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Chapter 1

Technological Innovations: Revolutionizing Aquaculture

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Abstract

The history of conventional aquaculture dates back about 4,000 years. Several factors, including a limited variety of improved cultivable species, inadequate feed and nutritional management, labor-intensive practices, environmental contamination, and insufficient product traceability, are hindering aquaculture production in relation to the growing global population. This context aims to discussion on world panorama of cutting edge practices and technological innovation that could provide solution for profitable production with minimal negative environmental impacts. Furthermore, the gap between technological innovations and their adoption could be optimize through integration, surveillance and government initiation into aquaculture.

Keywords Environmental impacts, Innovations, Integration, Traceability

1. Introduction

Aquaculture is the cultivation of aquatic organisms under human supervision for the purpose of increasing productivity in breeding operations, feeding, storage and predator protection, among other uses. It has a long history of being the fastest-growing sector among food production industry and provides quality proteins with less fat. Throughout the last fifty years, the swift advancement of aquaculture has been facilitated by the utilization of new technologies and scientific applications. Aquaculture has a wider range of species, feeds, production strategies, diseases, products, business structures and marketing strategies than other food production industries. The world's fish production was estimated by the FAO to be around 177.8 million tonnes in 2020, with 90.3 million tonnes coming from fisheries and 87.5 million tonnes from aquaculture. A total of 60 million tonnes

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of live weight or 151 billion USD, were exported from the world's aquatic products in 2020, excluding algae. When compared to brackish and salt water (33.1 million tons, or 37.8% of the global total), the largest amount produced through freshwater (54.4 million tons, 62.2% of the global total) was exclusively related to aquaculture. The COVID-19 pandemic continued to spread globally in 2020, but regional variations as well as variations among producing nations within each region caused the global aquaculture production to continue growth. For many years, the majority of aquaculture was made up of finfish farming, which found little variation at roughly 66%, 57.5 million tonnes (or 146.1 billion USD) of farmed finfish were produced in 2020; this amount included 49.1 million tonnes (or 109.8 billion USD) from inland aquaculture and 8.3 million tonnes (or 36.2 billion USD) from sea and coastal aquaculture on land (Yue and Shen, 2022). Furthermore, the growth of aquaculture has shown varying trends among regions with the highest prominence in freshwater aquaculture, followed by seaweed aquaculture. Asia has produced 91.6%, of the world's fisheries and algae in 2020, solidifying its decades-long dominance in the aquaculture industry.

Aquaculture production has benefited greatly from the application of advances of science and technology in nearly every aspect. Even though there are many obstacles, implementing new technology will enable production to rise quickly in the future. Additionally, new production methods will boost output and bring high-value species closer to the market. The global food security crisis is getting worse and aqua protein will always be important for both developing and developed nations. To feed the growing population more aquaculture products must be produced, despite the formidable obstacles. Climate change, declining fish meal supplies and deteriorating environmental conditions will all have a significant impact on the ability to produce enough to meet the demand. Novel approaches to improve worldwide aquaculture production and farmer profitability will be provided by some disruptive and emerging technologies. In order to give a comprehensive overview of these technologies, we have briefly described and discussed such emerging technologies that have potential to reimagined the aquaculture sector.

2. Technological Innovations in Aquaculture

2.1. Cage Culture

In the field of aquaculture, cage culture is an innovative method based on the idea of exploiting natural aquatic habitats with the least amount of negative environmental impact. In order to provide a healthy environment for the culture organisms, modern cage culture systems are outfitted with cutting-edge monitoring and management technologies that enable real-time measurement and control of water quality parameters. Cage culture reduces the negative environmental effects of traditional land-based aquaculture, such as pollution, habitat destruction and excessive resource consumption, by utilizing natural water bodies. Innovative cage designs like the "aquapod system", optimizing feed distribution, monitoring and water column positioning, it push the limits of production efficiency. Modern technology such as automated feeding systems, data analytics and remote sensing are seamlessly combined with cage culture to allow for precise management and increased output.

