Technological applications and adaptations in aquaculture for progress towards sustainable development and seafood security

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Abstract. Fish demand has been steadily increasing globally. Due to stabilization of harvest from capture fisheries the aquaculture has grown rapidly at the rate of 7.5 – 9.2 annually. Currently, the contribution of this sector to the global seafood supply has exceeded the landings from the sea. A review of fish production and consumption scenario was carried out in a systems approach that envisaged case-based reasoning for the synthesis of new knowledge. This enabled the identification of ways and means of applying modern technologies to the existing aquaculture production methods. How the aquaculture systems can be transformed by such interventions to further enhance its contribution to food security which is at the heart of all the Sustainable Development Goals has been elaborated. Technology access and adoption, workforce transformation, and adjusting to the global value chains are the issues that have to be addressed. In this context, research and development institutions can help by leveraging their resources and expertise in motivating a review of the existing policies and knowledge transfer to the farming communities to shape the development of aquaculture along the sustainability pathways.

1. Introduction

The rapid growth of aquaculture, amounting to 7.5-9.2% per year since 1970, makes it the fastest-growing food-producing sector. In 2018, aquaculture supplied more than 50% of the fish produced in the world used for human consumption [1]. The total global fish production was estimated at 178.5 million tonnes. When production of seaweeds that comes from farming is included this figure rises to 210.9 million tonnes.

Harvest from capture fisheries amounted to 96.4 million tonnes (inland = 12 and marine = 84.4 million tonnes) and that from aquaculture reached 114.5 million tonnes (aquatic animals = 82.1 and algae as seaweed = 32.4 million tonnes). Considering animal production (termed as fish production), the estimated values are 51.3 million tonnes for the inland harvest and 30.8 million tonnes for the marine. It is for the first time in history that the aquaculture production has exceeded the amount landed by the capture fisheries.

The quantity of production used as human food stands at 156.0 million tonnes. This level of production has a significant stake in the global economy with the first-sale value of all fisheries and aquaculture production to the tune of US$ 401 billion, out of which aquaculture shares US$ 250 billion. This trend of growing this projected to continue (Figure 1) based on the analysis of data for the period of UN Sustainable Development Goals (SDGs) until 2030. This chapter will mainly focus on fish
production. The projections contained in [1] include an additional 25 million tons of fish production that will be needed just to maintain the present level of consumption in 2030 [3] (Figure 2).

Figure 1. Percentage contribution of capture fisheries and aquaculture to global fish production [1]

Figure 2. Contribution (%) of fisheries and aquaculture to the global food fish consumption in 2018 and 2030 [1]
Based on the assessment of the stabilization of capture fisheries, the increase in production will come from aquaculture. The rise in global capture fisheries production has been calculated to be +14% for the period 1990 – 2018 [1]. This has been at the cost of biological sustainability. In 1990, 90% of the fish stocks were within biologically sustainable levels and this percentage dropped to 65.8% in 2017. The spurt of interest seen in developing aquaculture should, therefore, come as no surprise. When measured from 1990 to 2018, increase in aquaculture production is a staggering +527% [1]. Furthermore, there are challenges facing agriculture due to degradation and shrinking of natural resources, loss of biodiversity and climate change. This will further intensify interest in fish as food. Fish demand has continued to increase with population growth as well as public interest due to health reasons. For the same time (1990 – 2018), the rise in total food fish consumption was recorded to be +122% [1]. A continued trend could result in global annual per capita fish consumption increasing from 20.5 kg in 2018 to 21.5 kg by 2030 [1].

While the sustainability of capture fisheries will remain a topic of utmost importance and relevance, aquaculture has demonstrated its potential of increasing food production on a fast-track. This is because the ownership of fish farms is defined, as is usually the case with the aquaculture, farms are operated at different (small, medium and large) scales, and commonly independently managed, unlike global commons for the exploitation of capture fisheries. Measures such as Ecosystem Approach to Fisheries Management (EAFM) and other regulatory frameworks, and marine biodiversity conservation, especially through expansion and enforcement of Marine Protected Areas (MPAs), will help in mitigating the overfishing and other impacts on wild fish populations and sustain the landings at about 96 million tonnes by 2030 [1]. On the other hand, investment in fish farming will continue to propel the production of farmed fish. It is an opportunity for aquaculture to produce high-protein food in sustainable ways to address the global food security - a fundamental requirement for making progress towards the United Nations Agenda 2030 for sustainable development [2]; [3].

