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Review

Sustainable Aquaculture Systems and Their Impact on Fish Nutritional Quality

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Abstract: The growing global demand for fish necessitates the exploration of sustainable aquaculture practices. This has led to a focus on the quality and sustainable production of fish products with minimal environmental impact. Thus, the objective of this review is to study and evaluate how different aquaculture systems impact the quality and nutritional profile of fish. Fish are rich sources of protein, containing almost 20% protein and essential amino acids and vitamins. The nutritional value and quality of fish products are directly related to the conditions under which they are produced through aquaculture. This article considers various aquaculture systems, including closed-loop systems, pond farming, marine aquaculture, and aquaponic systems. The operating principles, advantages, and inherent limitations of each fish-rearing system are subjected to rigorous critical analysis in this review. Such practices are necessary to meet the growing demand for fish and to maintain the integrity of aquatic ecosystems for future generations.

Keywords: fish nutritional value; aquaculture; aquaculture systems; RAS; aquaponics

Key Contribution: This review provides a comprehensive analysis of sustainable aquaculture practices, emphasizing their role in ensuring high-quality fish production while minimizing environmental impact. It critically examines the nutritional composition of fish, the microbial processes involved in water purification, disinfection strategies, and various aquaculture systems, evaluating their operational principles, benefits, and challenges, as well as the potential solutions for sustainable fisheries management and their impact on fish quality.

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1. Introduction

In recent decades, healthy eating has been emphasized in routine human life. Nutritional behavior significantly influences a person's physical and mental well-being. Nutrients and their metabolites in the human body provide the fundamental building blocks for cellular structures and primary energy sources [1–3]. Additionally, they function as direct regulators of protein activity, potent signaling molecules, and inducers and repressors of gene expression [2]. A deficiency in specific nutrients could increase disease risk, particularly due to reduced immunity [4]. Consequently, it is important to select foodstuffs that are rich in nutritional value.

Fish meat is a precious product that contains many nutrients. The global consumption of fish meat is increasing annually [5]. Fish meat is recognized globally for its high nutritional value, particularly as an important source of omega-3 fatty acids, iodine, and vitamin D [6]. Global fish consumption has significantly increased, with 89% of the total aquatic animal production—approximately 157 million tons in 2020—allocated for human consumption [5]. This rising demand for fish protein highlights its critical role in global food security [5]. However, many countries still experience fish deficiency in their diets for various reasons, including cultural and ethnic characteristics, geographic location, and economic status [7–9]. Fish consumption deficits may increase over time due to population growth, the decline of declining ocean fish stocks, and water pollution [10]. A lack of fish consumption results in deficiencies of certain nutrients. The most prevalent deficiencies are omega-3 and iodine, which are primarily sourced from fish [11]. In the future, countries with high fish consumption may see an increase in various cases of iodine, vitamin D, and omega-3 deficiency, which could lead to a deterioration in quality of life [10,12].

It is worth noting that the credibility of commercial fishing is decreasing every year [13–15]. This is because water resource pollution entails a decrease in the quality of fish products [13,14]. In addition, fishing greatly reduces the ecological diversity of fish [15]. Additionally, fisheries in freshwater rivers are losing their credibility due to water resource pollution and an increase in helminthiasis in fish [16,17]. However, various measures are being taken to reduce risks and ensure stable fish production, such as monitoring aquatic ecosystems and breeding fish under controlled conditions [18,19].

Despite these efforts, contemporary aquaculture systems encounter considerable obstacles concerning sustainability, efficiency, and nutrition. Sustainable aquaculture must tackle challenges such water overexploitation, nutrient contamination, and the substantial dependence on fishmeal and fish oil sourced from wild populations, which jeopardize marine biodiversity [20,21]. Furthermore, stressors produced by climate change and antibiotic resistance persist in undermining fish health and productivity [22].

Innovative solutions are emerging to address these restrictions. This encompasses the utilization of precision aquaculture instruments, such as automated feeding mechanisms, water quality sensors, and artificial intelligence for real-time surveillance, to improve production efficiency and environmental management [23]. Sustainable feed alternatives like insect meal, microbial protein, and algae-based ingredients are being explored to reduce dependence on marine resources while maintaining high levels of omega-3 fatty acids [24,25]. Furthermore, advances in selective breeding and genome editing are being investigated to improve fish resistance to disease and enhance nutritional traits [26]. The integration of aquaculture with hydroponics (aquaponics) and bioremediation techniques signifies a promising advancement in circular, resource-efficient fish farming [27]. Despite these advancements, there remain significant knowledge gaps regarding how various farming methods specifically influence the nutritional composition of farmed fish. Addressing these gaps through targeted research can substantially enhance productivity, sustainability, and the nutritional benefits of aquaculture products, ultimately contributing to improved global nutrition and public health outcomes.

The following section will examine the role and importance of various components of fish with respect to their effects on the human body. The benefits of fish products and the deficiency of some nutrients serve to highlight the relevance of fish farming worldwide.

2. Nutritional Benefits of Fish to Humans

The seafood and products of freshwater ecosystems are vital components of a healthy diet and lifestyle [28,29]. In particular, fish are the most consumed aquatic product [30]. Consuming fish meat has a beneficial effect on the human body, providing it with essential nutrients [5]. This is because fish meat is rich in high-quality proteins, essential amino acids, vitamins (especially A, B, and D), phosphorus, and other minerals (Figure 1) [31,32]. Fish play a central role in sustainable food systems due to their high feed conversion efficiency, low environmental footprint compared to terrestrial livestock, and their ability to deliver dense nutritional benefits in relatively small servings [33]. Compared to red meats, fish offer more favorable lipid profiles and lower levels of saturated fats, making them ideal for cardiovascular and metabolic health [34]. Comparing plant-based proteins to fish proteins, fish deliver a more complete amino acid profile and offer higher bioavailability of key nutrients such as vitamin B12, iodine, and long-chain omega-3s—nutrients typically lacking or present in limited forms in plant-based sources [35,36]. The importance and nutritional profile of fish were discussed in this review.