2.2. Multiple Stocking and Multiple Harvesting Techniques

Multiple stocking and multiple harvesting (MSMH) is a creative and calculated technique that entails introducing several batches of fish or other aquatic organisms into a production system at various points in time, followed by a staggered harvesting schedule. The purpose of this technique is to maximize the performance of the system as a whole, production efficiency and resource utilization. The MSMH technique allows for a continuous supply of harvested products over an extended period of time by allowing different groups of fish to be stocked at different intervals. Every batch of fish has a unique growth cycle that allows for the most efficient use of the resources at hand and the least amount of waste. This type of technique ensures a continuous and regular supply of harvesting, reducing the risk of market fluctuations and provide a reliable source of income for farmers. Better production planning and management are made possible by the staggered stocking and harvesting schedules, which improve production ability to meet market demands. By lessening the possibility of disease outbreaks impacting the entire population at once, this can help with disease management. Farmers can attain a comprehensive and progressive strategy for sustainable seafood production by combining the novel ideas of compensatory growth and stunted fingerling production within the MSMH framework.

2.3. Recirculatory Aquaculture System (RAS)

RAS has recently gained momentum due to its ability to rear fish at high stocking densities in indoor tanks with a customized and controlled culture environment. Although the development of the contemporary RAS began about a century ago, significant advancements in solid capture, biofiltration and gas exchange have been made possible by innovative modifications to the original RAS construction and operation. Despite various advancements, the commercial implementation of RAS remains behind because of reasons such as risk factors, insufficient scientific knowledge of farming, complexity in design, financial commitment, high input and operating expenses and lack of skilled competence. Through the PMMSY (Pradhan Mantri Matsya Sampada Yojona), the Ministry of Fisheries, Govt. of India is encouraging RAS among aspiring farmers. Additionally, ICAR-DCFR has emphasized the start of large-scale outdoor rainbow trout culture in RAS system at Champawat, Uttarakhand (Singh *et al.*, 2017). As a result of the great potential and benefits, the government has designated several states for the application of RAS in the aquaculture sector include Pangasius and Tilapia, which are deemed suitable candidate species for RAS. The Blue Revolution initiative includes low-cost RAS, medium-range RAS and innovative activities. The amount and quality of feed, as well as the efficiency of the filtration process, are the primary factors influencing the RAS management process. In light of shifting customer preferences and expanding markets, backyard RAS facilities ought to be encouraged for small-scale and marginal farmers and business owners to increase fish production in urban and semi-urban settings.

3. Advances in Aquaculture Technologies

3.1. Biofloc Technology (BFT)

A promising new technology called Biofloc Technology (BFT) encourages the retention of waste and transforms it into floc, which is naturally occurring food for cultivable species. A wide variety of microorganisms, including bacteria, nematodes, zooplankton, dinoflagellates and diatoms, as well as particulate organic matter like excreta and uneaten feed, combine to form biofloc and work in symbiotic relationships to preserve water quality, biosecurity, support high density culture and lesser water exchange. Through an in-situ bioremediation process, the heterotrophic microbe in the floc transforms the organic nitrogenous waste into inorganic form, which is then transferred to single cell protein and microbial protein. Biofloc transforms the hazardous nutrients into useful food sources by adding inexpensive carbohydrate sources, such as molasses or tapioca, typically in an amount that maintains C: N = 12-15 : 1 in the water column to promote the growth of heterotrophic bacteria. The fundamental idea is to recycle nutrients by keeping the C:N ratio high, which encourages the growth of heterotrophic bacteria that turn ammonia into microbial biomass. The two main functions of the microorganisms are to maintain the quality of the water by absorbing nitrogen compounds and producing in situ microbial protein and to increase the viability of the culture by lowering feed costs. (Emerenciano *et al.*, 2022) reported to assess BFT's efficacy in larval rearing of the giant freshwater prawn. Depending on the species, like tilapia (*O. niloticus*), common carp (*C. carpio*), pangas (*P. hypophthalmus*), white leg shrimp (*L. vannamei*) *etc.* farmers can start a biofloc system for the first time can stock food fish at 50-100 fingerlings/ 1000 lit. of water and ornamental fish at 35-50 fingerlings/ 1000 lit. of water.

