International Journal of Innovative Research and Scientific Studies, 9(3) 2026, pages: 11-20

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Water use optimization in fish farms: Efficient strategies to reduce environmental impact

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Abstract

Aquaculture has now become an important agricultural activity in meeting global food needs. However, the intensification of this activity places daily pressure on water resources and aquatic ecosystems. The goal of this study was to find efficient ways to optimize water use in fish farms, helping to reduce their environmental impact. We did a literature review using systematic mapping that combined analysis of scientific databases with defined inclusion and exclusion criteria. The results showed that there is a growing interest in the search for technologies that enable water savings and efficient use in the aquaculture chain, notably recirculation, biofloc, aquaponics, and biofiltration, which can reduce water consumption and minimize the pollutant load in water. It is concluded that the adoption of alternatives for water resource management in aquaculture is a viable path that contributes to the sustainability and competitiveness of this economic activity.

Keywords: Fish farms, Pollution, Recirculating aquaculture systems, Water footprint, Water resources.

DOI: 10.53894/ijirss.v9i3.11316
Funding: This study received no specific financial support.
History: Received: 16 December 2025 / **Revised:** 2 February 2026 / **Accepted:** 6 February 2026 / **Published:** 4 March 2026

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

Worldwide population growth has enlarged the food demand, including aquaculture goods such as fish [1]. In 2023, global per capita fish ingesting reached 21.2 kg, surpassing that of chicken and pork [2]. In Colombia, aquaculture production stretched 200,000 tons in 2024, with a per capita consumption of 8.8 kg and more than 3,000 registered fish farms, 500 of them located in Cauca Department [3]. This activity engenders more than 215,000 jobs, becoming an important economic sector. However, fish farms face environmental challenges such as contamination from antibiotics, feed residues, and frequent water exchanges, which impinge on ecosystem quality [4, 5]. In regions such as Cauca, water overexploitation and pollutant discharges intensify pressure on aquatic ecosystems, which leads into the need of considering sustainable strategies to optimize water use.

2. Materials and Methods

This bibliographic analysis aims to identify and label efficient strategies to optimize water use in fish farms in order to reduce their environmental impact. The research encompassed both qualitative and quantitative approaches, based on a comprehensive analysis of studies focused on the effects of aquaculture, particularly on aquatic ecosystems.

A systematic mapping was conducted following the methodology proposed by Chary, et al. [6] through a search of scientific literature in databases such as Scopus, ScienceDirect, Redalyc, SciELO, and Virtual Pro. The search focused on published papers addressing environmental impacts and water optimization strategies in fish farming systems.

The following research question was defined:

What might be the strategies for optimizing water use in fish farms?

The inclusion criteria were:

I. Studies that mention water optimization in fish farms.

II. Articles addressing issues related to water contamination in these systems.

III. Published papers describing specific methods seeking the improvement of the use of water resources.

The exclusion criteria were:

I. Technical guidelines or reports.

II. Prior Publications to 2016.

III. not available digital format documents.

IV. Articles written in languages other than Spanish or English.

Subsequently, a scientometric analysis was applied based on Ministerio de la Producción (PRODUCE) [7] and Béné, et al. [8] using graphs and schemes to illustrate trends such as the number of publications per year and their thematic significance. Finally, an in-depth analysis of the most relevant studies was directed, which allowed the construction of a comparative matrix of strategies applicable to the Colombian framework, particularly in Cauca department.

3. Results and Discussion

From the ScienceDirect database, and in relation to the guiding research question mentioned above, it was observed, as shown in Figure 1 that between 2021 and the first quarter of 2025 approximately 6,127 articles on fish farming were published. Of these, around 1,665 correspond to review articles, 3,385 to research articles, 153 to encyclopedia entries, and 924 to book chapters.