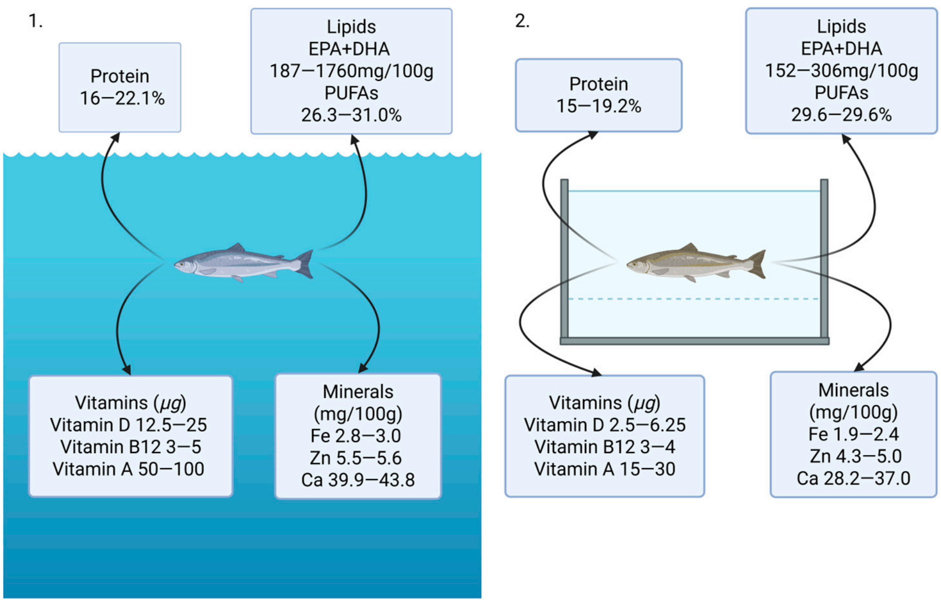

Figure 1. Main nutrients found in wild fish (**1**) and farmed fish (**2**) [31,37–41]. EPA—eicosapentaenoic acid; DHA—docosahexaenoic acid. Values reflect ranges reported in recent literature and may vary with species, diet and environment. Created by BioRender (v3.45.0).

2.1. Fatty Acids

Fish are the most valuable source of omega-3 polyunsaturated fatty acids as the human body is unable to produce these essential nutrients [42,43]. Therefore, they must be obtained through food [5]. Seafood is the sole source of long-chain omega-3 polyunsaturated fatty acids (PUFAs), including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [31,32]. EPA and DHA play significant roles in preventing cardiovascular disease, inflammation, and cancer [44,45]. These fatty acids have been demonstrated to exert a favorable effect on several cardiovascular risk factors, including blood lipid levels, blood pressure, heart rate, and platelet aggregation. In this context, blood concentrations of EPA and DHA are associated with a reduced risk of cardiovascular disease (CVD) and coronary heart disease [46]. Omega-3 PUFAs also possess anti-inflammatory properties, which may be beneficial in the treatment of diseases such as psoriasis, asthma, and rheumatoid arthritis [47]. Furthermore, omega-3-derived metabolites (resolvin and maresin) are employed in the treatment of inflammatory skin diseases [47].

Omega-3 and omega-6 polyunsaturated fatty acids are essential for the normal function of neurons and cell membranes [48]. In this regard, various neurodegenerative diseases (e.g., Alzheimer's disease and schizophrenia) and emotional distress have been linked to HUFA deficiency [49]. Furthermore, blood concentrations of EPA, DHA, and arachidonic acid (AA) have been linked to the development of mental illness. Children with attention deficit hyperactivity disorder (ADHD) have been observed to have lower blood concentrations of these fatty acids than control children. Consequently, the clinical application of omega-3 PUFAs is frequently regarded as a promising approach for the treatment of brain diseases [46]. A diet rich in omega-3 polyunsaturated fatty acids has been demonstrated to be an effective treatment for depression [50].

However, the potential risks of fish oil supplementation include hypervitaminosis A and D, vitamin E deficiency, increased bleeding times, and decreased platelet counts [51]. Long-term supplementation may also be linked to increased cancer risk, possibly due to oxidation products or the addition of vitamin E [52,53]. Common side effects include gastrointestinal disturbances, nausea, and a fishy taste [51,52]. While moderate consumption appears relatively safe, caution is advised for high-dose, long-term supplementation, especially during vulnerable life stages. Further research is needed to determine the therapeutic benefits and potential risks of omega-3 fatty acid supplementation [53].

2.2. Proteins and Essential Amino Acids

Fish are a rich source of protein, containing between 18 and 20% protein and essential amino acids such as lysine, methionine, and cysteine [54]. These amino acids possess antioxidant and antihypertensive properties that maintain blood quality, repair muscle tissue, and regulate the human body system [55]. For instance, asparagine, glycine, and glutamic acid facilitate the process of regeneration. Tyrosine, lysine, and methionine are reactive radicals in oxidative reactions [56]. Furthermore, the consumption of fish protein has been demonstrated to have a beneficial effect on reducing hypertension. This is due to the alteration of amino acid sequences, which, in turn, affects blood glucose metabolism. This is achieved by inhibiting dipeptidyl peptidase-4 and altering the intestinal microbiota, which, in turn, promotes increased conjugation of bile acids [57].

Fish protein hydrolysates (FPHs) are derived from fish and are frequently utilized as active ingredients in the production of food products. The extraction of proteins from fish is a key step in the production of hydrolysates. This process involves the removal of proteins from the skin, flesh, and waste (head, fins, etc.) of fish [58]. In addition to its antioxidant and antimicrobial activities, FPHs also exhibit antitumor and ACE inhibitory properties. Notably, ACE plays a pivotal role in regulating blood pressure and maintaining normal heart function [59]. FPH has shown promise in promoting skin, bone, and cartilage health, improving blood lipid profiles and aiding in weight management [60].

Fish consumption has both positive and negative health implications. While fish provide essential nutrients such as omega-3 fatty acids, proteins, vitamins, and minerals, they also accumulate persistent bioaccumulative and toxic substances (PBTS), such as methylmercury and organohalogenated pollutants [61,62]. Fish protein consumption has been linked to increased circulating levels of trimethylamine-N-oxide and accelerated aortic lesion formation in mice [63]. Moreover, fish eaters have shown greater cardiometabolic risk than those following plant-based diets [64]. Given these complex factors, a reassessment of the health risk-benefit ratio and sustainability of fish consumption is warranted [64].

2.3. Vitamins

Fish are a rich source of various vitamins [31,32]. The following vitamins have been identified in fish: vitamins A, D, B, and E [54]. Vitamins are organic, low-molecular-weight substances that are essential for the normal functioning of the body [65]. Most vitamins are not synthesized within the human body, which can result in vitamin deficiency. It is therefore of great importance that these substances enter the body through food [66].

Vitamin A, or retinol, is a vital nutrient for maintaining optimal vision and the integrity of epithelial cells [67]. This is accomplished by stimulating the development of new cells and by exerting a protective effect against infections. Fish are the most readily available source of vitamin A, which is deposited in the liver. The highest concentration of vitamin A is found in the livers of sea bass, swordfish, and lingcods. In comparison to regular cod, these species can exhibit up to a hundredfold the amount of retinol in their livers [68].