Looking at the trend of growth of aquaculture, it is understandable that the global demand for fish can be met by using knowledge and technology. Although aquaculture is known to have been in practice since around 4,000 years but it has witnessed a rapid pace of development with the application of science and technology. The number of farmed species has grown from a few initially to as many as 580 aquatic species [3]. The farming systems have also greatly diversified over time.

The digitization-driven industry 4.0 is creating opportunities for a possible quantum leap in productivity and more sustainable production but there are challenges related to technology access and adoption, workforce transformation, and adjusting to the new global value chains due to glaring differences in the scale of the enterprises.

This paper discusses the technological developments as related to aquaculture diversification and highlights the importance of making transitions by blending various approaches, knowledge and technologies for sustainable development of this sector.

2. Result and Discussion
2.1. Diversification of Aquaculture Systems
Aquaculture has been diversifying since its origin [4]. In fact, diversification and different levels of interventions are integral to the range of activities that constitute aquaculture of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants [2]. This comprises some form of intervention in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. The farming also implies individual or corporate ownership of the stock being cultivated [5]. The aquatic organisms are harvested by an individual or corporate body which has owned them throughout the rearing period.

There have been various forms of technical interventions in the aquatic farming system, but the application of technology became more widespread with the development of hatcheries and the availability of newer tools that helped in aquaculture operations. An example of a simple technical intervention that produced a visible impact on the production of Nile tilapia (Oreochromis niloticus) is that of [6]. These authors examined the effect of colour light on the growth of the fish while keeping the
other variables constant. The culture system exposed to red light had the highest survival, growth and lowest Food Conversion Ratio (FCR) (Table 1).

Table 1. Survival, food conversion and growth of tilapia exposed to different light treatments [6].

| Parameters                          | Exposure to different lights |
|-------------------------------------|-----------------------------|
|                                     | Red | Green | Blue | Natural (sunlight) |
| Initial biomass (g)                 | 30  | 30    | 30   | 30               |
| Initial weight of fish (g/fish)     | 0.2 | 0.2   | 0.3  | 0.3              |
| Final individual weight of fish (g/fish) | 17.7±0.33 | 16.8±3.1 | 15.5±2.8 | 16.2±3.0 |
| Survival (%)                        | 95.5| 59.9  | 84.7 | 74.3             |
| SGR, %/Day                          | 6.0 | 5.9   | 5.6  | 5.7              |
| DWG, g/day                          | 0.2 | 0.2   | 0.2  | 0.2              |
| FCR                                 | 0.8 | 1.3   | 1.2  | 1.0              |

Note: SGR = Specific Growth Rate; DWG = Daily Weight Gain; FCR = Food Conversion Ratio

There numerous other interventions that have contributed to the efficiency of aquaculture production. Application of knowledge and technology has been responsible for increasing the marine aquaculture production from 1950 onwards. Production of merely 1.0 million tonnes in 1953 rising to 31 million tonnes in 2018 [1] represents significant growth.

Drivers of aquaculture diversification have varied over time and can be grouped into 6 categories, namely demand, profit, competitive edge, system resilience, environmental compatibility and climate change (Table 2). This trend is likely to prevail as the seafood demand continues to grow and pressure mounts for transforming the farming systems towards greater efficiency and sustainability. Innovations and new technologies will shape the pace of transformations needed for aquaculture to meet the demand.

Farmers, scientists, consumers and entrepreneurs through new ideas have contributed to the different types of aquaculture systems. However, scientists have a larger share in terms of farming designs due to knowledge of the various aspects of the biology of selected species and their rearing under captive conditions gained through research.

Table 2. Key drivers of aquaculture diversification [7]

| Category               | Details                                                                 |
|------------------------|-------------------------------------------------------------------------|
| Demand                 | Increase in the world’s population. Limitations of land-based agriculture. Stabilization of capture fisheries. Health benefits of fish. |
| Climate change         | Selecting species more resilient to the effects of climate change. Designing farming systems to withstand environmental fluctuations. |
| Desire for increased resilience | Appropriate interventions in aquatic farming methods to buffer the effects of external factors and sustain the production cycle. |
| Environmental considerations | Interest in consuming fish, especially low-food chain species, and those that accept feed from sustainable sources. Nutrient cascading solutions. Species raised by environment-friendly methods. Farmed fish’s sparing effect on wild fish supply. |
| Profit                 | Economizing seed production and development of low-cost feeds will make the harvest more profitable to farmers. |
| Competitive edge       | Unlimited innovation opportunities provided by aquaculture can provide competitive advantages |

The application of science and technology has a significant influence on shaping the industrialization of aquaculture [8] and its emergence as a major food security avenue [9][10]. Just as the technology
has diversified so has been its application and adaptation in aquaculture as the most diverse system of farming in the world in terms of the number of species, methods and the environments used for farming [11].