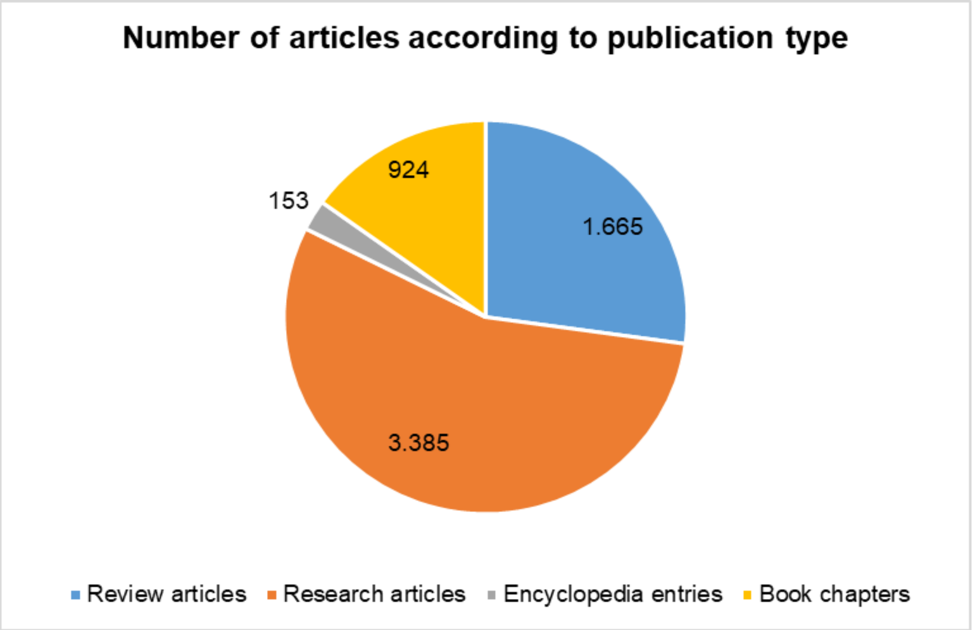

Figure 1.
Statistics of articles identified.

Regarding the search "strategies AND optimization AND water use in fish farms", as shown in Figure 2 a total of 3,375 research articles were identified between 2021 and 2025. This number shows an increasing trend: in 2024 alone, 1,017 studies were published, while in the first quarter of 2025 more than 500 research articles had already been reported.

These findings reflect the growing interest of both the scientific community and the productive sector in investigating and disseminating results related to aquaculture management, sustainability, and fish farming practices, as well as the increasing need to improve the productivity of this food source in many regions worldwide.

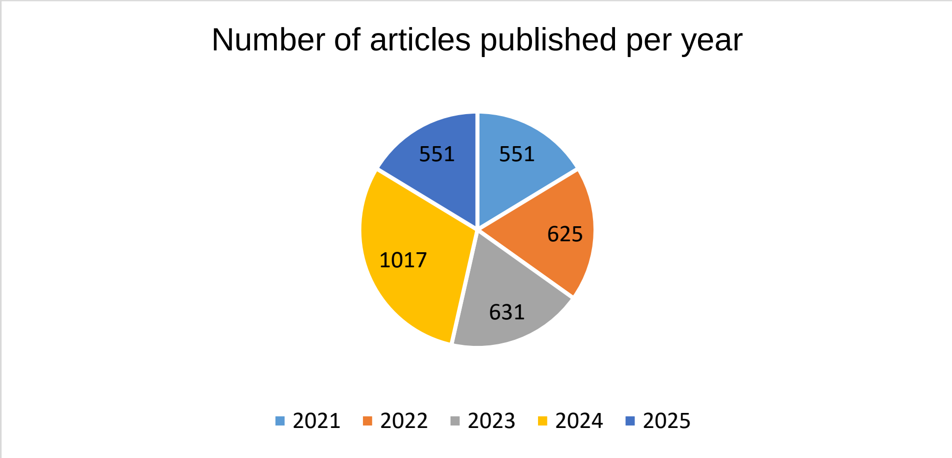

Figure 2.
Research articles published between 2021 and 2025.

