kg of production (Bosma and Verdegem, 2011; Verdegem and Bosma, 2009). Therefore, technologies pertaining to prevention and suppression of evaporation from aquaculture ponds need to be validated and disseminated to stakeholders. Freshwater extraction in inland aquaculture is approximately 16.9 m^3 per kg production; however, infiltration losses (6.9 m^3) and water replacement (3.1 m^3) might be considered green water if pollution is minimized. Infiltration and subsequent percolation, in addition to lateral seepage, are estimated to be 5 to 10 mm/d based on soil texture and pond topography. However, when the groundwater table is high, such as during the monsoon season, fish pond losses are limited to percolation below besides lateral seepage to nearby farms and rivers. Intensification of aquaculture can drastically reduce the evaporation loss per kg of production and thus research should focus on increasing pond water productivity while reducing its environmental impacts.

Water use, water productivity and economic efficiency

Water is the most important natural resource, thus conservation and its judicious use is critical for increasing productivity and sustaining quality. By 2030, increased water diversion for agriculture and the industrial sector, as well as rising aqua-food requirements, will necessitate increased aquacultural water productivity. Aquacultural water productivity (*i.e*. the ratio of the net benefits from aquacultural systems to the amount of water used) reflects the objectives of producing more food, income, livelihood and ecological benefits at minimal social and environmental cost per unit of water consumed (Molden *et al*., 2010). Further, water productivity is an index of the economic value of water used (Boyd, 2005), a useful indicator of efficient water management practices (Dasgupta *et al*., 2008) and is used to define the relationship between crop produced and the amount of water used in crop production (Ali and Talukder, 2008). Higher water productivity not only reduces the need for additional water, but also minimizes the operational cost.

Water use efficiency appears to be an important measure of efficient, environmentally conscientious shrimp farming. Demand-driven water use improves water use efficiency, total water footprint, and water productivity while lowering pumping costs (De Schryver et al., 2008; Mohanty et al., 2017). Though intensification seeks to conserve fresh water, it is not applicable in shrimp production because shrimp farms use brackish water. Nonetheless, using less water per metric ton of shrimp reduces the energy required for pumping. Pumping cost is important where total water is pumped in to aquaculture facility with expense of energy which ultimately reflects the operational cost. Thus, to evaluate the efficiency of water management and operational cost, the gross total water productivity (GTWP), net total water productivity (NTWP) and net consumptive water productivity (NCWP) can be calculated keeping the total volume of water used in to the account as shown below:

$$GTWP = \text{Total economic value of the produce (Rs.)} / TWU\ (m^3) \quad \ldots\ldots\ldots(1)$$

$$NTWP = \text{Total economic value of the produce (Rs.)} - \text{Production cost (Rs.)} / TWU\ (m^3) \quad \ldots\ldots\ldots(2)$$

$$NCWP = \text{Total economic value of the produce (Rs.)} - \text{Production cost (Rs.)} / CWU\ (m^3) \quad \ldots\ldots\ldots(3)$$

To evaluate the efficacy of water management, total water use efficiency (WUE_t) and consumptive water use efficiency (WUE_c) are estimated as follows:

$$WUE_t\ (kg\ m^{-3}) = \text{Biomass production in kg } ha^{-1} / TWU \text{ in } m^3 \quad \ldots\ldots\ldots(4)$$

$WUE_c\ (kg\ m^{-3}) = Biomass\ production\ in\ kg\ ha^{-1} / CWU\ in\ m^3$……………………………………(5)

Further, enhancing water productivity in brackish water and freshwater aquaculture is the prerequisite and there has been the necessity to determine ideal quantity of water essential for successful culture operation (Krummenauer et al., 2016). In addition to water quality assessment and monitoring in shrimp and fish culture, aquaculture water management also aims at quantification and minimization of water use. The future expansion of shrimp and fish culture requires responsible management to increase operational efficacy and help avert wasteful use of water, effluent release and environmental deterioration of receiving water bodies through water cutback approach. Water budgeting and density-specific water use are two major necessities in refining both the coastal grow-out shrimp culture and freshwater aquaculture practice (Mohanty et al., 2016; 2017; 2018a; 2018b).

Hydrological water balance study in aquaculture

Hydrological water balance estimation in fish and shrimp culture ponds not only aids in calculating density-dependent water use in aquaculture operations, but also improves water use efficiency and productivity (Fig. 5). To make a precise estimates of water use in ponds, hydrological water balance equation *i.e.* inflow = outflow ± change in volume (ΔV) is used. Water use in aquaculture may be categorized as either total water use (TWU) or consumptive water use (CWU). TWU (probable inflows to ponds) = initial water filling (W_f) + management additions or regulated inflows (I) + precipitation (P) + runoff (R). CWU (possible outflows) = intentional discharge or regulated discharge (D) + overflow (O_f) + evaporation (E) + seepage (S_o) + transpiration (T) + water content in the harvested biomass (W_b). The difference between the total and consumptive water use, refers to non-consumptive water use (NWU). Commercial fish or shrimp ponds rarely have direct inflow from streams or rivers. Furthermore, aquatic weeds are prohibited from growing in and around pond margins, and water is rarely used for purposes other than farming. Therefore, creek input and transpiration are rarely substantial problems. Embankment fish or shrimp ponds have small watersheds, thus runoff is negligible, and groundwater intrusion is not a significant factor. Water content in harvested biomass is minimal, at 0.75 m^3/t, and can be ignored. Thus the governing water balance equation is:

$P+I = E + S_o + O_f + D \pm \Delta V$ ………………………………………………………………………(6)

A water level gauge can be installed in each pond to quantify the average water loss (evaporation + seepage) in order to estimate the CWU. When adding and withdrawing water, the outflow and inflow are also recorded using a water level gauge. Additionally, the following equation is used to estimate evaporation in order to distinguish it from regular water loss:

Pond evaporation (mm) = Pond-pan coefficient × Class-A pan evaporation (mm) ……………(7)

Eq 7 allows for the use of the pond pan coefficient of 0.8, which is best suited for ponds (Boyd and Gross, 2000; Mohanty and Mishra 2020). The evaporation loss is subtracted from the total loss to determine the amount of seepage from a pond. The following is an estimate of the consumptive water usage index (CWUI), which indicates the volume of water consumed per unit of fish or shrimp production:

CWUI= CWU (m^3)*/ total biomass (kg)*……………………………………………………………(8)

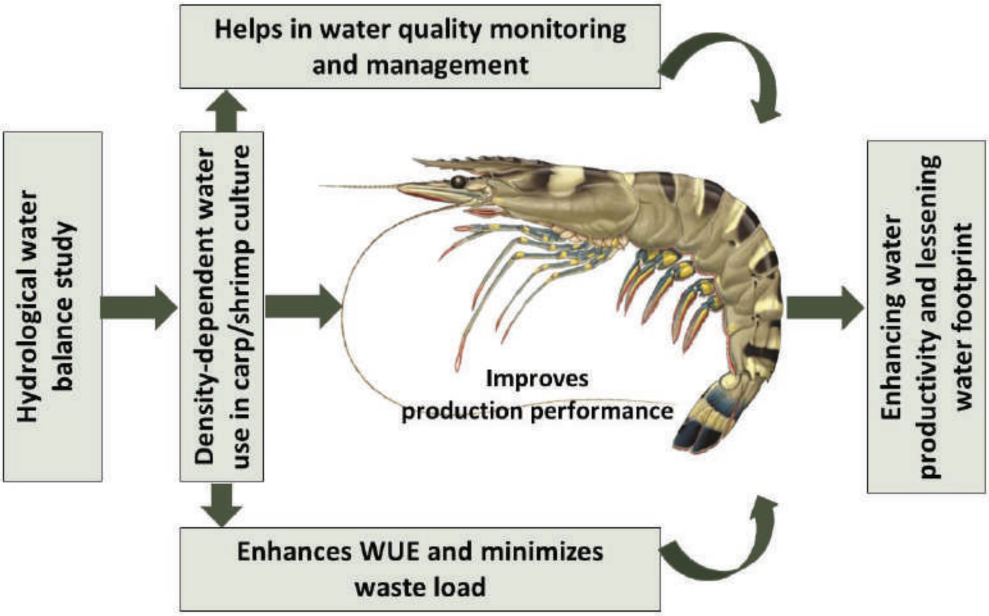


Fig. 5: Advantages of hydrological water balance estimation in aquaculture

Carbon footprint of aquaculture : measures to reduce GHG emission

A carbon footprint is the total amount of greenhouse gases (GHGs, including carbon dioxide and methane) that are generated mainly by anthropogenic activities. Increasing level of atmospheric GHG is a global climate challenge. Carbon dioxide (CO_2) and methane (CH_4) are two important GHGs, accounting for approximately 60% and 20% of the atmospheric radiative forcing, respectively (Zhang, *et al*., 2022; World Meteorological Organization, 2021). India is the world's third largest emitter (2,310 MMT) of greenhouse gases (GHGs), after China (9,877 MMT) and the US (4,745 MMT). India contributes about 7.2% to global greenhouse gas emissions and about 6.9% to global CO_2 emissions. Presently, India's CO_2 emissions are 2.88 Gt and will be 4.48 Gt by 2030 in a business-as-usual scenario (Devasena et al., 2022). The IPCC recommends that global greenhouse gas emissions must be reduced by 45% by around 2030 and reach net zero emissions by 2050 to avoid the worst impacts of climate change. Therefore, the ultimate goal of carbon credits is to reduce the emission of greenhouse gases into the atmosphere (1 carbon credit represents 1 metric ton of carbon dioxide that is reduced or removed from the atmosphere).