The levels of human intervention and controls are very different. In many types of extensive farming systems such as those where seawater is pumped into ponds and juvenile fish caught from the sea are released for harvesting at the marketable size, the human intervention is minimal. Species stocked this way depend on natural food products and are harvested by simple gears. On the other hand, the semi-intensive and intensive culture systems require specific designs, care, controls, material inputs, monitoring and selective harvesting. The range of operations includes those that are labour-intensive, technology-intensive and capital intensive. Commercial-scale supply of seed comes from the hatcheries, bulk quantities of feed are produced in factories, water quality is determined by digital instruments and artificial feeders are regulated by timers, and molecular tools are applied in broodstock selection and health management.

The recent interest in developing integrated multi-trophic aquaculture (IMTA) where different species of aquatic animals and plants are integrated in one production unit has posed many challenges on account of different nutritional and water quality demands of stocked species, nutrient cascading that should occur in this type of production module and biofiltration that is a key factor in water quality dynamics. Operation of these modern farming systems not only requires the deployment of accurate equipment but also skilled professionals who can exercise controls and managerial processes with their expertise in instrumentation and knowledge-based judgement on which is based the survival of stocked species and economic investment in the seafood farming.

With the sustainability concept taking the centre stage, it is most likely that the course of diversifications will be based on knowledge and innovations that can address the environmental and socio-economic issues [9]. Some of the responsible paths to diversification as suggested by [12] are listed below: 1. commercial viability, 2. adoption by farmers, 3. precautionary approach, 4. managerial feasibility, 5. Biosecurity, 6. addressing knowledge gaps, 7. conservation of environmental resources, 8. production and product certification, 9. climate change adaptation, 10. mitigating carbon footprint, and 11. insurability.

2.2 Application of Technology in Commercial Aquaculture

Captive breeding in hatcheries for seed production, larval rearing and grow-out management require biological knowledge and environmental controls. Aspects that have received more attention are captive breeding, food and feeding habits, growth and water quality (temperature, dissolved oxygen, pH, salinity and metabolic wastes). Many instruments are available to measure environmental quality, and their accuracy has improved over time. Yellow Springs Incorporated (YSI) produces some of the most widely used YSI water quality sampling and monitoring meters such as multiparameter aquaculture monitor that simultaneously measures dissolved oxygen, pH, conductivity, salinity, oxidation-reduction potential, temperature and other parameters. The readings are stored in a data logger and relayed to mobile apps to integrate the process controls and help in increasing the efficiencies of the processes, improving water conservation, lowering the energy consumption, reducing stress on captive stocks, and curtailing labour costs. These data generate a greater understanding of the biological systems that are at work in aquaculture and guide the development of intelligent management systems. Incorporating artificial intelligence (AI) in these sub-systems, as far as possible, will significantly enhance these benefits [13]. Earlier, [14] highlighted the use of specialized information technology (IT) tools in upscaling the aquaculture industry. [15] have reviewed models of smart fish farming systems based on water quality inputs and elaborated the significance of neural networks of the AI system in effectively managing the land-based marine aquaculture.

Aquaculture industries (big enterprises) are aspiring to benefit from the latest disruptive technologies to meet the rapidly growing demand of farmed seafood [14]; [16]. How these technologies can be adapted to meet the sustainable development criteria of aquaculture are summarized in Table 3.
### Table 3. Technologies disrupting aquaculture systems.