The countries with the highest annual scientific output, as shown in Table 1 reflect the growing interest in optimizing the use of natural resources in systems such as aquaculture. This increase responds to the effects of climate change, the degradation of aquatic ecosystems, and the need to reduce pollutants generated by human activities. Furthermore, the high demand for aquatic protein has driven innovations that enable production with lower water and energy consumption, while maintaining greater environmental control. In 2023, global per capita fish consumption was 20.7 kg, and it is estimated to reach 21.4 kg by 2030–2032 [2, 7].

Table 1.
Countries with the highest research output and their respective topics.

Rank	Country	Main Topic	Geographic Scope
1	China	Agriculture, aquaculture, biofiltration, photocatalysis	Global
2	Norway	Industrial system efficiency	Global
3	United States	Agriculture, aquaculture, biofiltration	Global
4	Australia	Sustainable water use (wastewater)	Global
5	India	Photocatalysis, aquaculture, food industry	Global
6	Germany, Spain, Netherlands, United Kingdom	Biofiltration, aquaculture residues	Europe–Global
7	Iran, Brazil	Photocatalysis of wastewater	Regional–Global

Source: Froehlich, et al. [9]**;** Ottinger, et al. [10]; Lala-Pritchard and Johnstone [11]; Troell, et al. [12]; Rebours, et al. [13] and Li, et al. [14].

Countries such as China, Norway, the United States, Australia, India, and several European nations have developed technologies to optimize water use in aquaculture. China leads research on water treatment [15, 16] while Norway and Spain stand out for their use of RAS systems and efficient water management [10, 17, 18]. The United States promotes sustainable practices through institutions such as Auburn University [19] whereas other countries are advancing in water sustainability and biofiltration [13, 20].

4. Impacts Generated by Fish Farming Activities

In 2022, global fish production reached 223.2 million tons, representing an increase of 4.4% compared to 2020 [2]. China, Southeast Asia, Peru, Nigeria, and Egypt face challenges such as pollution, biodiversity loss, and mangrove destruction [21, 22]. In Colombia, with 36,464 production units, fish farming is concentrated in Huila, Antioquia, Meta, and Caquetá, generating impacts such as water pollution, ecosystem alteration, and the emergence of invasive species. This situation has driven the search for strategies to reduce environmental impact and optimize water use, particularly in the Cauca region [3].

4.1. Matrix of Fish Farming Impacts in Colombia

Based on information compiled from the consulted bibliographic sources [9, 10, 23, 24] the following information can be summarized:

Table 2.
Matrix of fish farming impacts in Colombia.

Category	Positive Impact	Negative Impact
Environmental	• Improved use of water resources in controlled fish farms under ideal regulations.	• Water pollution from feed and medication use. • Alteration of natural ecosystems. • Introduction of invasive species.
Social	• Creation of direct and indirect employment in rural areas. • Development of aquaculture communities.	• Displacement of local communities due to water scarcity. • Conflicts over water resource use.
Economic	• Greater diversification of the local economy. • Increased food production.	• Economic dependence on a single activity. • Impact on small farmers and traditional fishers.
Public Health	• Increased availability of high-quality animal protein.	• Use of antibiotics and chemicals can cause resistance to various pathogens and contribute to the transmission of zoonotic diseases. • Health risks associated with water contamination.
Regulation and Governance	• Implementation of best practices and sustainable technologies.	• Lack of adequate regulation and supervision. • Issues with compliance and corruption.

Source: Froehlich, et al. [9]; Ottinger, et al. [10]; El-Sayed [23] and Partelow, et al. [24].

Fish farming can cause positive impacts when managed appropriately, such as efficient water use, job creation, and the production of high-quality protein. However, it can also lead to contamination, social conflicts, negative effects on small-scale producers, and health risks if not properly managed [25]. Its sustainability depends on effective regulation and the implementation of responsible practices [4].