The carbon footprint of the aquaculture industry is the result of a combination of factors such as feed production, energy consumption, transportation and waste management. Aquaculture consists of several operational phases such as pond construction, water filling, weed control, stocking, feeding, water quality management and harvesting. All these operations are either directly or indirectly involved in releases of greenhouse gases into environment. In 2018, the global aquaculture production used 1765.2×10^3 TJ energy, 122.6 km^3 water and emitted 261.3 million tons of CO_2-equivalent greenhouse gas (GHGs) to the atmosphere, representing approximately 0.47% of total anthropogenic emissions. Devasena et al., (2022) reported that presently aquaculture produces 0.49% of man-made greenhouse gases or 263 million tonnes of carbon dioxide equivalent (MtCO2e). There are estimated 3.2×10^9 small shallow ponds globally, both natural and man-made, covering a total area of approximately 8.0×10^7 ha (Holgerson and Raymond, 2016). Assessment of GHG fluxes from these shallow ponds, especially aquaculture systems, has attracted much attention in recent years due to their role as potential hotspots for CO_2 and CH_4 emissions (Yuan et al., 2021) probably due to much higher biological density and productivity and enrichment from fertilizer and feeds (Kosten et al., 2020) that favour high respiration and methanogenic rates, leading to high CO_2 and CH_4 emissions (Kosten et al., 2020; Yang et al., 2021).

CO_2 and CH_4 fluxes are mainly affected by management measures and can be reduced significantly by the use of larger aquaculture system (depth and area), pond aeration, precise feeding and stringent water quality management (Zhang, et al., 2022). Life cycle analysis (LCA) indicates that formulated feed is the major contributor to GHG emission from aquaculture. Ecological intensification by growing fish and shrimp within the carrying capacity of the pond, minimizing high-energy supplemental feed by triggering the natural food web of the pond (periphyton-based aquaculture), using renewable energy such as solar power for farm operation, and efficient water management, can help to reduce GHG emissions (Kabir *et al.,* 2020). There are lot other of ways to reduce emissions, including developing genetically improved breeds suitable for lower feed conversion rates, improving health, using more precise site-specific feeding methods, and improving on-farm energy efficiency. The most important impacting factor is the use of electrical energy, which is required to maintain dissolved oxygen using aerators and for pumping the large volumes of water needed for water exchange or addition due to evaporation and seepage loss. Farmed carps, other finfish and crustaceans have the lowest greenhouse gas, nitrogen and phosphorus emissions, but highest water use. To minimize water use in aquaculture hydrological water balance model can be employed to enhance water productivity and lessening water footprint (Mohanty and Sarangi, 2023). Further, possible mitigation strategies for reduction of GHGs from aquaculture systems include (1) Prevention of aquaculture in ecologically sensitive natural sites of high carbon sequestration (*viz.* mangroves, salt marshes, estuaries and other wetlands), (2) Practising integrated multi-trophic aquaculture (IMTA), hybrid system of aquaculture (aquaponics) and periphyton-based fish polyculture system with relatively less formulated feed supplementation and (3) Pond bottom sediment treatment and management.

Importance of water quality assessment in aquaculture

Aquaculture is carried out in ponds, enclosures or in open water bodies and thus involves continuous interaction with the environment. Aquaculture can be a sustainable activity, if it is carried out in socially and environmentally responsible manner, by adopting good aquaculture practices (GAP). Adoption of Best Management Practice (BMP) would result in enhanced production, productivity and returns on one hand and environmental and social responsibilities on the other. Rapid expansion of the coastal aquaculture may pollute the coastal water bodies and interest of other users in agriculture and allied sector. Due to the disposal of organic and nutrient-rich shrimp and fish pond effluent through water exchange, environments of receiving water bodies can suffer from oxygen depletion, reduction of transparency, changes in benthic population structure and eutrophication. Deteriorating water quality has become one of the major factors that bottleneck the shrimp and fish output and breakage of the production process. As water quality affects early life stages, reproduction, growth and survival of aquatic organisms, its monitoring and assessment would play an important role in controlling harmful crisis in aquaculture. Particularly, in shrimp aquaculture, water quality suitability index (WQSI) can be used to transform large amounts of water quality data into a single number and provide the whole interpretation of the behaviour of the water quality parameters. Apart from water quality monitoring and assessment, WQSI (Mohanty and Sarangi, 2023) also helps in determining water exchange requirement and minimization of water use in coastal shrimp culture.

Water footprint in aquaculture

In general, blue and green water contribute to water footprint (cubic metre of consumptive water used per tonne of fish or shrimp produced, $m^3\ t^{-1}$) in aquaculture. Water footprint is estimated considering all four components of water loss to the catchment such as (1) evaporation or evapotranspiration, (2) water content in harvested biomass, (3) contaminated water, and (4) non-return of water to the same area from where it was withdrawn. However, seepage and percolation loss is not considered for estimation of water footprint as these losses are not a loss to the catchment and later can be reused in the same area. Usually, blue (surface and groundwater) and green (precipitation) water contribute to water footprint in aquaculture. Thus, the equation for its estimation is:

$$\text{Total water footprint } (WF_t,\ m^3\ t^{-1}) = (D_i + O_f + E + W_b\,)\,/\,E_{cy} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

Where, D_i = intentional or regulated discharge in m^3, O_f = overflow including other losses in m^3, E = evaporation in m^3, W_b = water content of harvested biomass in m^3 and E_{cy} = Economic crop yield in t ha^{-1}.

Benefits of water budgeting and management in aquaculture: Case studies

ICAR-Indian Institute of Water Management (Bhubaneswar, Odisha, India), a premier Institute with a pan-India presence and a mandate for water management in agriculture, aquaculture, and allied sectors, conducted field experiments on water requirement, WUE, water productivity, and water footprint of high-value aquaculture (Tables 1 and 2) from 2011 to 2022. Water budgeting in coastal shrimp aquaculture assisted in a) water saving up to 30-33%, b) energy/ fuel saving up to US $ 310-320 per ha/ crop, c) manpower saving up to USD 72-80 per ha/ crop, d) input saving (lime/ dolomite) up to US$ 88-90 per ha/ crop, e) reduced sediment load by 12-16%, f) lessening water exchange probability/ less effluent discharge by 30% and thus minimal adverse impact on flora, fauna and benthic population structure of effluent induced water body. Similarly, in different carp polyculture system *viz.* a) IMC grow-out culture : *Single Stock-Single Harvest system*, b) IMC grow-out culture : *Single Stock-Multi Harvest system*, c) IMC grow-out culture : *Multi Stock-Multi Harvest system*, d) intercropping of IMC-Minor carp helped in water saving up to 18-22%, energy or fuel saving up to US $ 220-240 per ha/ crop, manpower saving up to USD 60-65 per ha/ crop, input saving (lime/ dolomite) up to US$ 65-72 per ha/ crop, reduced sediment load by 8-12% besides lessening water exchange probability or less effluent discharge by 20%. This indicated the importance of water budgeting and its subsequent impact on total water requirement, water use efficiency, water productivity and water footprint (Mohanty et al., 2016; 2017a; 2018a; 2018b).

Water budgeting in aquaculture-based Integrated Farming System was carried out by integrating various components such as aquaculture (carp polyculture), agriculture (*kharif* rice followed by green gram and vegetables with sprinkler and drip irrigation), on-dyke horticulture (banana and papaya with drip irrigation) and poultry '*Vanaraja*'. Out of System's total crop water use (3.14×10^4 m^3 240 d^{-1}), the estimated TWU, consumptive water use index (CWUI) and productivity in carp polyculture alone was 2.3×10^4 m^3 240 d^{-1}, 2.6 m^3 kg^{-1} fish production and 2.86 t ha^{-1}, respectively. The estimated evaporation and seepage losses were 2.8 and 2.1 m^3 water kg^{-1} fish production respectively and contributed significantly to CWU. However, system as a whole, resulted in net profit of Rs.1,77,117 ha^{-1} with an output value - cost of cultivation ratio of 3.1 and net consumptive water productivity of Rs.19.2 m^{-3}.