| Disruptive technology | Application in sustainable aquaculture |
|-----------------------|----------------------------------------|
| Robots                | Automation in artificial feeding; operating large offshore fish cages, including cage repair, removal of dead fish, relocating the roaming cage, if required; control of biofouling. |
| Drones                | Aerial and underwater drones helping in inspecting overall condition of cages, environmental monitoring and surveillance. This obviates the need for physical presence of people under hazardous sea conditions. Data collected and relayed by the drones can be used to create algorithms that can guide in generating new software and novel technology tools for improved environmental tracking and production analysis. |
| Sensors               | Drones, robots or other devices such as marine buoys make use of sensors to collect data such as dissolved oxygen, salinity, pH, turbidity and pollutants through multi-parametric probes. Algorithms specifically developed for modulating water quality are deployed for performing tasks related to survival of the stocked fish without the on-the-spot presence of humans at the aquaculture sites in the deep sea. The scan sonars can collect data beneath the sea cages. Biological sensors can detect a metabolic condition of the fish, and measure its growth and level of hunger to trigger the automatic feeder. |
| 3D Print              | Hydroponics, aquaponics and most components of IMTA systems can be made much more easily and with longer durability using the 3D printing technology. The 3D printed artificial shelters or ‘fish home’ that are placed in tanks for a culture of different species can replace the fabricated structures currently in use. Robotic fish, shrimp or lobster designed by 3D printer mimics the movements of stocked species without looking different while the camera and sensors in its body continue to provide feedback on the condition of the aquaculture system, including farmed species, water quality and on any structural problem with the culture facilities that require maintenance. |

A surge of interest in recent years towards ‘smart’ aquaculture and in embracing the Industrial Revolution 4.0 technologies has led to an interest in the deployment of AI. Aquaculture is bracing up to use smart machines capable of performing roles that typically require human judgement. AI-integrated robots can be programmed to simulate human intelligence and mimic human actions to carry out routine culture and problem-solving operations. With the increasingly sophisticated and sensitive sensors that collect accurate data on water quality, the AI output can create predictive analytics for improving and expediting the decision-making for sustaining the culture system. For example, water quality variables are reliable tools for predicting certain nutrients generated as a result of metabolism of fed species. Some of the high-tech smart farming modules that have been recently developed are described in Table 4.

AI, through camera systems in its loop, can also help in identifying which of the wild stocks of fish are procured unsustainably [21]. This is important in addressing the criticism that about 20 million tonnes of fish caught from the wild for manufacture of aquaculture feed [22] is disturbing the marine ecosystem balance. Other potential applications are in predicting the harmful algal blooms that are a global threat to cage culture industry and to the consumer health.

It is evident from the above discussion that AI application in aquaculture has opened up immense opportunities for innovation in production, resource efficiency and governance. Many human factors that constrain certain high-risk and difficult functions can be replaced by stable, durable and promptly responding programmed machines. As far as the coordination of large amounts of data of water quality, fish condition, physical integrity of culture systems, conditions of the deep sea and health and wellbeing of the cultured stocks are concerned, the Internet of Things (IoT) provides a unique connectivity and consolidation by computing and communicating the structured information to a remote user on
smartphones or computers. Undoubtedly, accurate predictions, timely assessment of water quality, health of captive stocks and stability of holding (grow-out) facilities under rough sea conditions are based on comprehensive data. This is more practical, rather than giving unduly high weight age to a limited number of factors, for accuracy of predictive modelling and analysis of sustainability of aquaculture in all its dimensions (environmental, social and economic). A common example is expressing water quality through Water Quality Index (WQI) using about 5 or more parameters. This is where the new field of ‘Big Data’ can help by offering ways and means of systematically analyzing and extracting information from data sets that are too large or complex to be dealt with by traditional tools of data-processing. While highlighting the significance of Big Data application in aquaculture industry, [23] has explained its relevance in boosting productivity, improving feed conversion, reducing feed wastage, minimizing energy consumption and mitigating biological stress, and postharvest marketing benefits to the farming community. It will be particularly useful for integrated aquaculture where multiple species with different water quality requirements are farmed in one production unit. Table 5 shows water quality requirements of 3 different species that can be stocked in a farming system. This does not include the species performing biological filtration and taking part in chemical dynamics in the water quality.

Table 4. Different aquaculture models with artificial neural networks.

| Model | Description | Purpose | References |
|-------|-------------|---------|------------|
| Back-propagation neural network (BPNN) for an intelligent feeding system. | Neural network and algorithms based on data on temperature, dissolved oxygen, fish weight, and stocking density inputs. The corresponding feed intake is obtained using this model. | Feed-intake prediction and minimizing feed loss. | [5];[17] |
| Autoregressive-back propagation neural network (ARBPNN) model for dissolved oxygen prediction. | Utilizes data on past dissolved oxygen and other parameters (for example, temperature, pH, radiations) to make near-term predictions of dissolved oxygen profile. | Intensive aquaculture management of species such as sea cucumbers. | [5];[18] |
| Hybrid deep neural network model. | Records number of fish specimens as input data to intelligently measure production dynamics. Accurate assessment of biomass is necessary for aquaculture economics. Fish count is helpful is optimizing feed quantity, deciding broodstock number in a tank and determining optimal harvest time in addition to other benefits. | Provide an essential reference for feeding and breeding operations. | [19] |
| IoT based fish farming system. | Processes quantitative data on achieving trade-off between water pumping duration and flow rate through optimizing water volume. Uses sensors, algorithms and simulation. | Reduced energy consumption and pumping duration in the tank for healthy fish production with optimal resource utilization. | [6];[20] |
Table 5. Water quality requirements of three species that can be integrated in the same farming unit