The next essential substance that can be derived from fish is vitamin D [69]. A notable quantity of vitamin D is found in the liver of fish, with fatty fish (e.g., salmon and tuna) exhibiting particularly high levels. Vitamin D plays a pivotal role in the regulation of calcium and phosphate metabolism [69]. These functions are of significant importance for the development of bone tissue and other biological processes [70]. Furthermore, vitamin D deficiency has been linked to cardiovascular health [71]. In addition to being an essential substance, fish also contain vitamin B12 and folic acid. Fish tissues and viscera are significant sources of folic acid, which is essential for the normal formation of red blood cells. Vitamin B12 is extracted from fishmeal, fish viscera, liver, kidney, and glandular tissues [68]. It is important to consume an adequate amount of vitamin E to prevent the development of cardiovascular disease and immune and neurodegenerative disorders. Vitamin E is a fat-soluble antioxidant that plays a role in the function and protection of lipids within the body [72]. It is derived from the germ oils of plants, including sunflower and olive. Furthermore, fish oil contains this substance, which is why fish are recommended for use in modern diets [73].

2.4. Minerals

Fish are rich in various minerals, including iron (Fe), zinc (Zn), calcium (Ca), phosphorus (P), and selenium (Se), among others [5,74]. The elements are of significance for the equilibrium of various bodily functions. The concentration of minerals in fish varies considerably depending on factors such as the species of fish, the source of accumulation, and the habitat (Table 1).

Table 1. Some minerals are extracted from fish.

Minerals	Functions and Properties	Highest Accumulation of Fish
Fe	Hemoglobin and myoglobin transport oxygen in the body [31]	Liver, spleen, gills, and kidneys [75]
Ca	Support bone and teeth structure; Muscle contraction and relaxation; Facilitates nerve impulse transmission [31]	Fish bones are almost 24% in fish scales [75]
Zn	Influence cellular metabolism; Affects immune system function; Regulates protein synthesis; Impacts regeneration [31]	Were obtained from the liver, muscle, bone, and scales of tilapia [75]
Se	Reproduction; Thyroid hormone metabolism; DNA synthesis [31]	Fish filet [75]
P	Essential for ATP synthesis; Supports teeth and bone development; Promotes healthy aging [3]	Fish bones [3]
I	The biosynthesis of thyroid hormones: thyroxine and triiodothyronine [76]	Fish skin [76]

Consequently, the consumption of fish can be regarded as a beneficial prophylactic measure against a range of ailments. A diet comprising fish is beneficial for maintaining both physical and mental health. The benefits of fish make it one of the most consumed types of animal meat. According to the United Nations Food and Agriculture Organization (FAO), the average global consumption of fish in 2020 was 20.2 kg per capita. This figure has more than doubled since the 1960s. These calculations indicate that the consumption of fish and fish products is projected to reach 21.4 kg per capita by 2030 [5].

3. Methods for Growing Fish for Food Purposes

Aquatic pollution poses significant threats to fish quality and human health. Environmental toxicants, including heavy metals, can accumulate in fish tissues, affecting their physiological state and biochemical parameters [77]. These pollutants can lead to changes in antioxidant defense enzymes, liver enzymes, and other biochemical markers in fish, ultimately impacting meat quality and fish production [77]. The contamination of water bodies with industrial, agricultural, and domestic waste contributes to the increasing pollution of aquatic ecosystems [78]. In particular, heavy metal pollution can weaken the immune system of fish, increasing their susceptibility to parasitic, bacterial, and fungal diseases [78]. Furthermore, the consumption of contaminated fish can result in various human health issues, including food poisoning, gastroenteritis, diarrhea, and severe conditions such as typhoid and paratyphoid [79]. Environmental concerns are also associated with fish consumption, as increasing demand is damaging marine biodiversity [64]. While fish farming may reduce some contaminants, such as methylmercury, it may introduce other substances and have detrimental ecological impacts [64]. These findings underscore the urgent need for effective pollution control measures and fish farming methods to protect both aquatic ecosystems and human health.

The high demand for fish of various species of high value in both food and trade has led to the development and improvement of artificial rearing systems (Table 2) [5]. Aquaculture systems exhibit a considerable degree of diversity regarding breeding methods, practices, equipment, and integration with other agricultural activities. Ponds represent the most prevalent type of facility utilized for freshwater aquaculture. Nevertheless, in recent years, there have been notable advancements in the development of integrated breeding systems for freshwater aquaculture, which have been optimized to function alongside agricultural systems. This has resulted in increased productivity, more efficient resource use, and reduced environmental impacts [80].

To achieve optimal performance, it is necessary to create optimal conditions for the fish. The condition of the fish is largely dependent on the rearing environment [81]. These include water parameters (pH, salinity, and other organic compounds), physical parameters (light, temperature, and water flow), and the influence of feeding and fish density in aquaculture. Regardless of the method of fish farming, it is imperative to consider these factors to ensure the optimal performance of fish and fish products. There are numerous techniques employed in the practice of fish culture. The methods differ according to the specific characteristics of the facilities, the frequency of water exchange, and the intensity of the culture. When selecting a method, consideration is given to the regional context, local climate, and fish species (Table 2) [82]. The availability of different aquaculture systems is contingent upon the objective of creating optimal conditions and increasing fish production. This review describes the principal methods of fish farming, namely, closed water devices (CWDs), pond farming, aquaponic farming, and marine farms.

Table 2. Comparative analysis of fish rearing systems. It has advantages and disadvantages.

System Type	Description	Advantages	Disadvantages
Structure			
Ponds	Built a dam across a natural watercourse or dug a hole in the ground. May have little or flow-through water exchange, depending on the construction method [83].	• Optimizes animal welfare. • Enhances water treatment stability. • Minimizes environmental and public health impacts. • Promotes sustainable aquaculture development [84].	• Pond management is closely linked to environmental conditions. • Accumulation of waste materials. • Eutrophication harms fish health. • Requires engineered water circulation and filtration. • Ecological imbalances in lakes/reservoirs. • Disease outbreaks lead to significant losses [85].
Cages	Enclosed natural bay where shoreline forms all but one side, typically closed by net/mesh barrier [86].	• Cost-effective and convenient for aquatic organisms. • Suitable for over 30 freshwater and 40 marine species. • Easy cage construction (artisanal or sophisticated). • Simple stock observation, feeding, and management [86].	• Overloading causes ecological imbalances in lakes, reservoirs, and bays. • Disease outbreaks lead to major losses [83,85]. • Pond fish utilize natural food and cage fish have limited access. • High stocking density in cages increases stress and weakens immunity. • Higher disease risk in cage systems. • Indiscriminate cage installation harms biodiversity and affects water flow. • Increases local sedimentation and environmental impact [87].
Tanks	Fish tank aquaculture involves rearing fish in controlled, artificial tank systems, which can be indoor (recirculating aquaculture systems, RAS) or outdoor [88].	• Higher fish density and better environmental control than ponds [89]. • Easier stock management and higher yield on smaller land areas. • Multiple tank designs (circular, rectangular, oval) with specific flow patterns [90]. • Tank color affects fish growth, survival, stress, and consumer appeal [91]. • RAS enables water reuse and effective waste management. • Enhances environmental sustainability [92].	• High operational costs due to energy use for water circulation and aeration [93]. • Waste buildup degrades water quality, requiring expensive filtration [88]. • Confined systems increase disease spread, leading to antibiotic reliance [94]. • Tank systems demand significant land and water, limiting scalability [95].