Table 1. Technologically validated field trial result of water use in high-value aquaculture

Water management parameters	Carp polyculture	Monoculture of *P. monodon*	Monoculture of *L. vannamei*
Optimum density, ha^{-1}	8000 fingerlings	200000 PL	500000 PL
Culture duration	180 days	125 days	120 days
Water depth (m) maintained	1.2 up to 90 DOC 1.75 up to 180 DOC	1.0 up to 30 DOC 1.2 up to 125 DOC	1.2 up to 30 DOC 1.5 up to 120 DOC
Evaporation losses, ($\times 10^4$, m^3)	0.58	0.63	0.62
Seepage losses, ($\times 10^4$, m^3)	0.49	0.55	0.52
Regulated outflow, ($\times 10^4$, m^3)	-	0.70	0.63
Other losses, ($\times 10^4$, m^3)	0.06	0.08	0.05
Total loss (CWU), ($\times 10^4$, m^3)	1.13	1.96	1.82
Initial water level, ($\times 10^4$, m^3)	1.20	1.00	1.20
Precipitation, ($\times 10^4$, m^3)	0.6	0.46	0.51
Regulated inflow, ($\times 10^4$, m^3)	1.02	1.40	1.55
Total Water Use, ($\times 10^4$, m^3)	2.82	2.86	3.26
Consumptive Water Use Index, m^3kg^{-1}	2.88	4.28	1.72

Productivity, t ha^{-1}	3.92	4.58	10.58
Feed Conversion Ratio, FCR	1.74	1.40	1.63
Sediment load, m^3 t^{-1} biomass	53.0	42.1	46.3
OV-CC ratio	1.81	2.47	2.11
Total Water Productivity , ₹ m^{-3}	5.9	26.6	46.6
Consumptive Water Productivity, ₹ m^{-3}	10.3	37.9	83.3
Total water footprint (WF$_t$, m^3 t^{-1})	1633	3079	1229

(Source: Mohanty and Sarangi, 2023).

Table 2. Technologically validated field trial result of water use in different freshwater carp polyculture systems.

Water use parameters	Single stock-single harvest	Single stock-multi harvest	Multi stock-multi harvest	Intercropping of IMC-Minor carp
Stocking density ha^{-1}	10,000 IMC fingerlings	10,000 IMC fingerlings	4,000 IMC fingerlings**	8,000 fingerlings Including 50% IMC
Culture duration	360 days	360 days	360 days	360 days
Water depth (m)	1.2 up to 180 DOC 1.5 up to 360 DOC	1.2 up to 180 DOC 1.5 up to 360 DOC	1.2 up to 180 DOC 1.5 up to 360 DOC	1.2 up to 180 DOC 1.5 up to 360 DOC
TWU, (× 10^4, m^3)	2.40	2.53	2.5	2.43
CWU, (× 10^4, m^3)	0.73	0.84	0.82	0.76
CWUI, m^{3}kg^{-1}	1.97	1.95	1.78	1.77
Productivity, t ha^{-1}	3.7	4.3	4.6	4.3
WUE$_c$ (kg m^{-3})	0.50	0.51	0.57	0.56
FCR	1.76	1.63	1.51	1.72
NCWP, ₹ m^{-3}	7.7	8.1	9.2	8.3
WF$_t$, m^3 t^{-1}	1122	1093	998	1026

TWU-total water use; CWU-consumptive water use; CWUI-consumptive water use index, WUE-water use efficiency; NCWP-net consumptive water productivity; WF$_t$-total water footprint; WUE$_c$-Consumptive water use efficiency; FCR-feedconversion ratio; DOC-days of culture, **partial harvesting was carried out at 6th and 9th month followed by restocking @1.25 times of the harvested numbers. (*Source: Mohanty and Sarangi, 2023*).

Smart aquaculture: ICT in aquaculture water management

Smart aquaculture system (Fig. 6) is nowadays one of the sustainable development trends for the aquaculture industry using the artificial intelligence and automation protocols to reduce labor, enhance aquaculture production, and eco-friendly. In Aquaculture, ICTs are being used across the sector, from resource assessment, capture or culture to processing

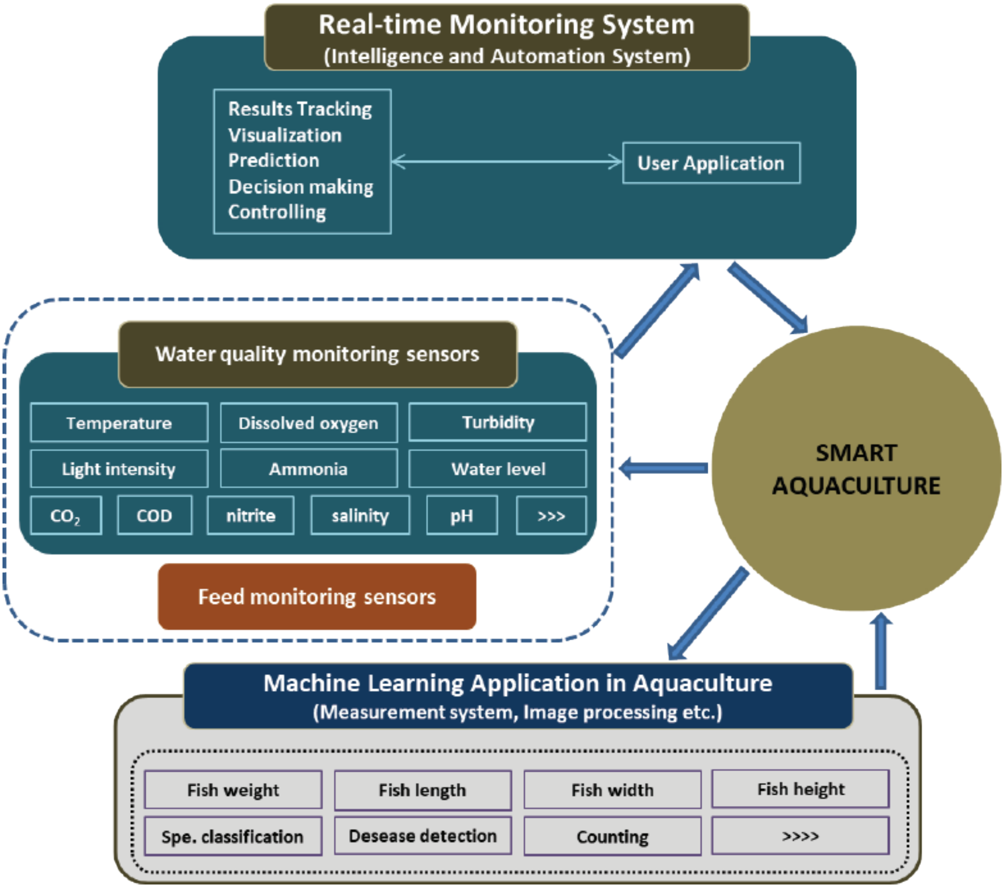


Fig 6. Overview of a system architecture on use of machine learning, smart aquaculture sensors and monitoring systems in aquaculture.

and commercialization. At the production level, ICT can be used for technical designs of sensors for automatically monitoring and controlling in-pond water quality assessment, continuously monitoring important water quality parameters such as temperature, dissolved oxygen, pH, salinity, etc., and real-time adjustments to ensure the growth and survival of fish and shrimp (Antonucci and Costa, 2020).

Recently, Machine Learning is a subdivision of artificial intelligence (AI) helps in smart aquaculture including measuring the size and weight of cultured species, fish diseases, fish count, classification and identification, feed controlling and monitoring *in-situ* water quality (Vo et al., 2021). Integrating smart pipes with water measuring device and sensors within the aqua farms (*i.e.* reservoirs, feeder channel, pond inlet and outlet in shrimp farms, biofloc units, aquaponic units etc.) enables key functions such as the detection of events based on the monitoring of flow rate, pipe pressure, stagnant points, slow-flow sections, pipe leakage, backflow, and water quality to be monitored. A smart aquaculture management system (SAMS) based on the Internet of Things (IoT) has recently gained much attention for fulfilling the growing demand for aquaculture products. The SAMS uses cutting-edge sensing technologies with a modern networking system to continuously monitor water quality, water budgeting, health, and feeding management of cultured species to improve the productivity (Yadav et al., 2022). Introduction of IoT-based technologies, e.g., different sensors, software interfacing, artificial intelligence, cloud computing, and storage, to develop reliable and robust SAMS which is very much essential for real time water quality monitoring and budgeting of different aquaculture systems.