3.2. Integrated Predator-Prey Aquaculture

Integrated predator-prey aquaculture (IPPA) is a novel method that entails co-cultivating predator and prey species in the same aquatic system. The idea is based on natural ecosystems, where predator-prey dynamics aid in population control and ecological balance maintenance. By assisting in the management of prey species populations, predators help avoid overpopulation and the detrimental effects it can have on the availability of resources and the quality of the water. It is possible to cultivate prey species, like smaller fish or crustaceans to feed predator species. This reduces the need for outside feed sources and improves feed conversion efficiency.

IPPA can encourage a more harmonious and sustainable relationship between aquaculture operations and the environment by imitating natural ecological interactions. Examples of PPA are following: (1) co-cultivation of tilapia with predatory fish like featherbacks or murrels; (2) mosquito fish-gold fish system, where mosquito fish are used as natural predators to control mosquito larvae in decorative goldfish ponds; and (3) shrimp-fish system, where certain fish species, such as groupers, barramundi or cobia, can be farmed as predators alongside shrimp. This strategy preserves the ecosystem equilibrium while increasing total production.

3.3. Microbubble Diffusion Technology

Dispersion of microbubbles, which are much smaller than regular bubbles, into water systems improve a variety of aspects of fish farming by means of enhance fish health, water quality and overall production efficiency, is known as microbubble diffusion technology. Because of their large surface area compared to volume, microbubbles effectively transfer oxygen to water. Microbubble diffusion ensures that fish have an adequate supply of oxygen and reduces stress by increasing dissolved oxygen levels. The uniform distribution of oxygen, nutrients and other essential elements within the water column is promoted by the gentle turbulence and water movement created by the microbubbles diffusion. This keeps fish in a consistent environment throughout the culture process and helps prevent stratification. The ability of microbubbles to disturb and loosen biofilms that may accumulate on surfaces in aquaculture systems has been demonstrated. This contributes to improved immunity and disease resistance by reducing the risk of illness and preventing the accumulation of organic load. Diffusion of microbubbles can improve water clarity and lower suspended solids, which has a positive effect on turbidity and transparency. Microbubbles can also help bioflocs aggregates of microorganisms that support nutrient recycling and improved water quality.

3.4. Aquaponics

Hydroponics and aquaculture are combined in aquaponics, where in the wastewater from aquaculture is mineralized by microorganisms to provide nutrients, while the plants themselves reduce the load from water by extracting nutrients. The primary conversion of nutrients takes place when nitrifying bacteria convert ammonia (NH_3) to nitrate (NO_3). Nutrient-rich effluent is then filtered into a hydroponic system as manure, where it is then absorbed by the roots of the plants and microorganisms. After remediated of accumulated nutrients, the water is recycled back into the aquatic rearing tanks. Moreover, hydroponics or conventional RAS stand-alone systems are likely less efficient than aquaponics in terms of water usage. The main pathway for water loss in an aquaponics system is evaporative loss.

Toxic compounds like ammonia, nitrite and suspended particles that are produced autochthonously and must be removed from culture systems, a high-quality filtration system is necessary for culture operations. These could seep into the surrounding environment, degrade the soil and eutrophicate water bodies if left unchecked. In comparison to hydroponics, aquaponics systems use about 50% of the nutrients from originally supplemented fish feed as plant fertilizer, requiring significantly less fertilizer to be added and in some cases, none at all. Furthermore, aquaponics systems can be fine-tuned in controlled settings to reduce production losses brought on by urbanization.