Table 2. *Cont.*

System Type	Description	Advantages	Disadvantages
Water Exchange			
Static (Static Ponds)	Involves fish production in earthen or lined ponds without continuous water flow. These systems rely on natural processes (e.g., photosynthesis, microbial activity) to maintain water quality [94].	• Cost-effective with low operational expenses [96]. • Minimal energy needed for water circulation. • Utilizes natural nutrient recycling via phytoplankton [97]. • Reduces reliance on external feed. • Larger water volume offers thermal stability. • Scalable for rural livelihoods and food security [5].	• Metabolite buildup (e.g., ammonia) degrades water quality. • Limited water flow heightens disease risk. • Nutrient overload leads to eutrophication [95]. • Constraints reduce stocking density and productivity vs. intensive systems [96].
Closed (RAS)	Closed water exchange aquaculture, also known as recirculating aquaculture systems (RAS), is a highly controlled production method where water is continuously filtered and reused within the system. Recirculating systems with <10% daily water exchange, using mechanical and biological filtration [88].	• Minimal water use and low effluent discharge [98]. • Enhanced biosecurity lowers disease transmission [88]. • Enables year-round production, unaffected by weather [99]. • Precise control of water parameters (temperature, oxygen, pH). • Improves feed conversion and accelerates growth rates [98].	• High capital and energy costs for filtration [88]. • Technical complexity demands specialized training [99]. • System failures can quickly degrade water quality [98]. • Poor nitrate management stresses fish and lowers productivity [88].
Semi-closed (Mariculture + RAS)	Replaces 10–50% water daily, blending seawater and recirculation [100]. Hybrid systems now use 15–30% exchange with tidal synchronization.	• Cuts energy costs by 30–50% compared to RAS [101]. • Retains beneficial plankton for improved ecosystem balance [102].	• Requires coastal locations. • Biofouling raises maintenance costs. • Fouling organisms clog pipes and needs monthly cleaning [100].
Open (Sea Cages)	Net pens rely entirely on natural water exchange via currents [103].	• Lowest operational costs among marine systems. • No energy needed for water exchange [104]. • Relies on natural productivity.	• High risk of disease and parasite transmission [105]. • Environmental contamination due to waste discharge [103].
Culture Intensification			
Intensive	High stocking density with 20–100% daily exchange [81].	• Maximizes production per unit area. • Precise environmental control [106].	• High effluent pollution. • Elevated feed costs [5].
Semi-intensive	Moderate stocking density with 5–20% daily exchange [94].	• Balanced productivity and cost. • Reduced disease pressure compared to intensive systems [81].	• Significant effluent pollution [5]. • High feed and energy inputs [81].
Extensive	Minimal intervention with <5% daily exchange [97].	• Minimal infrastructure requirements (basic pond and aeration) [5]. • Supports local biodiversity via polyculture [97].	Very low productivity [97].

Table 2. *Cont.*

System Type	Description	Advantages	Disadvantages
Integrated Fish Farming			
Rice+fish (Paddy fields)	Fish (e.g., carp) reared in flooded paddies. Water exchange via monsoon rains [107].	• Synergistic nutrient use: fish waste supplies 25–30% of rice nitrogen needs. • Diversified income: 40–60% higher earnings than rice monoculture [107].	• Limited to flood-tolerant species [108]. • Pesticide contamination [109].
Duck+fish (Ponds)	Duck waste fertilizes ponds with natural exchange [110].	• Ducks remove 80–90% of mosquito and midge populations through foraging. • Reduces or eliminates the need for chemical pesticides in integrated systems [110].	• Risk of disease crossover [111]. • Water quality issues: ammonia spikes require weekly testing [105].
Aquaponics	Combines RAS with hydroponics; <5% daily exchange [27].	• Zero discharge with 90% water savings [102]. • Produces fish and plants with minimal water use; highly popular method [112].	• pH balancing challenges (optimal range: 6.8–7.2). • High startup costs [99].

3.1. RAS Cultivation

A recirculating aquaculture system (RAS) or closed-loop aquaculture unit (CLU) is a covered land-based facility for the rearing of fish in a controlled environment [113]. This method of fish farming does not necessitate a constant supply of water, thereby markedly reducing water consumption. In contrast to pond and marine aquaculture, closed-loop aquaculture has only recently emerged, with the first documented instances occurring in the 1950s. Efforts have been made to purify and reuse water [27]. The fundamental operational principle of the RAS is the continuous re-circulation of water (Figure 2). The water must be kept free of fish waste at all times. Furthermore, it is essential to provide fish with an adequate supply of oxygen to ensure their optimal health and well-being [81].

The utilization of mechanical filters is a fundamental aspect of the process of eliminating solid waste. These compounds are generated from fish waste, feed, colloids, and other organic solids. Mechanical filters may be distinguished according to the material from which they are constructed, their dimensions, and the mechanism by which they operate. For example, they include rotary drum filters, quick-acting sand filters, and others [114]. The mandatory mechanical treatment occurs upstream of the biofilter.

One of the most crucial elements in the reuse of water in the RAS is biofilters. Biological filters are essential for the conversion of ammonium to nitrate. This is because the ammonia released from the gills of fish becomes toxic at elevated concentrations. The concentration of ammonium/ammonia in water is contingent upon the most minute fluctuations in pH [115]. To achieve a balance of ammonia and ammonium, aerobic ammonia-oxidizing and nitrite-oxidizing bacteria, such as *Nitrosomonas* sp. and *Nitrospira* sp., are employed. These bacteria form colonies with specific substrates, thereby creating biofilters (e.g., a fixed-bed filter) [116,117].

Before the water is returned to the aquarium, it must be aerated to remove the accumulated gases. The most common and reliable method of oxygenation is the use of aerators to oxygenate the water [118]. The use of chemical components in this stage of water treatment has been on the rise in recent years. The use of hydrogen peroxide not only enhances the oxygen concentration but also has disinfectant effects [119]. Subsequently, ultraviolet (UV) disinfection is employed to reduce the bacterial density of the water without adversely affecting the aquatic microbiota [120]. In certain instances, photochemical treatment with ultraviolet light and hydrogen peroxide is employed. This method is more efficient than UV LEDs [121].