Nutrition-sensitive aquaculture: targeting the underlying determinants of malnutrition

Nutrition-sensitive aquaculture is a food-based approach to aquaculture development that ensures nutritionally rich foods, dietary diversity, and food fortification at the heart of overcoming malnutrition and micronutrient deficiencies. This approach seeks to ensure the production of a variety of affordable, nutritious, culturally appropriate and safe food fishes in adequate quantity and quality to meet the dietary requirements of populations in a sustainable manner (FAO, 2016). If widely applied to aquaculture, this approach could create large impacts on the nutritional status and health of populations, within both resource- poor and better-off populations (Genschick et.al., 2015). Further, nutrition sensitivity examines and explores how nutrition can be prioritised within aquacultural policies, strategies and investment plans, and demonstrates the power of aquacultural bio-diversity, social behavioural change, enterprise diversification, and women's empowerment in improving nutrition in rural areas. *Mola-Carp polyculture* is an example of best nutrition-sensitive aquaculture practice. They play a crucial role in promoting *nutrition-sensitive aquaculture* in India and South Asia and have the potential to significantly reduce under nutrition through food-based strategies. Unlike large fish, mola is consumed whole with head and bones, provide a significant source of bioavailable calcium, zinc, iron and vitamin-A (Bogard *et al.* 2015). If consumed within the household, mola *(Amblypharyngodon mola)* could contribute half of the vitamin-A and a quarter of the iron intake recommended for a family of four, annually (Castine *et al.* 2017). A 100g mola contains approximately 1,960 µg vitamin-A, 1,071 mg calcium and 7 mg iron (Roy *et al*. 2015). Combining small indigenous fish species (SIS/SIFs)with large species in homestead pond polyculture, offers opportunity to increase household dietary diversity and micronutrient intake (Bogard *et al*. 2015).

Small indigenous fish species (SIS/SIFs), defined as species that grow to a maximum length of about 25 cm and are indigenous in origin (Nandi et al., 2013), are in high demand in both rural and urban markets due to their nutritional value, taste/ flavor, and low to moderate market prices. Besides being a rich source of easily digestible high quality protein, and a wide variety of vitamins and minerals, SIS is a unique source of essential nutrients including long chain Omega- 3 fatty acid, iodine, vitamin D and Calcium (Fiedler *et al*., 2016; Thilsted *et al*., 2016) and they contribute to enrich the quality of the aquatic ecosystems (Aditya *et al*., 2012), food security (Fiedler et al., 2016; Thilsted et al., 2016) and the livelihood in India and many other Asian countries (Belton & Thilsted, 2014).

There are many small fish in *viz.* mola (*Amblypharyngodon mola*) , Chela. (*Salmophasia bacaila*), Punti (*Puntius* sp.), Tangra (*Mystus vittatus*), Pabda (*Ompok pabda*), Singhi (*Heteropneustes fossilis*), chapila *(Gudusia* chapra), bata *(Labeo bata),* dhela *(Osteobramcotio cotio cotio),* colisa *(Colisa fasciata),* kacki *(Corica soborna)* etc., which are potential SIS/SIFs for freshwater aquaculture. Small fish are not only cost-effective, but also nutrient-rich solution in the face of growing challenges. SIFs can be many times richer in micro-nutrients, vitamins, minerals, essential fatty acids and amino acids than commonly farmed carps that can prevent micronutrient deficiencies in children and pregnant women. Therefore, Mola and other SIFS have the potential to play a significant role in food-based strategies to address malnutrition within environmental boundaries. Accessibility is also important – small fish are often cheaper than other animal-source foods and can be purchased in small quantities. Food insecurity and poverty can also be addressed through the harvesting and production of small fish, which form an important part of local livelihoods. Therefore, key recommendations for large-scale adoption of nutrition-sensitive aquaculture (Fig. 7) would help in achieving many agenda of SDGs. WorldFish has already pioneered nutrition-sensitive aquaculture by promoting the addition of SIS/ SIFs to conventional carp farming systems (Dubey et.al., 2023).

- Facilitate crop/production diversification
- Provide package of practice & technical assistance
- Avoid 4 Os: over stocking, over feeding, over fertilization, over medication
- Improve water quality and periphyton growth as natural food
- Multi-sectoral collaboration & coordination
- Assess local nutrition status & include nutrition education
- Include nutrition in social safety nets
- Monitor access and consumption of nutritious SIS/SIFs
- Maintain / improve natural resource base
- Incentives for scaling-up production
- Improve equity for vulnerable population & empower women in aquaculture
- Expand markets, easy availability of inputs & access for vulnerable population
- Capacity building

Fig. 7: Key recommendations for large-scale adoption of nutrition-sensitive aquaculture

4.0 Water management and nutrition–sensitive aquaculture: Problem and prospects

Due to the problem of low economic output in grow-out aquaculture (as a result of increased feed price, power supply, chemicals and aqua-drugs etc.), it has become imperative to minimize the operational cost by improving the water productivity. In fact, uncertainty in monsoon rain, scare and limited availability of freshwater resource necessitated judicious use of water in aquaculture sector to increase water productivity. World in general and India in particular, the freshwater supply and reserve is now under threat due to increased population pressure followed by increasing demand of water in agriculture, industry and domestic sectors. The limited nature of the water resource, therefore, warrants a more holistic approach to water management. Moreover, water budgeting and its judicious use should be a primary requisite towards development of protocols for best water management practice (BWMP) in commercially important grow-out aquaculture.

In static water pond, the evaporation, percolation and seepage represent the highest water loss, which results in poor water productivity due to nutrient loss and fluctuation in water quality. To substitute and maintain such water loss, pond fertility and survivability of stocked animal besides, replenishment or exchange of water becomes essential. Many a times, farmers replace pond water with an intent of higher production without considering its necessity and operation cost which sometimes become counterproductive and uneconomical. However, quantification of water requirement plays a critical role which depends on various factors *i.e.*, species, stocking density, growth stage, biomass, plankton and nutrient status, water loss, agro-climatic condition etc. Water requirement is a function of soil, climatic condition, species to be stocked, culture method and management practices. Therefore, it is necessary to assess the necessity of replenishment or exchange followed by quantification of water for replenishment to minimize wasteful use of

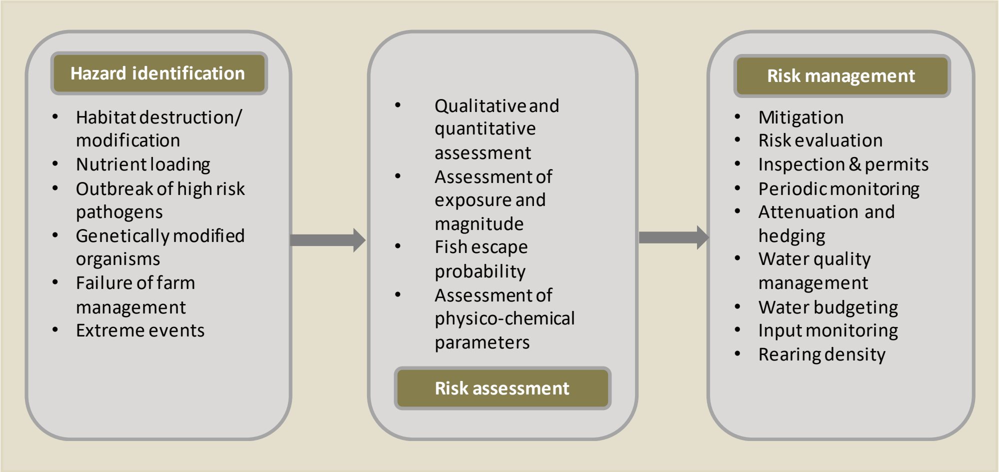


Fig. 8: Risk analysis for achieving sustainability in nutrition-sensitive aquaculture

water. Further, risk analysis for achieving sustainability in nutrition-sensitive aquaculture (Fig. 8) is of paramount importance towards development of good aquaculture practice (GAP). The water budgeting analysis pertaining to different species and aquaculture water productivity may form the practical tools for generating useful information for mitigating the water availability issues for aquatic production.