5. Problems Related to Water Resources Associated with Fish Farming in the World and Colombia Water Pollution

In fish farms, uneaten feed and feces accumulate in ponds and can be released into natural water bodies, causing eutrophication, decreased oxygen levels, and negative effects on aquatic biodiversity [15]. This is compounded by the excessive use of antibiotics and chemicals, which not only affect wild species but also promote disease resistance [26]. Excess nutrients, such as nitrogen and phosphorus, further deteriorate water quality, negatively impacting the food chain and ecosystem balance [27].

5.1. Alteration of Aquatic Ecosystems

Aquaculture has accelerated the loss of wetlands and aquatic ecosystems, which are crucial for biodiversity and water regulation. Since 1970, 35% of global wetlands have been lost, three times faster than forests [28] with a cumulative loss of over 3.4 million km² since 1700 due to agricultural and urban expansion [15]. In Colombia, the Bogotá Wetland has lost approximately 99% of its original area, and the Ciénaga Grande de Santa Marta has seen its mangroves reduced by about 300 km², accompanied by salinization and social deterioration [29]. Furthermore, fish farming introduces exotic species such as tilapia, destroys natural habitats through pond construction, and reduces water flow due to intensive water extraction [30].

5.2. Competition for Water Resources

In regions with limited water availability, intensive fish farming competes with other sectors such as agriculture, industry, and domestic use, generating social and environmental conflicts. This situation jeopardizes the water sustainability of strategic basins, primarily affecting rural communities that rely on these resources for their livelihoods [3, 17]. The lack of integrated planning and proper allocation of water flow exacerbates these conflicts [2] highlighting the need for effective water governance that prioritizes basic human access and traditional uses.

6. Efficient Strategies for Optimizing Water Use in Fish Farms

According to the methodology implemented for systematic mapping, relevant information was obtained regarding the most commonly used strategies that achieve the best results in terms of higher productivity and lower environmental impact. These strategies include the following:

Table 3.
Efficient strategies for optimizing water use in fish farms.

Category	Strategy	Description	Leading Countries	References
Chemical	Reduction of harmful antibiotics and chemicals	Use of probiotics and alternative methods for controlling fish diseases, achieving an average reduction of 50.7% ammonia in ponds treated with probiotics.	Norway, Chile, Japan	Food and Agriculture Organization of the United Nations (FAO) [31]; Garcia and Rosenberg [32]; Gentry, et al. [33] and N'souvi, et al. [34]
	pH and water quality control	Adjustment of chemical parameters to maintain optimal conditions without excessive water exchange. Reduces free ammonia (NH_3) from 28% (pH 9) to 0.3% (pH 7). Improves TAN nitrification rate by up to ~320% (pH 6 → 8). Maintains total NH_3 below 0.02 mg/L.	United States, Australia, Spain	
Biological	Biofloc Technology (BFT)	Use of microorganisms to recycle nutrients and improve water quality, achieving efficiencies of up to 88.9% for ammonia, 93.0% for nitrite, 83.7% for nitrate, and over 90% phosphorus reduction.	Brazil, Indonesia, India, Ecuador	Costello, et al. [29]; Edwards [30]; Borrego, et al. [35]; Gilbey, et al. [36] and Kumar and Engle [37]
	Use of biofilters and advanced treatments	Application of chemical filtration systems to remove contaminants and improve water quality by up to 95%, with significant reductions in nitrites (up to 45%), nitrates (up to 47%), and chemical oxygen demand (up to 85%).	Netherlands, Germany, Canada	
	Aquaponics	Integration of fish farming with crop production to reuse water. Achieves up to 86% ammoniacal nitrogen, 92% nitrite, 87% nitrate, and 85% phosphorus removal.	United States, Germany, Mexico	
	Use of resistant and adapted species	Farming fish with lower water demand and higher disease resistance. Recent studies show that genetic improvement in rainbow trout can reduce nitrogen and phosphorus (N & P) load in water by 18%, while increasing feed-to-biomass conversion efficiency.	Vietnam, Peru, Brazil	
Physical	Recirculating Aquaculture Systems (RAS)	Water reuse through mechanical and biological filtration, reducing consumption. Allows efficient recirculation of 90–99% of used water, reduces consumption to less than 100 L per kg of fish, decreases effluent discharge by up to 98%, and reduces eutrophication in the surrounding environment by 26–38%.	Norway, Denmark, China, Canada	Ministerio de la Producción (PRODUCE) [7]; Asche, et al. [20]; Kholodnyy, et al. [38]; Abdul Kari [39]; Little,
	Monitoring and automation of water quality	Use of sensors and software to manage parameters such as oxygen and temperature. Studies indicate this strategy can reduce water exchange by 25%, decrease antibiotic use by up to 30%, and lower operational costs by 30%, while improving fish survival rates and maintaining system environmental quality.	South Korea, United States, China	
	Wastewater treatment and	Application of constructed wetlands, biological filtration, and purification systems. These low-energy natural systems can remove nutrients and contaminants with proven efficiencies: up to 95.5% ammonia, 98% total nitrogen, 78% phosphorus, 86%	France, Australia, Netherlands	