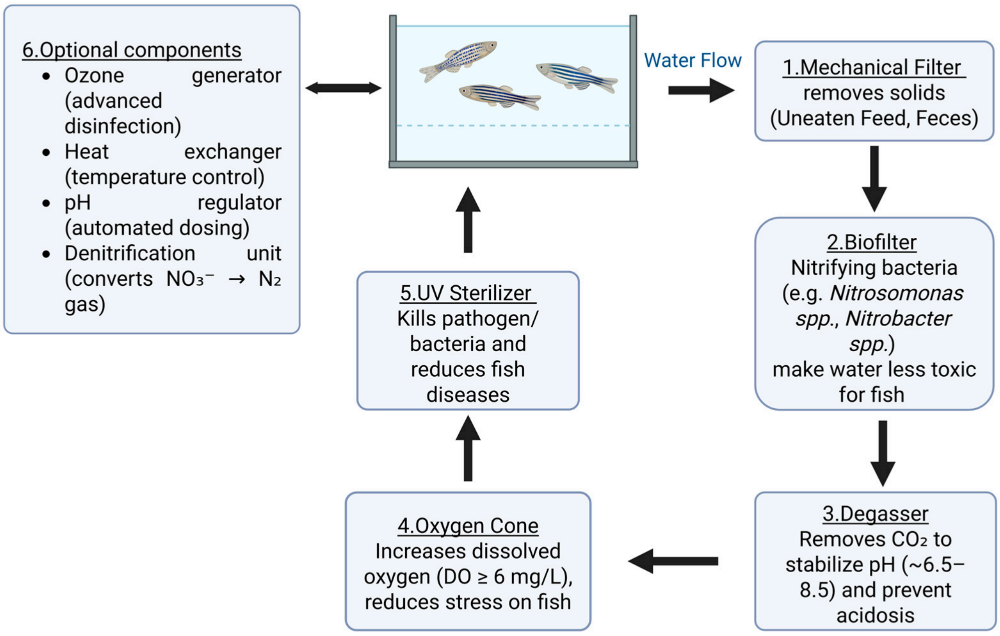

Figure 2. Simplified scheme of the closed water supply device: the water comes from the outlet of the aquarium to the mechanical filter (1), and then biofiltration (2) is carried out. Subsequently, the water is degassed and purified from carbon dioxide (3) and oxygenated (4). Before being returned to the aquarium, the water was treated with ultraviolet light (5). Various devices (6), such as ozone treatment, heat exchange, automatic pH regulation, and denitrification devices, are added to the RAS as required [81]. Created by BioRender.

Beyond these essential elements, a range of optional components can be integrated into RAS to further optimize water quality parameters, including temperature, pH, and nitrogen compound levels, ultimately enhancing fish health, growth rates, and overall system efficiency [122]. An ozone generator is a device that produces ozone (O_3), a highly reactive and potent oxidizing agent, from oxygen (O_2) present in the air. Once dissolved in the water, ozone engages in a variety of reactions. Its strong oxidizing properties allow it to break down organic waste products, ammonia, and nitrites present in the system [123]. Optimization of temperature and pH in aquaculture plays an essential role in fish welfare. Most freshwater fish species thrive in water with a pH range of 6.5 to 9.0, while marine species typically require a more alkaline environment, with pH levels between 7.5 and 8.4 [122]. Therefore, it is important to monitor these parameters [124]. Recent advances in sensor technology and Internet of Things (IoT) systems enable real-time monitoring of critical water quality factors such as dissolved oxygen, temperature and pH [125]. The principal advantage of RAS systems is water capacity reuse of up to 90–99%. The production of a substantial quantity of fish products with minimal water consumption is ecologically beneficial for humanity. Moreover, land-based closed-water supply systems can be implemented in diverse geographical regions with varying climatic conditions. Nevertheless, such systems have the potential to contribute to the greenhouse effect and result in high energy costs [113]. Recirculating aquaculture systems are characterized by high energy consumption, mainly due to the continuous operation of pumps for water circulation, sophisticated filtration systems and environmental control mechanisms such as temperature regulation and aeration. For example, the production of one tone of Atlantic salmon in a RAS facility can require over 7500 kilowatt-hours of electricity [126].

Some RAS facilities may also employ diesel generators, particularly as a means of backup power in case of grid outages. Consequently, the carbon footprint of RAS is intrinsically linked to the carbon intensity of the local electricity grid or the specific fuel source being utilized [127]. Despite the energy intensity of RAS operations, a potential advantage in terms of carbon footprint lies in the possibility of locating these facilities closer to consumer markets, especially within urban environments. This strategic placement can lead to a reduction in the transportation-related emissions associated with the distribution of the final seafood product [128]. Adding to this, if RAS facilities can effectively source their energy needs from these cleaner alternatives, the greenhouse gas emissions associated with their operation could be substantially reduced, positioning them as a more environmentally sound option for aquaculture.

The controlled environmental conditions of RAS cultivation significantly influence the nutritional composition of fish, enhancing their nutritional quality. Specifically, RAS allows for precise management of dietary inputs and water quality parameters, leading to improved fatty acid profiles characterized by higher concentrations of beneficial polyunsaturated fatty acids (PUFAs), such as omega-3 fatty acids, which are crucial for human health [129,130]. Additionally, stable and optimized feeding conditions in RAS can result in fish with elevated protein content and improved amino acid profiles compared to traditional aquaculture systems [131]. Furthermore, precise nutrient supplementation in controlled RAS environments facilitates higher retention and consistent levels of essential micronutrients like selenium, iodine, and vitamins, thereby augmenting the overall nutritional value of the fish produced [132]. Thus, the RAS approach offers clear benefits in producing nutritionally superior fish products that address both consumer health and sustainable aquaculture objectives.

3.2. Pond Farming

Pond farming is also widely recognized as "organic aquaculture", which is considered to be a developed practice and refers to open systems of fish farming [133]. The practice of raising fish in a pond is rather ancient, yet it remains an effective method. Those engaged in agricultural pursuits are more likely to be interested in this method. The construction of a pond on a plot of land allows the owner to not only enhance the aesthetic appeal of the landscape but also engage in fish production. The most common fish species are tilapia (*Oreochromis niloticus*), carp (*Cyprinus carpio*), and white amur (*Ctenopharingodon idella*) [134].

One of the defining characteristics of pond aquaculture is the influence of soil on water parameters, which subsequently affects fish [135]. The composition of the soil at the bottom of the pond has a significant impact on the concentration of nitrogen (N), the carbon-to-nitrogen (C/N) ratio, and the presence of other organic matter [136]. In this context, the quality of the soil is a factor to be considered when establishing an aquaculture operation. The most favorable conditions for establishing aquaculture are found on land with a neutral or slightly alkaline pH [135]. Once pond aquaculture is established, the soil reaches the bottom of the pond, where various organic and inorganic compounds fall and accumulate. Subsequently, favorable conditions are established for the proliferation of bacteria that decompose these substances [137,138].