Moreover, to achieve higher production from limited land and water resources, crop diversification and intensification of different aquaculture practices is being undertaken. However, unplanned intensification of the culture system questions the sustainability of aquaculture in India. Diversification of production system in carp farming has been emphasized in recent years for sustainable yield enhancement and reduced dependence on supplementary feed. Introducing small indigenous fish species (SIS) in carp polyculture (nutrition-sensitive aquaculture practice) and promoting periphytic growth on artificial substrate which serves as an *in situ* food production method, is gaining popularity among the farmers. Further, there is a tendency in carp polyculture system that, farmers' once stock fingerlings at the culture season and sell their entire crop at the harvest season, keeping their family away from fish intake. If small indigenous fish species (SIS) and large fish could be cultured together, farmers would have the opportunity to harvest small fish (***service species***) periodically round the year and feed the family members with nutrient rich small fish and could sell their pellet-fed large carps (***target species***) as cash crop. They will also have option for selling harvested SIS intermittently before harvest of the cash crop. Periphyton-based culture of carps and SIS in stand-alone ponds not only increase production and productivity, but also improve the water quality and nutritional quality of the fish produced. These technologies can boost household income for millions of Indians, and help build healthy families through the consumption of micronutrient rich SIS. The contribution to food security and the livelihood are valued ecosystem services attributable to the SIS (Thilsted et al., 2016). Inclusion of SIS in carp polyculture systems in stand-alone ponds is currently being promoted as a means to enhance productivity, income and food and nutrition security of the rural poor. The focus on mola *(Amblypharyngodon mola)* in carp-SIS polyculture is primarily due to the extremely high vitamin-A content and therefore, the potential for mola production as a food-based approach to combat the high prevalence of vitamin-A deficiency in rural India.

5.0 Governance in aquaculture: existing policy and support framework

Governance and economy issues underlie most sustainable development challenges, constrain policy choices, and, when ignored or misunderstood results in persistent source of policy failure. Policy design must be closely linked to governance analysis, and adapted to national preferences and priorities as well as Institutional and economy realities. The dynamics of Institutional change in specific contexts are complex and uncertain, but analysis is essential for assessing the possibilities and formulating strategies to achieve transformational change. Policy oriented governance is fundamental for successful aquaculture development based on sound and enforceable legal and institutional framework. Such framework is fundamental to create an enabling environment to attract investment in aquaculture expansion. The main features of such governance are: participation, consensus orientation, strategic vision, responsiveness, effectiveness and efficiency, accountability, transparency, equity and the formulation of law. It includes legally binding rules, such as national legislation or international treaties. Adequate planning and policy-making are the key means by which aquaculture can be sustainable, nutritionally secure and remunerartive.

Effective governance of modern aquaculture (Fig. 9) must reconcile ecological and human well-being so that the industry is sustainable over time. Without effective policy, there will be misallocation of resources, and perhaps stagnation of the industry and irreversible environmental damage. There is a consensus that modern aquaculture has a business orientation, similar to any small or medium-sized enterprise. For resources to be invested, there must be an enabling economic environment and secure property rights. However, there must also be controls or incentives to curb short-sighted business approaches that damages the ecology or society. This requires that aquaculture be not only profitable but also environmentally sustainable, technically feasible and socially acceptable. Four governance principles – (1) accountability, (2) effectiveness and efficiency of governments, (3) equity and (4) predictability are suggested as necessary for sustainable development of the industry. Accountability and predictability provide assurances to entrepreneurs that property rights and contracts will be honoured, while intergenerational equity suggests ecological conservation. The principle of effectiveness and efficiency implies that regulation of aquaculture will be sufficient without being too onerous, and also perhaps decentralization and public participation. Based on these four principles, administrative and legislative frameworks can assist aquaculture to develop sustainably. In addition to governments, there are other participants in aquaculture governance such as communities, non-governmental organizations (NGOs) and FPOs' should also be involved in the governance of the industry.

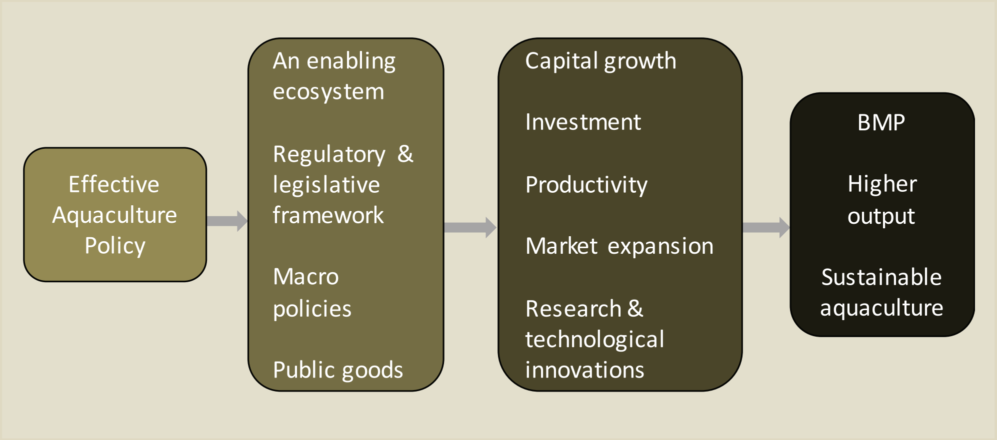


Fig. 9: Impact of policy formulations on nutrition-sensitive aquaculture

Institutional mechanisms are required to address adverse impacts and trade-offs between competing policy objectives. Innovative governance mechanisms can help reposition different sectors and actors as partners – rather than competitors leading to coordinated action towards food systems transformation. Engaging the range of stakeholders and facilitating partnerships are essential tasks in the governance process. Establishing the societal frameworks needed to eliminate hunger and ensure food security and nutrition for all remains an essential responsibility of States, but the way this responsibility is carried out needs to be adapted to changing climate, circumstances, knowledge, needs, risks and opportunities. Broad social participation is needed to sustain the efforts, even in the face of changes of government, limited budgets and socio-economic and climatic shocks. Cross-sectoral coordination and networks of communication within government as well as across the public-private divide are indispensable means for facilitating the effectiveness of policies and outcomes of food systems. Successful aquaculture governance and achieving sustainability transformation goals, five key approaches are necessitated (Fig 10).

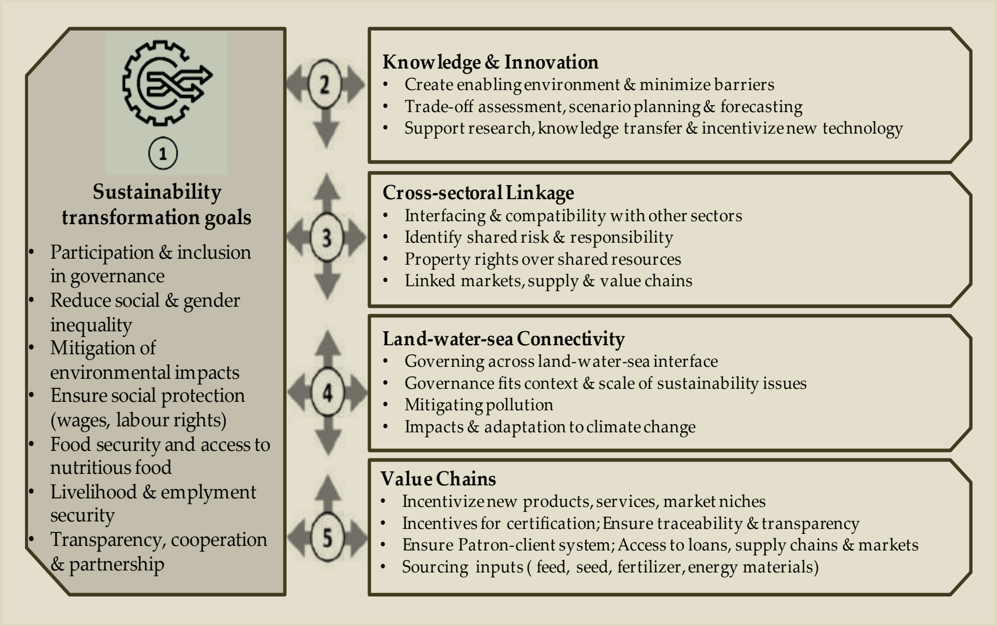


Fig. 10: Five key approaches for aquaculture governance and sustainability transformation.

Aquaculture development hinges on four key policy domains: public investments in infrastructure and R&D; policies supporting aquaculture value chains; regulatory policies providing environmental and social protections; and trade policies. Public investments in infrastructure (e.g., ponds, waterways, roads, cages, and ports) and basic research and development provide the foundations for aquaculture innovation and expansion in all producing Countries. Innovation is the engine for aquaculture productivity growth and reduced input prices for producers and consumers, as emphasized by Anderson et al. (2019). Aquaculture innovation often derives from market scarcity and other constraints

(e. g., declining wild fish stocks including forage fish for feeds, rising cost of fishmeal and fish oil in feeds, disease pressures) and is supported by technology and policy incentives (Asche and Smith, 2018).