3.5. Flow through Aquaculture

Flow-through or race-way aquaculture systems, which are based on the principles of conserving heat and water through water recycling and reuse, demonstrate a new standard in aquaculture profitability. The popular raceways are rectangular in shape made of concrete and have issues with the disposal of feces and surplus feed. Water runs through a succession of tanks down the axis. A typical raceway has an approximate plug flow and uniform water velocity over the tank cross section. Water velocities differ throughout the raceway breadth and depth due to friction losses at the tank-water and air-water boundary layers. The air-water interface has a slightly reduced velocity, the lowest velocity is located near the bottom and the highest water velocity is found at mid-depth. The viability of growing a variety of species, including carps, in the flow-through method for industrial aquaculture utilizing irrigation canal water was investigated by CIFA-Bhubaneswar. Since India has a diverse of agroclimatic zones, this technique works best in high altitudes where gravity readily facilitates flow through arrangements, primarily in areas beneath dams or hill streams. However, due to a shortage of practice materials and low public awareness, the technique has not been commercially marketed in India. However, the overuse of water and the large initial capital outlay needed to create these systems in the plains are their main drawbacks. Mahseer and rainbow trout mass seed production and culture technologies have recently been developed by ICAR- DCFR, Bhimtal, utilizing a hatchery system. With constant water flow, the system is farmer-friendly for breeding, incubating eggs and raising larvae.

3.6. Cluster Aquaculture

Small-scale aquaculture operations contribute significantly to both national fish output and economic prosperity. These producers typically have limited access to land, water, input material holding capacity and financial support, which results in low aquaculture productivity in many developing Asian and African countries. Additionally, globalization and its effects, such as those of climate change, market demands, inadequate infrastructure, export facilities, value chains and other factors have put small-scale aquaculture operations in jeopardy and raise concerns about the viability of marginal and small-scale cultures. By applying superior management practices, efficient managerial procedures and technological interventions, cluster aquaculture can be a good technical approach. Cage culture in reservoirs, composite fish farming, genetically improved farmed tilapia (GIFT) culture, genetically improved giant freshwater prawn scampi (GI-Scampi) culture, pangas culture in low-lying and upland hill areas and culture of white leg shrimp and brackish water fish species in coastal aquaculture as well as in inland saline water along with value chain development for ornamental fish production are some of the steps that have been initiated for small aquaculture development through cluster management by area development mode.

According to NABARD (2018), 87% of farmers have less than 2 hectares of cultivable land, demonstrating the significance of cluster aquaculture through the establishment of Farmer Producer Organizations (FPOs) for improving production performance through the adoption of better management methods. All maritime states have already benefited from the dissemination of the cluster aquaculture system by the Marine Products Export Development Authority (MPEDA), which has also established around 918 aquaculture farming societies with 19854 farmers in India.

4. Advances in Genetics and Breeding in Aquaculture

4.1. Genome Selection (GS) and Genome Editing (GE)

The aquaculture industry is about to undergo a significant transformation because of recent advancements in GS and GE, which will enhance economically significant traits of fishes. Using numerous markers as performance predictors, genomic selection (GS) is a novel approach to molecular breeding that produces more precise breeding value predictions. A wide range of aquaculture species are increasingly using GS genotyping, which uses SNPs (single-nucleotide polymorphism) covering the entire genome and/or specific SNPs associated with traits, to optimize selective breeding and accelerate genetic improvement. This is due to the ongoing advancements in sequencing and bioinformatic technologies as well as the declining cost of SNP genotyping.

Genome editing (GE) with CRISPR/CAS can accelerate the genetic improvement of aquatic organisms when the genes to be edited are known. With the help of genetic engineering, advantageous alleles can be quickly added to the genome, the frequency of desired alleles at the loci determining important traits can be increased, new alleles can be produced and advantageous alleles from other species can be introduced. Because of high fecundity and external fertilization, which allows for genome editing of multiple individuals at once, aquaculture species are particularly well suited for genetic engineering. Individuals should embrace these new technologies also in combination for genetic improvement in the aquaculture sector if they comprehend the advantages and hazards of genetic engineering.