The microbiota also plays a significant role in the field of pond aquaculture. Plankton, zooplankton, and various bacteria consume dead organic matter in water. When nutrients are scarce, fish consume plankton, thereby initiating a food chain. Nevertheless, this microbial community can also have a detrimental effect on fish. They reproduce at night and consume dissolved oxygen, which can result in a lack of oxygen in the water [138].

The next crucial parameter in pond aquaculture is dissolved oxygen (DO), which is typically produced in freshwater. The concentration of dissolved oxygen can be used to assess the degree of water pollution. A reduction in the concentration of DO results in increased stress for fish, which in turn increases the risk of mortality [139]. A reduction in DO is typically accompanied by an increase in water temperature and salinity. Furthermore, the use of herbicides for plants in ponds and the nighttime photosynthesis process can also influence the level of dissolved oxygen [140]. At present, several studies are being conducted to predict the trend of dissolved oxygen fluctuations. One such study employs the application of a neural network. By taking action in advance, it is possible to prevent the total loss of an entire farm [140].

Compared with other agricultural systems, pond farming is more closely integrated with the surrounding environment. In addition, the accumulation of unnecessary waste in water is a further consequence of this practice. Eutrophication (nutrient saturation) can have a detrimental impact on fish health. To circumvent such issues, the implementation of ecological engineering in pond farming is imperative [84]. To guarantee the hydrodynamic circulation of water, artificial reservoir schemes have been developed. Furthermore, it is essential to guarantee uninterrupted water filtration. To this end, specialized accumulation and filtration systems are installed at the terminus of drainage channels [101]. Conversely, the presence of sediment from fishponds can also be beneficial. The sediments at the bottom of the ponds are known to contain significant quantities of organic elements, including sodium, potassium, and phosphorus [141]. A series of fish waste treatment activities can be employed to derive plant fertilizer [142]. This fact serves to enhance the value of pond farming from an ecological standpoint.

Furthermore, pond aquaculture is significant in the context of biodiversity conservation. Ponds can be represented by habitats for a variety of animals, including fish and birds [143]. In this context, while pond aquaculture may be less efficient in terms of fish production, it plays a significant role in landscape conservation.

Pond farming often presents the advantage of lower initial investment costs when compared to more technologically advanced aquaculture systems such as RAS or offshore mariculture operations [144]. The availability and cost of labor are also important economic considerations that influence the location and scale of pond farming operations [145]. The nutritional quality of fish cultivated in pond farming can fluctuate considerably due to environmental interactions characteristic of open systems. Natural feeding behaviors, encompassing the ingestion of phytoplankton, zooplankton, and other microorganisms, frequently result in advantageous fatty acid compositions, notably elevated concentrations of omega-3 fatty acids such as EPA and DHA, in contrast to highly cultivated fish [146]. Inconsistencies in feeding practices and variations in environmental conditions might lead to inconsistent protein content and amino acid profiles, thereby impacting overall nutritional quality [147]. Pond farming generally provides fish with improved access to natural micronutrients, including carotenoids, selenium, and vitamins, hence enhancing the nutritional and sensory quality of the caught fish [78,148]. Consequently, notwithstanding certain discrepancies, pond aquaculture frequently enhances the nutritional attributes and consumer appeal of fish products.

3.3. Aquaponic Fish Breeding

An aquaponic system is an integrated combination of a closed water supply device and soilless organic crop production. The primary objective is to utilize the fish waste generated as a source of nutrients for plant growth, thereby producing two marketable products. Aquaponics is a combination of a closed water supply device and hydroponics. This system has the potential to achieve economically and environmentally beneficial production [149]. The fundamental principle of aquaponics is the integration of three distinct classes of organisms: aquatic organisms, bacteria, and plants (Figure 3).

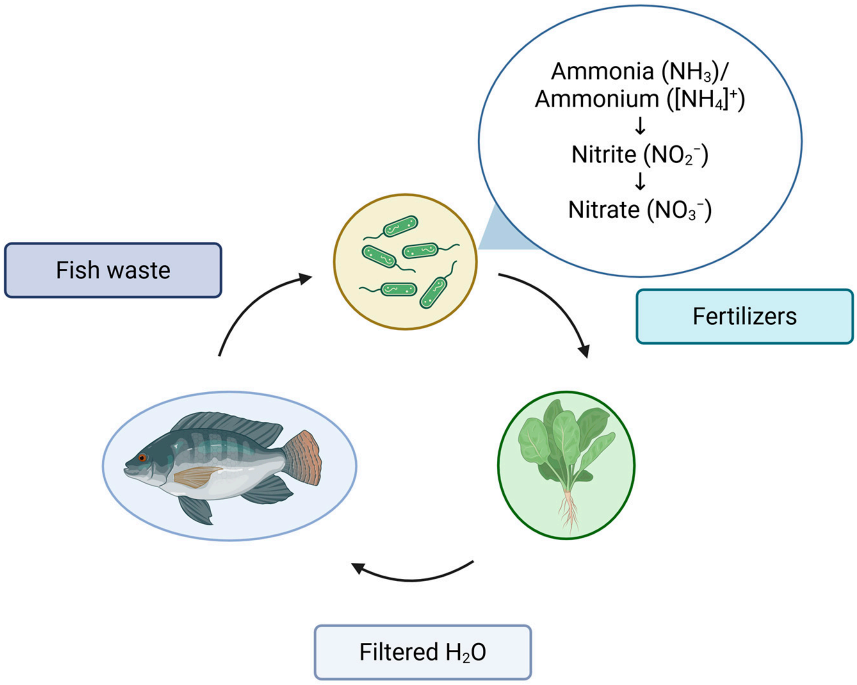

Figure 3. Nutrient cycle in an aquaponic system [27,150]. Created by BioRender.

In a closed system with water recirculation, these organisms mutually enrich each other. Water serves as a medium for the transfer of nutrients, primarily from dissolved fish waste. Bacteria transform these wastes into nutrients that facilitate plant growth. Ammonia is oxidized by specific bacteria, such as *Nitrosomonas* and *Nitrobacter*, to nitrite and then to nitrate [27].