Government policies have fundamentally shaped the geographic distribution of aquaculture growth, as well as the types of species, technology, management practices, and infrastructure adopted in different locations (Garlock et al., 2020). Most aquaculture policies aimed at economic development, aquaculture disease management, targeting location of aquaculture systems, environmental performance, and trade protection. However, there is a need to find the right policy balance between semi-subsistence farms, small and medium enterprises (SME), and large-scale commercial operations, particularly in low-income settings. It is important to address challenges of establishing nutrition-sensitive aquaculture, enhancing water use efficiency (*viz.* water budgeting , water productivity, water footprint), aquaculture disease pressures and misuse of antibiotics in India and many parts of the world.

Constraints in the growth of the Indian aquaculture sector

- Limited scope for horizontal expansion, weak regulation, inefficient management and prevalence of traditional aquaculture practices.
- Inadequate infrastructure for fish markets, landing centers, cold chain and distribution systems.
- Poor processing, value addition, traceability and certification and non-availability of skilled manpower too are added limitations.
- Issues related to tenure and lease rights of tanks/ponds/natural water bodies, coupled with low capital infusion are some of the significant limiting factors.
- The poor condition of resources, low input culture system, lack of diversity in cultural practices and species, lower productivity, and inadequate regulatory mechanism.
- Increased incidence of disease accompanied by low levels of investment, inadequate access to institutional credit and high cost of credit, and inadequate infrastructure for pre-production (seed production), grow-out production, post-harvest and processing facilities.
- Inadequate adoption of technologies/ up-scaling and shortage of skilled manpower in aquaculture and extension services.

How to achieve the objectives: the way out

(A) **Freshwater aquaculture**

- Establishing a uniform, integrated and concerted regulatory framework for planned and sustained growth of aquaculture in open-water resources.
- Promote development of scientific aquaculture in existing ponds or tanks, construction of new ponds in low-lying areas, lands with saline and alkaline soils, and lands not suitable for crop cultivation.

- Optimally harness the culture fisheries potential of the country by enhancing fish production and water productivity in a responsible and sustainable manner.
- Crop diversification and inclusion of SIS/ SIFs as service species with target species to ensure nutritional security.
- Robust resource management and regulatory framework based upon Ecosystem Approach of Fisheries Management (EAFM).
- Promote aquaculture through standardised SoPs, inputs and farming systems for sustainable and responsible culture.
- Conserve and manage native fish genetic stocks and associated habitats and ecosystems.
- ToT, easy access to essential inputs and formation of Farmers Producer Organisations (FPOs) to cater small pond holder's needs.
- To provide coordination support and address the cross-sector issues confronting the development of fisheries and aquaculture.
- Need of an 'Integrated Fisheries Development Plan'
- Traditional and small-scale fisher groups should be encouraged for undertaking resource specific integrated aquaculture for harnessing untapped potential of high value resources through infusion of modern technology and capacity building.
- Generate gainful employment and entrepreneurship opportunities along the value chain leading to higher income of fish farmers, improve their living standards and usher in economic prosperity.

(B) **Brackish water aquaculture**

- Promote development of aquaculture in suitable brackish water areas.
- To delineate *Aquaculture Zones* using modern tools for scientific and planned development of aquaculture.
- Market promotion, trade and export of globally competitive fish and value-added fish products benchmarking with global standards need to be promoted.
- Mandatory registration of aquaculture farms, simplification of legal and environmental requirements for farm registration and leasing need to be ensured.
- Adoption of Best Management Practices (BMPs) to minimise disease incidence and other ecological externalities to ensure sustainability.
- Coastal aquaculture development efforts need to be aligned with relevant national and global instruments, guidelines and good practices including Sustainable Development Goals (SDGs).
- Fool proof mechanism for monitoring, control and surveillance for disease control and animal health, traceability, standards, testing and certification of the aquaculture produce along with requisite regulatory framework and infrastructure.

- Encouraging Public Private Partnerships (PPPs) to leverage private sector investments in coastal shrimp farming.
- Strengthen and modernise value chain including creation of fisheries infrastructure to increase shelf life, reduction of post-harvest losses and production of value added products.
- Access to institutional credit as priority lending on the lines of the crop sector especially to small and marginal fish farmers and unemployed youth.
- Promote community partnerships, private participation and effective cooperative movement in the fisheries sector.

6.0 Sustainable aquaculture for *Atmanirbhar Bharat*: Opportunities & strategies to unlock its prospects

Increased productivity from sustainable fisheries and aquaculture can be a driver for rural development by mitigating risks to livelihoods and contributing to income generation and employment. Aquaculture, in particular, has tremendous potential to enhance food security and sustainability. Small-scale aquaculture is especially important for meeting the world's growing demand for fish. As fish requires a smaller environmental footprint than other animal source food, aquaculture is an environmentally viable ecological option for meeting the world's food needs than other animal source foods. Aquaculture has become an important and growing sector not only in India but across the world. India is home to more than 11 percent of the global biodiversity in terms of fish and shellfish species and has shown continuous and sustained increments in fish production. Aquaculture has not only led to substantial socio-economic benefits such as increased nutritional levels, income, employment and foreign exchange but has also brought vast un-utilized and under-utilized land and water resources under aquaculture.

Recently, the measures announced under the *Pradhan Mantri Matsya Sampada Yojna* (PMMSY) for fisheries and shrimp sector aim to boost export and rural employment are encouraging. These measures will boost rural entrepreneurship, enable wealth creation to boost the economy to make India self-reliant as envisioned by our Hon'ble Prime Minister. During the period 2020-2021 to 2024-2025, an estimated investment of Rs. 20,050 crores has been announced. Hon'ble Prime Minister also emphasized on deriving maximum benefits out of the PMMSY schemes towards making of *Atmanirbhar Bharat*. More focus has been given on strengthening the value chain, including infrastructure, modernization, traceability, production, productivity, post-harvest management, and quality control. Aquaculture can become a huge source of generating employment and livelihood. It can increase protein availability through adoption of *nutrition-sensitive* aquaculture practice, alleviate the issues related to rural employment and help achieve the food security goals. Especially with all the reverse migration happening across the Country due to the pandemic, aquaculture sector can help in rehabilitation of these migrants in post-pandemic phase and support in creating a livelihood for them. Therefore, for *Atmanirbhar Bharat* in sustainable aquaculture, greater emphasis should be given on

- 'Cluster based approach' with suitable forward and backward linkages having an equally strong focus on management and conservation of resources.
- Integration of various production activities such as (1) Production of quality fish seed by establishing new hatchery (2) Production of cost-effective feed using locally available ingredients (3)Adoption of feasible aquaculture technology (4) Creation of post-harvest facility (5) Marketing facilities in close vicinity to commercial aquaculture.
- Practicing integrated aquaculture farming for agricultural multi-enterprises development.
- Effective utilization of existing ponds and tanks through semi-intensive to intensive aquaculture.
- Emphasis on culture-based fisheries in open water systems and enclosure-based aquaculture in reservoirs.
- Supplementary stocking of fingerlings of native species in wetlands and reservoirs.
- Diversification of culture species, emphasizing on culture of small indigenous fish species (SIFS/SIS) under polyculture system.
- Women empowerment in aquaculture sector through training and capacity building.
- Strategic re-integration and group farming: strengthening farmer producer organizations (FPOs) and self-help groups (SHGs)

7.0 Recommendations

There is increasing demand on the aquaculture sector to increase resource efficiency in production. Aquaculture's "Blue Revolution," which refers to its paramount growth, has to "go green" by incorporating the concepts of "ecological aquaculture," which incorporates aquaculture water and nutrient management. Finding the perfect blend of water and nutrient in aquaculture system is essential for its success under the escalating shortage of water resources and associated risks of environmental impact. Responsible and environment-friendly practices are necessary for aquaculture's future growth in order to increase operational effectiveness, prevent wastage of water, and maintain the quality of pond water. Under such situation, a few specific recommendations would assist in enhancing aquaculture water productivity and promoting nutrition-sensitive aquaculture.

- With the increasing scarcity of water resources and threats of environment pollution, there is a need to determine the ideal amount of water necessary for successful aquaculture. To accomplish this, Internet of Things (IoT) enabled integrated water depth sensing system need to be developed to monitor the water depth of aquaculture ponds at regional scales. Data acquired from the water level depth sensors can be integrated with the volume of water required pertaining to different fish cultivars besides the best management practices to develop a mobile app on Aquaculture Water Management System for Enhancing Aquaculture Production (AWM-EAP).