4.2. Selective Breeding

Aquaculture technology such as selective breeding is cutting edge and futuristic and it has the potential to revolutionize the sector. The Genetically Improved Farmed Tilapia (GIFT) program is a prime example of the effectiveness of selective breeding. The World Fish Center developed it, a breed for quick growth, low feed conversion efficiency and resistance to disease. Selective breeding has been used in the salmon industry to improve qualities like fillet quality, growth rate and disease resistance. Farm-raised salmon strains, such as the Norwegian-developed 'Salmo Breed' strain, are breed specifically to flourish in aquaculture environments with minimal negative environmental effects and increased consumer appeal. Catfish selective breeding programs have been established in the US to generate strains that grow faster, resist disease and are more valuable commercially. 'Superspawners' a line of channel catfish distinguished by their remarkable growth rates and reproductive potential, are the result of these efforts. Shrimp farming has utilized selective breeding in an effort to generate high-yielding, disease-resistant shrimp. In order to fight diseases like White Spot Syndrome Virus (WSSV) and Early Mortality Syndrome (EMS), the "Super Shrimp" program in Vietnam aims to improve the genetic characteristics of black tiger shrimp. For many years, common carp have been the focus of selective breeding in China. The 'Amur carp' strain, renowned for its swift growth and versatility in diverse aquatic settings, has been instrumental in improving carp culture. These illustrations highlight how selective breeding can have a transformative effect to increased yields, improved resource utilization and decreased environmental impact by fine-tuning genetic traits.

4.3. All Male or All Female (Neo-Female) Fish Production

The innovative methods used in the production of both male and female fish stand out as prime examples of cutting-edge techniques meant to maximize growth performances and resource efficiency with genetic selection in the dynamic field of aquaculture. These methods, together referred to as monosex culture, have the power to change the fish farming industry by providing special benefits and solving practical problems. The biological phenomenon that male fish frequently grow faster and have higher feed conversion efficiencies than female fish serves as the foundation for this strategy. In species such as tilapia, where males can outgrow females, this phenomenon is especially noticeable. We can produce populations that are predominately male by adjusting sex ratios through hormonal treatments, genetic selection or environmental cues. When a species exhibits sexually dimorphic growth rates or when certain traits or genetic characteristics are desired in females, all female production approach may be beneficial. We can better control breeding and genetic selection if we concentrate on raising all female populations. For instance, in the farming of rainbow trout, females typically exhibit greater growth potential than males. Researchers can focus on selective breeding programs that highlight desirable traits like growth rate, disease resistance and product quality by using the all-female production techniques.

5. Advances in Nutrition and Feeding Management

5.1. Alternate Protein Sources for Feed

Fish meal and fish oil are major ingredients in most feeds used in the aquaculture sector. The depletion of global fish stock is a major concern for the availability of these which in turn affects the feed industry. In an effort to address the scarcity and fluctuating cost of fish meal, unconventional proteins sources emerged to satisfy the growing demand. Studies on plant-based proteins, such as soybean protein and fermented leaf meal have been conducted for a long time with encouraging outcomes. Enhancing algae feed and expanding accessibility are top priorities for numerous aquafeed manufacturing companies. Fish meal can also be substituted with proteins derived from insects; Crickets and Black Soldier flies are the most promising options for insect proteins. Single-cell proteins (SCPs) originate by bacteria, algae and fungi are another category of nontraditional proteins. While fish meal can be replaced with alternates few important factors that need to be taken into account including nutritional profile, cost, production efficiency and supply consistency.

5.2. Stunting Fingerling Production and Growth Compensation Technique

It is a strategic approach using controlled stunting in the early stages of development, manipulate the growth trajectory of young fingerlings to achieve specific size or weight targets. This method makes use of natural capacity for compensatory growth traits of fishes, which allow them to grow more quickly after experiencing a period of restriction. Fingerlings are deliberately exposed to controlled environments like increased stocking densities, restricted or low-quality feed and unfavorable water conditions impede their growth during the stunting phase. After the stunting phase, fingerlings are transferred to an environment that can support growth while preserving ideal water quality, reduced stocking densities and higher-quality feed. The phenomenon known as compensatory growth is set off by the transition, in which the fingerlings quickly accelerate their growth rates in order to reach their normal size potential.