	reuse	suspended solids, 55% COD. Some studies report over 90% removal of fecal coliforms.		et al. [40]; Tacon and Metian [41]

6.1. Efficient Strategies Applicable in Colombia and the Cauca Region

To optimize water, use in fish farms and reduce environmental impact in Colombia, particularly in the Cauca region, various efficient strategies can be implemented. These strategies can address both water use efficiency and the reduction of pollutants, while also protecting aquatic ecosystems.

6.1.1. Recirculating Aquaculture Systems (RAS) in Fish Farms

Recirculating Aquaculture Systems (RAS) are an advanced aquaculture technology that allows water to be reused within a closed system. These systems have gained popularity in countries such as Norway, Denmark, China, and Canada due to their ability to reduce water consumption and minimize environmental impacts. Detailed information on RAS—including their operation, benefits, challenges, and examples of successful implementation—has been described by various authors in their research [5, 42-44].

6.1.1.1. Operation of Recirculating Aquaculture Systems (RAS)

A typical RAS includes the following main components [36-38]:

1. Culture Tanks: Where the fish are raised.
2. Mechanical Filtration System: Removes solids and waste from the water.
3. Biofilter: Converts toxic compounds such as ammonia and nitrites into less toxic nitrates through the nitrification process.
4. Degassing and Oxygenation: Removes unwanted gases such as carbon dioxide and adds oxygen to the water.
5. Temperature Control: Maintains water temperature within the optimal range for fish growth.
6. Disinfection System**:** Uses UV light or ozone to eliminate pathogens and maintain water quality.

Table 4.
General Aspects of RAS.

Aspect	Description
Benefits of RAS	Water savings (90–99%), improved water quality, allows quality control, reduction of environmental impact, higher productivity and location flexibility, maintains water temperature within the optimal range.
Challenges of RAS	High initial costs, need for specialized maintenance, waste management, and risk of technical failures as the system is new to the country.
Recommendations for Colombia and the Cauca	Assess feasibility, train personnel, provide government incentives, promote research, and establish support networks.

Source: Ministerio de Agricultura y Desarrollo Rural [2]**.**

6.1.2. Aquaponics

Aquaponics is an innovative technique that combines aquaculture (fish farming) with hydroponics (soilless plant cultivation) in a closed and recirculating system. This method enables efficient use of resources, reducing water consumption and waste production, as reported by various studies. The following section describes the operation, system components, benefits, challenges, and examples, as documented by Li, et al. [14]; Allison and Bassett [19]; World Bank Group [45] and Tezzo, et al. [46].