- It is imperative to develop a *nutrition-sensitive aquaculture* to improve operational efficiency and prevent wasteful use of water and deterioration of pond water quality. To achieve this, an IoT enabled integrated water quality sensing systems need to be developed and standardized for real time water quality monitoring of aquaculture systems.
- Site-specific hydrological water balance study in catchment scale need to be undertaken to determine density-dependent water use for improving aquaculture performance. The hydrological models need to be integrated with aquaculture water budgeting protocol to estimate the water availability and subsequent demand for enhancing aquaculture water productivity. Water budgeting protocol under aquaculture system need to be integrated with climate change models or representative carbon pathways (RCP) scenarios to predict the future water requirement of different aquaculture systems.
- Effective utilization of existing ponds and tanks through semi-intensive to intensive aquaculture or integrated aquaculture need to be taken up for agricultural multi-enterprises development. Diversification of culture species and emphasizing on culture of small indigenous fish species (SIFS/SIS) under polyculture system would assist in ensuring *nutrition sensitive aquaculture*. Adoption of new aquaculture practices that require less water (biofloc system, aquaponics etc.) and pond-based aquaculture with demand driven low to moderate water exchange, not only serves to keep the water quality suitable for growth, but also improves water use efficiency, water productivity and helps in minimizing the water footprint, carbon credit, sediment load and effluent outputs. Water saving approaches in aquaculture system need to be integrated with the carbon dioxide reduction estimation protocol to highlight the carbon credit in aquaculture
- Water budgeting, density-dependent water use and monitoring of water quality are three major requirements for sustainable aquaculture production under changing climate and One-Health regime. Bringing aquaculture under ONE HEALTH umbrella is a necessity to address critical issues related to zoonotic disease, AMR, food safety (Safe Water for Safe Food), environmental contamination, food security and occupational health.
- Strategic re-integration and group farming or 'cluster based approach' with suitable forward and backward linkages besides strong focus on management and conservation of resources is need of the hour. Integration of various production activities such as (1) Production of quality fish seed by establishing new hatchery (2) Production of cost-effective feed using locally available ingredients (3)Adoption of feasible aquaculture technology (4) Creation of post-harvest facility (5) Marketing facilities in close vicinity to commercial aquaculture will strengthen aquaculture sector, farmer producer organizations (FPOs) and self-help groups (SHGs).

References

Aditya, G., Pal, S., Saha, N., Saha, G. K., 2012. Efficacy of indigenous larvivorous fishes against *Culex quinquefasciatus* in the presence of alternative prey: Implications for biological control. Journal of Vector Borne Diseases, 49, 217-225.

Ali, M.H., Talukder, M.S.U., 2008. Increasing water productivity in crop production- A synthesis. Agricultural Water Management, 95 : 1201–1213.

Anderson, J.A., Asche, F., Garlock, T., 2019. Economics of aquaculture policy and regulation. Ann. Rev. Resour. Econ. 11, 101–123.

Antonucci, F., Costa, C., 2020. Precision aquaculture: a short review on engineering innovations. Aquac. Int., 28: 41–57. https://doi.org/10.1007/s10499-019-00443-w.

Asche, F., Smith, M.D., 2018. Viewpoint: Induced innovation in fisheries and aquaculture. Food Policy 76, 107.

Ayyappan, S., 2006. National Aquaculture Sector Overview: India. Fact Sheets. FAO, Rome.

Belton, B., Thilsted, S. H., 2014. Fisheries in transition: Food and nutrition security implications in the global south. Global Food Security, 3, 59-66.

Bleischwitz, R., Hoff, H., Spataru, C., van der Voet, E., VanDeveer, S.D., 2018. Routledge Handbook of the Resource Nexus. London: Routledge, p. 517.

Bogard, J. R., Thilsted, S. H., Marks, G. C., Wahab, A., Hossain, M. A. R., Jakobsen, J., Stangoulis, J. 2015. Nutrient composition of important fish species in Bangladesh and potential contribution to recommended nutrient intakes. Journal of Food Composition and Analysis, 42, 120–133.

Bosma, R.H., Verdegem, M.C.J., 2011. Sustainable aquaculture in ponds: Principles, practices and limits. Livest Sci 139:58–68.

Boyd, C. E., 2005. Water use in aquaculture. World Aquacult., 36(3): 12–15 and 70

Boyd, C. E., Gross, A., 2000. Water use and conservation for inland aquaculture ponds. Fisheries Management and Ecology 7(1-2), 55-63.

Boyd, C. E., Tucker, C. S., Mcnevin, A., Bostick, K., Clay, J., 2007. Indicators of Resource Use Efficiency and Environmental Performance in Fish and Crustacean Aquaculture. Reviews in Fisheries Science 15, 327–360.

Carmona-Morena, C., Dondeynaz, C., Biedler, M., 2019. Position paper on water, energy, food, ecosystems (WEFE) nexus and sustainable development goals (SDGs). In EUR 29509 EN. Luxembourg: Publications Office of the European Union. http://doi.org/10.2760/31812.

Castine, S.A., Bogard, J.R., Barman, B.K., Karim, M., Hossain, M., Kunda, M., Haque, M., Phillips, M.J., Thilsted, S.H.,2017. Homestead pond polyculture can improve access to nutritious small fish. Food Sec. 9:785–801

Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shoa, L.,Wu, X.F.,Wei, W.D., Liu, S.Y., Li, Z., Li, J.S., Chen, G.Q., 2018. Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. Science of the Total Environment 613–614, 931–943.

DAHDF. (2017). Annual Report 2016-17, Department of Animal Husbandry Dairying and Fisheries. Ministry of Agriculture, Government of India. pp. 91-153.

Dasgupta, S., Pandey, B.K., Sarangi, N., Mukhopadhyay, P.K., 2008. Evaluation of water productivity and _ish yield in sewage-fed vis-a`-vis fertilized based carp culture. Bioresource Technology, 99 : 3499–3506.

de Fraiture, C., Wichlens, D., Rockstrom, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L.J., Hanjra, M.A., Hoogeveen, J., Huber-Lee, A., Karlberg, L., 2018. Looking ahead to 2050: Scenarios of alternative investment approaches. Irrigation Drainage Systems 22, 127.

De Schryver, P., Crab, R., Defoirdt, T., Boon, N., Verstraete, W., 2008. The basics of bioflocs technology: the added value for aquaculture. Aquaculture 277, 125–137.

Devasena, S., Padmavathy, P., Manimekalai, D., Rani, V., 2022. Carbon footprint in aquaculture –A review. Journal of Research in Environmental and Earth Sciences, 8 (7): 64-73.

DoF, 2022. Annual Report-2021-22, Department of Fisheries, Ministry of Fisheries,Animal Husbandry and Dairying, Government of India, p 112.

Dubey, R. F, Gogoi K, Das RR, Biswal SK, Padiyar AP, Rajendran S, Thilsted SH, Mohan CV and Belton B (2023) Cracking the code of hatchery-based mass production of mola (*Amblypharyngodon mola*) seed for nutrition-sensitive aquaculture. *Front. Aquac.* 2:1271715. doi: 10.3389/faquc.2023.1271715

EEA, 2015. The European Environment State and Outlook 2015. Assessment of Global Megatrends. Copenhagen: European Environment Agency, 140pp.

FAO, 2018. The State of World Fisheries and Aquaculture 2018. Meeting the sustainable development goals.

FAO. 2016. Strengthening sector policies for better food security and nutrition results. Fisheries and aquaculture. Policy Guidance Note 1. Rome: United Nations Food and Agriculture Organization.

FAO. 2022. The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation, The State of World Fisheries and Aquaculture (SOFIA). FAO, Rome, Italy. Doi: 10.4060/cc0461en.

Fiedler, J. L., Lividini, K., Drummond, E., Thilsted, S. H., 2016. Strengthening the contribution of aquaculture to food and nutrition security: The potential of a vitamin A-rich, small fish in Bangladesh. Aquaculture, 452, 291-304.

Garlock, T., Asche, F., Anderson, J., Bjørndal, T., Kumar, G., Lorenzen, K., Ropicki, A., Smith, M.D., Tveterås, R., 2020. A global blue revolution: Aquaculture growth across regions, species, and countries. Rev. Fish. Sci. Aquacult. 28, 107–116.

Garlock, T., Asche, F., Anderson, J., Ceballos-Concha, A., Love, D.C., Osmundsen, T.C., Pincinato, R.B.M., 2022. Aquaculture: The missing contributor in the food security agenda. Glob. Food Sec. 32 https://doi.org/10.1016/j.gfs.2022.100620.

Genschick, S., Phillips, M.J, Thilsted, S.H, Thorne-Lyman, A.L, & Subasinghe, R, 2015. Aquaculture and fisheries for nutrition: towards a nutrition sensitive approach. INFOFISH *International* **3**/2015. www.infofish.org: 4-17

Gleeson, T., Wada, Y., Bierkens, M.F.P. and van Been, L.P.H., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488, 197–200.