6. Strategy and Techniques for Sustainable Aquaculture

6.1. Precision Aquaculture

Precision aquaculture is a state-of-the-art that maximizes the production of culture organisms through the use of automation, real-time monitoring and data-driven strategies much like precision agriculture does in the case of terrestrial farming. The practice of precision farming necessitates the acquisition of amounts of data from diverse sources, including environmental monitoring systems, cameras and sensors. These data include feed consumption, temperature, oxygen concentrations and water quality interpreted to produce insights that can be put into practice using advanced analytics and modeling. Automated systems keep an eye on important variables all the time so they can react quickly when the environment changes. Precision farming utilizes automated feeders that precisely dispense feed according to the nutritional requirements of the cultured organisms and current conditions. This method maximizes growth rates, minimizes waste of feed and lowers pollution. Advance techniques control temperature, salinity and water flow among other environmental factors to minimize stress and foster ideal growth conditions. Early indicators of disease outbreaks are found with the use of data analysis and monitoring tools. This lowers the possibility of significant losses and the requirement for excessive medication by enabling prompt intervention and focused treatments. Precision farming maintains a balanced and healthy culture environment by calculating and modifying stocking densities according to available space, water quality and growth rates.

6.2. Integrated Multi-Trophic Aquaculture (IMTA)

IMTA is the farming of species incorporating vertical integration of different trophic levels with complementary ecosystem functions in a way that enables one species' uneaten feed and feces, nutrients and by-products to be recaptured and transformed into fertilizer, feed and energy for the other subsequent trophic level. This is meant to capitalize on the synergistic relationships between species in order to achieve biomitigation outcomes within the same system. With few synergistic benefits and overlapping feeding niches, organisms may share similar biological and chemical processes. In IMTA, fed species (shrimp/ finfish) are cultured simultaneously with inorganic extractive species (seaweed), which uses the inorganic wastes from aquaculture for growth and organic extractive aquaculture species (shellfish/herbivorous fish). The term "integrated multi-trophic subsystems" refers to the more intense cultivation of various species close to one another, connected by the transfer of nutrients and energy *via* water. IMTA should ideally have a balance between biological and chemical processes, which can be attained by carefully choosing and allocating different species to fulfill various ecosystem functions. Even though individual production is lower than what could be achieved in short-term monoculture practices, a functional IMTA system should lead to greater production for the system as a whole based on benefits to the co-cultured species with improved ecosystem.

6.3. Organic Aquaculture

In the field of aquaculture, organic aquaculture is a promising and progressive method that provides a sustainable and environmentally conscious answer to the problems associated with raising "safe fish" for a healthy population. The primary goal of organic aquaculture is to raise aquatic species in a way that minimizes adverse effects and resembles natural ecosystems. It aims to reduce reliance on fishmeal and oil obtained from wild stock, as these are frequently linked to overfishing and habitat degradation. Rather than using animal-based feeds, organic aquaculture encourages the use of plant-based feeds and feed formulations that minimize carbon footprint. Artificial fertilizers, antibiotics and pesticides are strictly prohibited in organic aquaculture. Rather, it places more emphasis on preventing disease through natural methods, like improving environmental conditions, enhancing immunity *via* herbs and using biological control techniques. It aims to reduce disturbance of habitat, stop farmed species from escaping and make sure that the overall effect on neighboring ecosystems is as low as possible.

6.4. Aquamimicry

Aquamimicry is a cutting-edge and futuristic method of designing and operating fish farming systems that takes its cues from naturally occurring aquatic ecosystems. Aquamimicry is based on the idea of "biomimicry," which is mimicking natural solutions to develop sustainable designs. Its goal is to imitate aquatic ecosystems' principles and functions to improve aquaculture operations resilience, efficiency and sustainability. A number of points are covered by aquamimicry, such as species selection, water management, system design and ecological interactions. The objective is to design self-regulating, harmonic aquaculture systems that closely resemble the dynamics of natural aquatic environments. Aquamimicry uses natural processes as a way to optimize energy use with the combination of passive heating and cooling methods, solar energy and natural water movement.

6.5. Floating Fish Farm

As the pinnacle of aquaculture technology, the floating farm model embodies a multi-tiered, highly efficient system that redefines sustainable food production. Tiered architecture incorporates a variety of features, all of which work together to create a balanced and self-sufficient ecosystem. At its peak, solar panels provide the system with power from renewable sources, supporting its ecological integrity. In the intermediate layer, lush fields produce an abundance of vegetables using careful aquaponic techniques, which naturally fertilize with nutrient-rich wastewater from fish ponds. At the same time, the produce nutrient for the fish, demonstrating a beneficial cycle of nutrient consumption. Water column teeming with thriving fish populations under this verdant layer lead to an integrated aquaculture practice that strikes a balance between fish culture and sustainable agricultural outputs. Flawless self-sustainability is a remarkable feature of it with modified design.