| Species                      | Water quality parameters | References |
|------------------------------|--------------------------|------------|
|                              | Temperature (°C)         | Salinity (ppt) | pH   | Dissolved oxygen (mg/liter) |           |
| Penaeus monodon              | 24 - 31                  | 28 - 33     | 7.5 – 8.5 | >5.0 | [24]                        |
| Holothuriasca bras           | 27-29                    | 26.2 – 42.7 | 6 - 9  | 5 – 6 | [25]                        |
| Kappaphycusa lvarezi         | 27 - 30                  | 30 - 33     | 7 - 9  | 5 - 6 | [26]                        |

Real-time monitoring of a large number of data sets processed by the system can constantly provide information pertaining to the evolving trends and making informed decisions. Such a system that helps in integrating multiple parameters of water quality and transmitting data through a wireless network (Wi-Fi), and is equipped with programs for data processing together with a controller to regulate the normal water quality dynamics is certainly a very useful technology intervention in aquaculture. A controller that has the capacity (installed in it in the form of required algorithms) of detecting and regulating water quality provides enormous help in managing a culture system. For example, reduction in dissolved oxygen beyond a range triggers the aerators; and when the sensors detect that the oxygen has increased to the desired level or beyond, its inbuilt automation will stop the operation of aerators [27].

A real-time water quality data combined with analytical tools can help in expressing the accurate value of WQI. It is a single number that expresses the overall water quality at a certain location and time, and is based on selected physical, chemical and biological parameters. Values of these parameters are aggregated according to the quality rating with the unit weight linearity following the concept of standard Analytical Hierarchy Process. The online WQI Calculator that computes the single value to express the complex water quality data has certain limitations in grading the water quality for different purposes. There are many other water quality parameters that are not included in the WQI calculation, and this limits the information that is often needed. New sensors for detecting more parameters and Big Data processing tools will be helpful in an accurate and comprehensive interpretation of WQI for aquaculture or other purposes.

2.3. Transition to Smart Ecological Aquaculture

There are several constraints facing the rapid transition of current aquaculture practices to smart production systems. One reason is the diversity of aquaculture systems that has allowed farming at different levels- small, medium and large, and has contributed significantly to the socio-economic development. The other reason is that more than 90% of the global aquaculture production takes place in developing countries, where it contributes to food security directly through consumption or indirectly as a source of income [28]. The application of IR 4.0 technologies to aquaculture is more likely to happen first in industrialized countries which currently share a relatively small percentage to the total output of the farmed fish.

The large commercial enterprises will most likely have the technical and financial capabilities to make the transition. High-value species such as the bluefin tuna raised in deep sea cages and marketed globally at a high price could benefit from smart technologies in the near future. Small and medium enterprises in developing countries that are either on their own or receive little support from the governments do not have resources and access to AI gadgets. Without government support to creating an enabling environment for adoption of modern technologies the process of transition will be slow and gradual.

Aquaculture industries located in developing countries have been developing and adapting to the situations. In some of the more progressive enterprises, the traditional and experiential practices were increasingly blended with hatchery technologies, water quality assessment tools and grow-out facilities.
These efforts have raised production that now more than equals the yield from capture fisheries. However, the rate at which the fish demand is rising requires investment in research and development for shaping the smart technologies according to the criteria of sustainability. It is, therefore, important to contextualize the technology application to all levels of enterprises, especially the smallholder farmers where food security has a cultural dimension and is a matter of paramount concern. Recognizing the fact that the food security is one of the major challenges of this century, the World Government Summit agreed on the need for exploring the benefits of disrupting the conventional systems with new technologies in three unique ways as shown in Figure 3 [29].