Gupta, P.K., Patel, J.G., Singh, R.P., 2021. Space based observation of Indian Wetlands. Space application centre, Indian space research organisation Ahmedabad, Gujrat, India. https://www.sac.gov.in. Accessed 30 May 2022

Holgerson, M.A., Raymond, P.A., 2016. Large contribution to inland water CO 2 and CH emissions from very small ponds. Nat. Geosci. 9 (222), U150. https://doi.org/10.1038/ngeo2654.

Hussan, A., Adhikari, S., Das, A., Hoque, F., Pillai, B., 2019. Fish culture without water. Int. J. Fish. Aquat. Sci. 7, 39–48.

Jägermeyer, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: Global simulation of processes and linkages. Hydrology and Earth System Sciences 19, 3073–3091. http://doi.org/10.5194/hess-19-3073-2015.

Jägermeyer, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., Rockström, J., 2016. Integrated crop water management might sustainably halve the global food gap. Environmental Research Letters 11, 025002. http://doi.org/10.1088/1748-9326/11/2/025002.

Kabir, K. A., Phillips, M., Verdegem, M. C. J., 2020. Reducing the Carbon Footprint from Pond Aquaculture in a Changing World. *Journal of the Indian Society of Coastal Agricultural Research*, *38*(2), 125-131.

Kosten, S., Almeida, R.M., Barbosa, I., Mendona, R., Barros, N., 2020. Better assessments of greenhouse gas emissions from global fish ponds needed to adequately evaluate aquaculture footprint. Sci. Total Environ. 748, 141247 https://doi.org/10.1016/j.scitotenv.2020.141247.

Krummenauer, D., Poersch, L.H., Fóes, G., Lara, G., Wasielesky, W., 2016. Survival and growth of *Litopenaeus vannamei* reared in Bft System under different water depths. Aquaculture 465, 94–99

Masia, S., Trabucco, A., Spano, D., Snyder, R.L., Sušnik, J., Marras, S., 2021. A modelling platform for climate change impact on local and regional crop water requirements. Agricultural Water Management 255, 107005. http://doi.org/10.1016/j.agwat.2021.107005.

Mohanty, B.P., Mahanty, A., Ganguly, S., Mitra, T., Karunakaran, D., Anandan, R., 2019. Nutritional composition of food fishes and their importance in providing food and nutritional security. Food Chemistry 293 (2019) 561–570, https://doi.org/10.1016/j.foodchem.2017.11.039

Mohanty, R.K., Ambast, S.K., Panda, D.K., Thakur, A.K., Mohanty, S., 2017a. Density-dependent water use in carp polyculture: Impacts on production performance and water productivity. Aquaculture, 470: 32-39

Mohanty, R.K., Ambast, S.K., Panigrahi, P., Mandal, K.G., 2018a. Water quality suitability and water use indices: Useful management tools in coastal aquaculture of *Litopenaeus vannamei*. Aquaculture,485: 210-219.

Mohanty, R.K., Ambast, S.K., Panigrahi, P., Thakur, A.K., Mandal, K.G., 2018b. Enhancing water use efficiency in monoculture of *Litopenaeus vannamei*: Impacts on pond water quality, waste production, water footprint and production performance. Aquacultural Engineering, 82: 46-55.

Mohanty, R.K., Mishra, A., 2020. Water management in shrimp monoculture and carp polyculture. *Technical Bulletin*, ICAR-IIWM, p. 8.

Mohanty, R.K., Mishra, A., Panda, D.K., Patil, D.U., 2016. Water budgeting in a carp-prawn polyculture system: impacts on production performance, water productivity and sediment stack. Aquaculture Research, 47, 2050–2060

Mohanty, R.K., Sarangi, A., 2023. Water budgeting and cutback approach in aquaculture. *Technical Bulletin-85*, ICAR-IIWM, Bhubaneswar, India, 22p.

Mohanty. R. K., .Mishra, A., Ambast, S. K., Mandal, K. G., Panda, D. K., Panigrahi, P., 2017. Effects of various shrimp (*Penaeus monodon*) densities on their growth, water and sediment quality, and water budget. Aquacult Int 25, 2161–2176.

MoJS, 2023.Water Bodies First Census Report, Vol-I, Ministry of Jal Shakti, Govt. of India, New Delhi,179p.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management, 97 : 528–535

MPEDA, 2023. State-wise Aquaculture Production (Total Shrimp (Tiger, *L.vannamei*& Scampi) Production). https://mpeda.gov.in/?page_id=651 (accessed on 10.03.2023).

Nandi, S., Majumder, S., Saikia, S. K., 2013. Small freshwater fish species (SFFS) culture: Issues from nutrient security, carp-SFF integration and feeding ecology. Reviews in Fish Biology and Fisheries, 23, 283-291.

PIB, 2022. Press release (Release ID: 1858281,10 SEP 2022, 3:26PM) on occasion of 2nd Anniversary of Pradhan Mantri Matsya Sampada Yojana (PMMSY), Press Information Bureau, Government of India, Delhi

Rodell, M., Famiglietti, J.S., Wiese, D.N., Reager, J.T., Beaudoing, H.K., Landerer, F.W., Lo, M-H, 2018. Emerging trends in global freshwater availability. Nature 557, 651–659. http://doi.org/10.1038/s41586-018-0123-1.

Roy, N.C., Wahab, M.A., Ray, P.C., and. Thilsted, S.H., 2015. Optimization of Stocking Density of Mola (*Amblypharyngodon mola*) in Carp Polyculture under Low Cost Management for Rural Bangladesh. World Journal of Fish and Marine Sciences 7 (4): 221-227

Sood, A., Nicol, A., Arulingam, I., 2019. Unpacking the Water–Energy–Environment–Food Nexus: Working Across Systems. International Water Management Institute (IWMI) Working Paper 186, Colombo, Sri Lanka, 43pp. http://doi.org/10.5337/2019.210.

Thilsted, S.H., Thorne-Lyman, A., Webb, P., Bogard, J.R., Subasinghe, R., Phillips, M.J., Allison, E.H., 2016. Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61, 126–131.

Verdegem, M. C. J., Bosma, R. H., 2009. Water withdrawal for brackish and inland aquaculture, and options to produce more _ish in ponds with present water use. Water Policy 11, Suppliment 1:52-68.

Verdegem, M.C.J., Bosma, R.H., Verreth, J.A.J., 2006. Reducing water use for animal production through aquaculture. Water Resources Development, 22(1):101-113.

Vishwanathan, S.S., Garg, A., Tiwari, V., Kapshe, M., Nag, T., 2021. SDG implications of water-energy system transitions in India, for NDC, 2 ^{0}C, and well below 2 ^{0}C scenarios. Environ. Res. Lett.W 16, 085011 https://doi.org/10.1088/1748-9326/ac08bf.

Vo, T.T.E., Ko, H., Huh, J., Kim, Y., 2021.Overview of Smart Aquaculture System: Focusing on Applications of Machine Learning and Computer Vision. *Electronics*, 10(22), 2882; https://doi.org/10.3390/electronics10222882

World Bank, 2013. Water Papers: Thirst Energy (No. 78923), Rodriquez DJ, Delgado A, DeLaquil P and Sohns A (eds.), 72pp.

World Meteorlogical Organization, 2021. WMO Greenhouse Gas Bulletin No.17: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2020. https://library.wmo.int/doc_num.php?explnum_id=10931.pdf.

Yadav, A., Noori, M.T., Biswas, A., Min, B., 2022. A Concise Review on the Recent Developments in the Internet of Things (IoT)-Based Smart Aquaculture Practices. Reviews in Fisheries Science & Aquaculture, https://doi.org/10.1080/23308249.2022.2090228

Yang, P., Zhao, G.H., Tong, C., Tang, K.W., Lai, D.Y.F., Li, L., Tang, C., 2021. Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China. Agr. Ecosyst. Environ. 322, 107662 https://doi.org/10.1016/j.agee.2021.107662.

Yuan, J.J., Liu, D.Y., Xiang, J., He, T.H., Kang, H.J., Ding, W.X., 2021. Methane and nitrous oxide have separated production zones and distinct emission pathways in freshwater aquaculture ponds. Water Res. 190, 116739 https://doi.org/10.1016/j.watres.2020.116739.

Zhang, Y., Tang, K.W., Yang, P., Yang, H., Tong, C., Song, C., Tan, L., Zhao, G., Zhou, X., Sun, D., 2022. Assessing carbon greenhouse gas emissions from aquaculture in China based on aquaculture system types, species, environmental conditions and management practices. Agriculture, Ecosystems and Environment, https://doi.org/10.1016/j.agee.2022.108110

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