6.6. Greenhouse Fish Farming

Aquaculture is combined with carefully controlled environmental conditions given by a greenhouse structure in the novel and environmentally friendly method known as greenhouse fish farming. Combining aquaculture and agriculture has many advantages and is becoming more and more well-liked as a cutting-edge approach to fish farming especially for hills or temperate climates aquaculture. Fish raised in greenhouse fish farming are housed in a regulated interior environment that shields from the predators and temperature swings. The greenhouse protective structure allows for effective resource and water management while simultaneously preserving the ideal growth conditions for fish. Because greenhouses allow for precise temperature control, fish can be produced year-round regardless of the outside weather. This is especially helpful for species that need a certain range of temperatures to grow to their full potential or are sensitive to temperature fluctuations. Enclosed atmosphere in greenhouse lowers the possibility of disease transmission from outside sources like pollutants or wild fish. Fish like trout and catfish are frequently raised using greenhouse fish farming technology. These systems can be modified to satisfy the unique needs of various fish species and regional circumstances.

7. Smart and Autonomized Aquaculture Technology

7.1. Robotics

Robots can be used for labor-intensive tasks like feeding, vaccinating, cleaning ponds and nets and extracting sick fish. Robots have also been employed to monitor and stop farmed fish from escaping, as well as to assess the health of the fish. Actually, because they can operate continuously, without interruption, in harsh environments without the need for human assistance, robots can increase aquaculture profitability. Many research institutes and companies, including Robotfish, Cermaq, Innovasea, SINTEF, SeaVax, Sublue and Massachusetts Institute of Technology (MIT)'s AUV lab have developed and are developing various types of robots for aquaculture.

7.2. Drones

Drones, like the previously mentioned robots, have a wide range of applications in the aquaculture sector, both above and below the water. Both on freshwater and in marine water, fish farms can be observed by drones, particularly those located offshore. Drones can perform a variety of tasks, such as inspecting cages for damage and holes. More significantly, drones can gather unique data that is hard for humans to gather. Algorithms for future technological development aimed at increasing aquaculture production efficiency can be created using this data. Saildrone, for instance, tracked environmental conditions, analyzed fish stocks and gathered farm data. Aquaculture could easily make use of these data. Aquaculture industrial operations will be improved and costs will be reduced by using drones in conjunction with cloud computing and AI.

7.3. Sensors

Sensors that are primarily used to measure salinity, turbidity, pH, dissolved oxygen (DO) levels and pollutant concentrations in water. The state of feeding operations of cultured fish in cages, ponds and rivers can be tracked via underwater sensors linked to the internet, allowing feeding schedules to be adjusted accordingly. Appropriate feeding based on the level of hunger can significantly increase feed consumption and decrease feed waste, which lowers overall production costs.

China has developed a number of deep-sea cages equipped with numerous sensors to track fish movement, net status, water quality and fish hunger. Real-time sensors that can identify pathogens in water and gauge stress level will be crucial in the future. These sensors ought to be simple to install in live fish or submerge in water and they ought to be able to transmit powerful signals that satellites, boats and land-based equipment could pick up.

7.4. Artificial Intelligence (AI)

Despite the fact that sensors, robots and drones make it possible to gather data quickly and in real time, the volume of data available makes it exceedingly difficult to use the data to make informed decisions. Aquaculture can produce more quickly through the use of AI because it reduces the amount of labor required in the industry. It could manifest as any kind of labor at work. AI can be used for instance to manage feeders, water quality control, harvesting, processing and input waste management while also lowering costs. Thus, AI offers total control over fish-producing systems with minimal input costs and maintenance. To overcome the shortage of data on aquaculture production and marketing should be shared by large aquaculture companies and fish farms. Researchers and farmers will only be able to use a wider variety of sample data to develop improved algorithms to make more accurate and better decisions if there is sufficient data on the aquaculture production of each species under various culture conditions and databases are established in public domains.