Figure 3. New approaches to enhancing aquaculture production. AI = Artificial intelligence; IoT = Internet of Things; 3D = Three dimensional

Countries implementing the Sustainable Development Goals can develop policies and enabling conditions for possible adoption of appropriate technologies for aquaculture systems. This should be backed by research investigations on understanding the outcomes of the application of disruptive technologies on the sustainability of the aquatic farming systems. It is entirely possible to shape the application of technologies according to the principles of biomimicry, albeit through innovations. Biomimicry in aquaculture can integrate different disciplines of science and technology, traditional wisdom, creativity, innovation, and learning by doing specific activities in the farming process, and applying knowledge to address the issues concerning sustainability. It is a newly emerging sustainable aquaculture paradigm that opens up opportunities for innovative entrepreneurship. Its scope is unlimited and its applications may range from specific aspects to larger processes in the aquaculture production. Supporting their arguments by case studies, several authors [30]; [31]; [32]; [33]; [34]. have elaborated the relevance of designing innovative technologies and applications inspired by solutions offered by nature in seafood production in the oceans. There is, however, a need to seek common ground between the prevailing dominant models of industrial-scale production and nature-based ecological aquaculture. The growing popularity of aquatic food production systems like aquaponics and IMTA backed by scientific data point in no uncertain terms the importance of building synergies in sustainable aquatic food production that uses ecosystem services for nutrient cascading without an ecological footprint. The harvest of the aquatic food so produced is socially acceptable and economically profitable. Many designs of IMTA can sequester blue carbon by integrating seaweed and shellfish [35] and thus contribute to climate change adaptation and mitigation. Aquaponics and IMTA models also help in the empowerment of indigenous communities by taking the production system closer to homes, engaging the family members and inculcating the urge to find innovative solutions, the concept of which is rooted in traditional knowledge. This is a good way of unlocking the underutilized resource of the local knowledge that is easily accessible and flexible for design adaptations needed for a specific region.
Incorporating local knowledge in adaptation measures makes the communities feel inclusive, and develops a sense of ownership of knowledge and achievements that are sustainable [36]. This assumes importance in matters as important as food security. Aquaculture can continue along the sustainability pathways by remaining open to modern technologies as well as utilizing the local knowledge that is relevant to programs designed for specific places. Skilled workers and institutions investing in human capital with defined goals will enable the aquaculture to produce more with lesser inputs and shortening the harvesting time. More inputs and long farming periods to generate growth will no longer define success of aquaculture or serve as a benchmark of productivity.

2.4 Post-COVID-19 Aquaculture

COVID-19 is undoubtedly a topical issue. It is a major disruptive event that affected the lives and livelihoods of fishing and fish farming communities, and consumers. Other than improvement the seafood supply chains, the post-COVID-19 recovery is essentially a reiteration of the call for ecological or environment-friendly aquaculture. This has already been emphasized in the SDGs. The latest report of the [37] has characterized the sustainable aquaculture as ‘nature-positive aquaculture’. The key elements of this approach include Aquaponics and IMTA systems, expansion of aquaculture of unfed species (for example, bivalves and seaweeds) to diminish the pressure on wild fisheries and controlling aquaculture effluents while providing food and biomaterials in a regenerative way that do not require land and freshwater. The challenges currently facing aquaculture need to be addressed by focused research on biosecurity systems, sustainable feeds, environmental thresholds and use of native species. The report highlighted the benefits of aquaculture in restored habitats such as mangroves. In a case study in Vietnam, the income of local farmers has been reported to have increased 200 – 800% through the production of oysters and shells in mangrove-integrated culture.

3. Conclusion

Fish farming will continue to develop in various ways, utilizing knowledge and experience combined with different levels of technology. While digital disruptive technologies could transition many of the currently labour-intensive farming operations into ‘hands-off’ activities through smart devices to help increase production significantly but several steps along the production cycle will still depend on the ‘hands-on’ approach that has always characterized the growth trajectory of aquaculture.

Diversification of aquaculture will continue to be driven by demand, cost, resilience and sustainability (in all its dimensions), and advances in science and technology. While the application of technologies provides opportunities for increasing productivity and meeting the new challenges and targets, it also carries the risk of widening the disparities among small, medium and large enterprises, and for that matter, between developing countries and high-income nations. To address this problem, the government policies will have to be reviewed for creating an enabling environment for innovations in aquaculture and its allied sectors, and supporting the entrepreneurial initiatives and community welfare. In this context, the social innovations led by industries or research and development organizations that can leverage their resources for strengthening the coastal farming communities will be very helpful. Progress in seafood production will be increasingly shaped by the criteria for sustainable development as that provides a convincing blueprint for socio-economic benefits of developing this sector within environmental thresholds.

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