The processes of nitrification and denitrification are highly important for addressing nitrogen toxicity in recirculating aquaculture systems [151]. As illustrated in Figure 3, the conversion of NH_3/NH_4 to NO_2 (the initial step) and then to NO_3 (the subsequent step) occurs during the nitrification process. Each of these steps is influenced by different microorganisms. In the initial stage, bacteria such as *Nitrosomonas*, *Nitrobacter*, and *Nitrosococcus*, among others, are involved. In the second step, bacteria such as *Nitrobacter*, *Nitrococcus*, and *Nitrospira* convert NO_2 into NO_3 [117,152]. Notably, denitrification results in a 50% reduction in nitrogen in the system. Microorganisms capable of converting nitrate to nitrogen include *Achromobacter*, *Aerobacter*, *Acinetobacter*, *Bacillus*, *Brevibacterium*, Flavobacterium, and others [153].

The quality of water is of paramount importance in aquaponics. It is essential to regulate a few parameters, including pH, temperature, NH_3/NH_4, NO_2/NO_3, and oxygen concentration. However, one challenge is the discrepancy in pH requirements between plants and fish. The optimal pH for plants is 6.0, while the pH range for fish is 7.0–8.0. Additionally, the optimal pH for the growth of nitrifying bacteria is 6.5–8.0 [27,154]. Consequently, a variety of technologies are employed to regulate the pH at an optimal level [155].

In addition to the pH, temperature can also negatively affect water quality. To create conditions that are equally conducive to the growth of plants and fish, an average temperature is set for both. For instance, tilapia are cultivated at a temperature of 25 degrees Celsius, which is conducive to optimal basal growth [27].

Not all fish and plant species can adapt to aquaponic farming. The most popular fish species are tilapia, trout, and perch. Depending on the density of the fish and the saturation of the water with organic compounds, plants are selected. Among them, greens (basil, mint, spinach) and vegetables such as peppers, cucumbers, and tomatoes are more commonly grown [156,157].

From an environmental perspective, aquaponics represents a promising technology. Aquaponics represents an alternative method of food production that contributes to sustainable development and prevents the release of aquaculture waste that pollutes water bodies and causes eutrophication [158]. However, aquaponic systems, especially those that are implemented indoors or as vertically integrated farms, can be energy-intensive in certain aspects. The overall carbon footprint of an aquaponic system is therefore heavily influenced by the energy efficiency of its design and the source of the electricity used to power it. Optimizing energy use through strategies such as implementing energy-efficient lighting systems (e.g., LEDs) and designing systems that minimize pumping requirements, along with transitioning to renewable energy sources, are critical for realizing the low-carbon potential of aquaponics [159]. Nevertheless, in comparison to other methods of fish farming, aquaponics represents a novel approach. The production of fish and plant products with minimal water inputs renders this method the most popular [112].

Aquaponic systems have been shown to enhance the nutritional quality of fish, especially their fatty acid composition, protein content, and micronutrient profiles. Aquaponically grown tilapia, for example, showed far greater polyunsaturated fatty acid (PUFA) levels (30.45%) than their conventionally grown equivalents (18.64%) and lower saturated fatty acid (SFA) levels, hence producing a nutritionally better lipid profile [98]. Aquaponically bred fish typically exhibit a more advantageous omega-6 to omega-3 fatty acid ratio, offering cardiovascular health benefits to customers [160]. The protein content in aquaponically produced fish is usually optimized through regulated dietary practices, typically ranging from 25% to 35%, and can rise to about 45% in carnivorous species, thus ensuring balanced amino acid profiles, including essential amino acids such as lysine and methionine [161,162]. Moreover, aquaponic integration might result in increased micronutrient accumulation, such as elevated levels of vitamin C and carotenoids, hence enhancing the nutritional quality and consumer appeal of fish products [163]. Aquaponics presents a sustainable approach that enhances the nutritional qualities of cultivated fish, benefiting both producers and consumers.

For commercial aquaponics operations, strategic proximity to key sales channels such as local farmers' markets, restaurants that prioritize fresh and sustainable ingredients, and opportunities for direct-to-consumer sales are particularly important factors that influence their location decisions [164]. The economic viability of commercial aquaponics ventures is significantly influenced by their ability to effectively access markets that place a high value on locally sourced and sustainably produced food.

3.4. Sea Farming

Marine farms and pond aquaculture are classified as "organic aquaculture". Mariculture, also known as marine aquaculture, refers to the cultivation of aquatic species at sea, either throughout the entire production cycle or solely during the cultivation phase. Alternatively, mariculture is defined as the rearing phase of the production cycle, during which the species is grown in land-based hatcheries and, on occasion, even in freshwater, as exemplified by the Atlantic salmon [5].

Most marine fish farms are situated in shallow, sheltered, and coastal waters. This is primarily to ensure the safe operation of the facility and the accessibility of necessary service facilities for the feeding, incubation, storage, maintenance, and processing of harvested fish [165]. The establishment of coastal sea farms is also beneficial for water conservation. In recent years, there has been a growing application of the "Strategic Programme for Climate Resilience" principle in marine aquaculture. This approach is based on water purification with nitrifying bacteria and subsequent reuse [166].

As with pond aquaculture, mariculture farms produce effluents with high levels of fish waste and chemicals. The discharge of mariculture effluents can cause several significant environmental problems, including hypoxia, eutrophication, heavy metal pollution, and habitat destruction [167]. The primary objective of mariculture wastewater treatment is the removal of organic carbon, nitrogen, and phosphorus. The separation of organic solid wastes can be effectively achieved using sedimentation or filtration techniques. The residual organic carbon and nutrients must be removed by functional microorganisms and/or algae [168].

The next significant challenge in marine farming is biofouling, which refers to the accumulation of undesired aquatic species. The introduction of these organisms alters the hydrodynamics within and surrounding the cage, which has a significant impact on water quality. Furthermore, the probability of disease transmission is elevated due to the introduction of additional aquatic species and their associated pathogens [169]. For instance, the probability of biofouling by anemones and hydroids is considerable on salmon farms. Furthermore, farmed fish are at risk of Cnidaria stings due to the accumulation of these organisms on farms [170].

A multitude of factors are considered during the design of offshore fish farms. These include water depth, current velocity, seabed conditions, and favorable conditions for fish. The design of flexible/solid floating, semisubmersible, and submerged cages is informed by this consideration [165].

Mariculture substantially impacts the nutritional quality of fish, specifically their fatty acid profiles, protein levels, and micronutrient concentrations. Marine-farmed dentex (*Dentex dentex*) demonstrated omega-3 fatty acid concentrations, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), nearly double those observed in other prevalent aquaculture species such as sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) [171]. The protein content in mariculture-produced fish generally varies from 18% to 22%, with essential amino acids comprising approximately 50% of the total amino acid profile; species like Atlantic salmon (*Salmo salar*) and axillary seabream (*Pagellus acarne*) exemplify these high-quality protein characteristics [25,172]. Furthermore, fish cultivated in marine environments typically demonstrate increased concentrations of vital micronutrients, such as vitamin D (approximately 8–20 μg per 100 g), vitamin B12 (up to 10 μg per 100 g), selenium (30–50 μg per 100 g), and iodine (100–300 μg per 100 g), thereby substantially enhancing nutritional sufficiency and human health [173,174]. Consequently, mariculture significantly improves the nutritional attributes of cultivated fish, establishing it as a vital element of global food security initiatives.