7.5. Augmented Reality (AR)

Aquaculture operations are extremely unpredictable, labor-intensive, species and location specific and dependent on culture environment. This can reduce expenses, free up time and make it easier for underwater drone and robot operations, such as keeping an eye on dead fish, net holes and fish behavior to be carried out. Using Augmented Reality (AR), farmers can operate more efficiently and risk-free while gaining a better overview of production areas. In the aquaculture sector, AR has been used to measure a variety of water parameters, track and analyze mortality rates and improve field production efficiency. AR with cloud is also being used in education and training purposes. In order to teach students about fish welfare, disease prevention, escaping fish and hazardous working conditions, the Norwegian University of Science and Technology has developed and implemented augmented reality (AR) and virtual reality (VR).

7.6. Blockchain

Blockchain technology allows for decentralized data sharing, whereby no single entity individual, corporate or governmental owns or controls the data. Its primary benefits are the security and tamper-proofing of the data in the chain made up of individual blocks of data. Applications based on blockchain technology are created and used to facilitate distributed cloud storage systems, digital identity protection, payment processing, data sharing and money transfers. The aquaculture supply chain can go digital help of blockchain technology, allowing for complete traceability from farm to consumer and bringing together global stakeholders. Large data sets from various aquaculture industry segments can be collected, shared and analyzed with this technology in a safe and efficient manner.

8. Conclusion

For more than 20 years, aquaculture has been the area of food production with greatest rate of expansion and a significant contribution to the supply of quality proteins. Various disruptive technologies and contemporary strategies what we have discussed have the potentiality to revolutionize the aquaculture production. Even though the aquaculture industry is very much lagging to adopt new technologies, industry have realized that recent technological advancements can provide opportunities for profitable and sustainable aquaculture. All of these technologies have the potential to completely transform some aspects of aquaculture, especially small-scale operations. The availability of innovative and disruptive technologies and their practical uses in the aquaculture sector, however, differ significantly. It can be challenging to integrate different technologies into distinct aquaculture systems. Corresponding working voltages, communication interfaces, transmission modes and other equipment variables are required for these facilities. To maximize efficiency, the layout facilities in the integrated fish farming system should be optimized. Subsequently, every kind of tools will be linked to the Internet of Things network for oversight and management. A individual farmer or aquaculture company would never be able to complete this difficult endeavor considering all of these factors. To make the aquaculture sector economically feasible and environmentally viable, farmers, scientists, engineers, software developers and economists should collaborate to effectively integrate these technologies into every aspect of operations. While aquaculture extension system, venture capital and investors might encourage innovative start-ups for integrating disruptive technologies onto the industry, governmental organizations may provide research funds on multidisciplinary fields. It is established that the aquaculture sector will become significantly more resourceful and environmental friendly because of novel and disruptive technological developments. Additionally, these technologies will open up possibilities for employment and business, particularly for women and young. Ensuring the implementation of productive management practices is crucial in leveraging emerging technologies to enhance aquaculture long-term viability rather than jeopardize it.

9. References

Emerenciano, M.G.C., Rombenso, A.N., Vieira, F.N., Martins, M.A., Coman, G.J., Truong, H.H., Noble, T.H., Simon, C.J., 2022. Intensification of penaeid shrimp culture: An applied review of advances in production systems, nutrition and breeding. *Animals* 12(3), 3. DOI: https://doi.org/10.3390/ani12030236.

FAO, 2022. The State of World Fisheries and Aquaculture towards Blue Transformation; Food and Agriculture Organization of the United Nations, Rome, Italy.

Singh, A.K., Pandey, N.N., Ali, S., 2017. Current status and strategies of rainbow trout (*Oncorhynchus mykiss)* farming in India. *International Journal of Aquaculture*, 7.

Yue, K., Shen, Y., 2022. An overview of disruptive technologies for aquaculture. *Aquaculture and Fisheries* 7(2), 111-120. DOI: https://doi.org/10.1016/j.aaf.2021.04.009.