4. Impact of Fish Farming Methods on Fish Nutritional Value

Aquaculture practices significantly influence the nutritional value and quality of farmed fish. Some studies have demonstrated that the flavor, chemical composition, and texture of fish fillets can be influenced by the culturing practices employed [175]. Intensive aquaculture practices may result in increased lipid content in fish, whereas extensive methods may result in the development of different flavors [175]. The fatty acid profile of farmed fish can be modified through dietary manipulation, which may enhance nutritional quality [175,176]. Pond-raised fish typically exhibit higher levels of polyunsaturated fatty acids (PUFAs), especially omega-3 fatty acids, than cage-raised or wild fish [177,178]. Additionally, pond-raised fish exhibit elevated levels of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in comparison to other cultivation methods [131,177]. Amino acid profiles have been observed to vary between culture systems, with pond-raised fish potentially exhibiting higher levels of certain amino acids [131]. While studies have demonstrated that fish reared in the RAS may exhibit elevated dry matter, fat, and calorie content relative to their pond-raised counterparts, they may also display reduced levels of beneficial fatty acids, including EPA and DHA [131]. Nevertheless, the integration of seaweeds, such as Ulva sp., into an RAS has been demonstrated to enhance fish growth, elevate protein and lipid content, and augment EPA and DHA levels in fish while also improving water quality [130]. The cultivation of microalgae in RAS wastewater has the potential to produce valuable biomass for use as aquaculture feed, with the filtration process capable of influencing the fatty acid content of certain species [179]. These integrated systems can utilize metabolic byproducts from fish production to facilitate the growth of secondary crops with economic value, thereby creating a more efficient and sustainable aquaculture system.

The integration of fish and plant culture in aquaponic systems affects the approximate composition and fatty acid profiles of fish fillets [180]. Furthermore, alterations to the fatty acid profile may be achieved. For instance, freshwater aquaponic systems have the potential to reduce the levels of saturated fatty acids in certain fish species [180]. An aquaponic system has the potential to produce fish of comparable or higher quality than that achieved by conventional methods while simultaneously growing plants [181,182]. The efficiency of the system is contingent upon maintaining an optimal ratio between daily feed intake and the area devoted to plant growth [183]. The feasibility of cultivating marine species, such as the European sea bass, in aquaponic systems, encompassing both freshwater and saltwater environments, has been substantiated. This suggests the viability of maintaining product quality across diverse ecosystems [180]. Additionally, increasing dietary levels of EPA and DHA in Atlantic salmon reared in sea cages has been shown to enhance growth performance and overall quality. Recent research indicate that intensive aquaculture systems, particularly those employing high-energy meals, might elevate total lipid content in fish fillets by as much as 25% and may diminish omega-3 levels when plant-based feeds are overly utilized [184]. Organic farming methods, characterized by reduced stocking densities and natural feed inputs, are linked to leaner fish with elevated protein levels (up to 22% in fillet muscle) and improved fatty acid ratios [185]. In sea cage systems, environmental factors like water velocity and temperature influence fat deposition and texture, frequently resulting in fish with enhanced muscle growth and reduced intramuscular fat [186]. Feed is essential in determining fish nutrition; conventional fishmeal-based diets increase protein content and omega-3 levels as well as plant-based feeds may increase these advantages unless augmented with marine oils or microalgae [187].

Moreover, research shows that the use of a fish-intensive culture (sea farming) method also affects the nutritional composition of farmed fish. Compared with their wild counterparts, cultured sea bream showed greater total lipid content, with differences in fatty acid profiles [175]. Similarly, compared with wild fish, farmed sea bass exhibit altered protein and fatty acid compositions [188]. The fatty acid profile of cultured red sea bream was found to be directly influenced by the feed composition, with fish-fed sardines showing higher levels of EPA and DHA [25,189]. Proteomic and chemical analyses have revealed significant differences between farmed and wild fish, emphasizing the impact of aquaculture on food quality [188]. Furthermore, nutritional supplements and functional ingredients are being investigated as potential means of enhancing fish health, stress resistance, and disease resilience in aquaculture settings [176].

5. Conclusions and Future Directions

Fish, as a food source, offer a range of health benefits to humans. As previously stated, fish meat is a rich source of essential fatty acids that support cognitive development, improve health indicators, and enhance overall immunity [190]. Furthermore, fish consumption has been demonstrated to reduce the risk of cardiovascular disease [191]. Fish meat proteins are well digested and have high biological value [192]. Fish contain biomolecules that enhance physical and mental health [193]. The vitamins and minerals present in fish have been demonstrated to exert a beneficial influence on several cellular processes within the body [194]. These findings confirm that fish are a valuable source of nutrients essential for human health.

The practice of fish farming will continue to be relevant in terms of the production of fish products for human consumption [5]. A variety of fish farming techniques are employed to maximize production and efficient rearing. These include pond farming, confined rearing, aquaponics, and marine aquaculture. Importantly, selecting sustainable aquaculture system is a context-dependent process, shaped by structural features of the system, water exchange frequency, crop intensity, and integration with other organisms [82]. In addition, it is highly dependent on a range of factors, including the specific geographical location, the prevailing climate, the availability of critical resources such as land, water and energy, and the specific management practices that are employed. For instance, recirculating aquaculture systems (RAS) may be the optimal choice in urban areas where water scarcity is prevalent but renewable energy is accessible, while mariculture may be the most sustainable option in coastal regions where environmental conditions are conducive. Regardless of the rearing method employed, maintaining optimal water quality parameters remains essential. Fish behavior and stress responses are intimately linked to the quality of their aquatic environment [195]. In closed and open water exchange systems, the pH, salinity, temperature, NH_3/NH_4 ratio, NO_2/NO_3 ratio, and other substances are considered to be uniform, contingent upon the specific characteristics of the growing environment [196].

Consequently, the significance of fish as a source of sustenance for humans and the optimal methods for their cultivation have been subjected to rigorous investigation. An understanding of fish characteristics and their associated benefits is essential for selecting the most appropriate aquaculture techniques. An examination of the various rearing methods reveals the necessity for the continuous improvement of the qualities of aquaculture. The advancement of ecological knowledge and the development of technological innovations are facilitating the evolution of fish farming practices. Importantly, there is a need for research scientists to explore the relationship between diet and the lipid profile in different rearing systems. Understanding this connection can contribute to improving the nutritional quality of fish products and support the design of optimized feed strategies.

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