6.1.2.1. Operation of Aquaponics

In an aquaponic system, the waste produced by the fish provides essential nutrients for the plants. In turn, the plants help purify the water, which is recirculated back to the fish tanks. The basic operating process includes the following steps:

- Fish Tanks: The fish produce waste rich in ammonia, which is toxic at high concentrations.
- Biofiltration: Microorganisms in the biofilter convert ammonia into nitrates through the nitrification process. Nitrates are less toxic and serve as nutrients for the plants.
- Plant Grow Beds: The plants absorb nitrates and other nutrients from the water, helping to purify it.
- Water Recirculation: The purified water returns to the fish tanks, completing the cycle.

6.1.2.2. Components of an Aquaponic System

- Fish Rearing Tanks: The volume and configuration vary according to system scale, stocking density, and the species under cultivation.
- Biofiltration Units: Essential for the nitrification process, facilitating the biological conversion of toxic ammonia (NH_3/NH_4^+) into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-) by nitrifying bacteria.
- Plant Cultivation Units: These may include media-filled beds (e.g., gravel or expanded clay), nutrient film technique (NFT) channels, and deep-water culture (DWC) or floating raft systems.
- Water Circulation Pump: Ensures continuous recirculation of water among system components, promoting nutrient transport and system stability.

- Aeration Devices**:** Maintain adequate dissolved oxygen (DO) concentrations to support fish respiration, root health, and microbial activity within the biofilter.

Table 5.
General Characteristics of Aquaponic Systems.

Aspect	**Expanded Description**
Benefits of Aquaponics	Aquaponics enables highly efficient water use, achieving up to 90% water savings compared to conventional agriculture. It integrates fish and crop production within a single recirculating system, generating diversified income streams. Environmental footprint is reduced through minimized effluent discharge and decreased reliance on synthetic fertilizers. Furthermore, aquaponic systems are adaptable to both urban and rural settings, including small-scale operations and water-scarce regions.
Challenges of Aquaponics	Aquaponic systems require high initial capital investment in infrastructure and technical expertise in aquatic biology and water chemistry. Failure of any system component may compromise overall performance, necessitating continuous monitoring and management. Additional challenges include the selection of compatible fish and plant species, as well as maintaining optimal physicochemical parameters suitable for both organisms.
Examples of Common Species	Fish: Nile tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchus mykiss*), European chub (*Squalius cephalus*).

Source: Ministerio de Agricultura y Desarrollo Rural [2]**.**

6.1.2.3. Improvements in Feeding Practices and Waste Management

Optimizing feeding strategies and waste management is crucial for enhancing sustainability in aquaculture, as it increases production efficiency, reduces operational costs, and minimizes environmental impacts. The use of species-specific formulated feeds designed to meet precise nutritional requirements promotes optimal growth and improved feed conversion ratios (FCR), thereby reducing undigested feed, nutrient excretion, and overall nitrogen (N) and phosphorus (P) loading in the culture water [5, 11, 16, 45, 47, 48].

Automated feeding systems, employing programmable dispensers that deliver feed at precise quantities and scheduled intervals, enhance feeding regularity, optimize FCR, reduce feed wastage, and decrease labor demands [4].

These systems also contribute to more predictable nutrient input rates, facilitating efficient biofiltration and waste management in recirculating aquaculture systems (RAS).

Additionally, the incorporation of functional diets supplemented with additives such as probiotics, prebiotics, and essential oils enhances fish health, immunity, and gut microbiota composition, improving digestibility and survival rates while mitigating nutrient discharge [23, 47].

Such approaches align with circular bioeconomy principles by promoting nutrient recycling and reducing the environmental footprint of aquaculture operations.

6.1.2.4. Alternative Waste Management Methods in Aquaculture

6.1.2.4.1. Mechanical Filtration

This method removes suspended solids, such as uneaten feed and feces, using technologies such as drum filters and sand filters. Drum filters, equipped with a rotating mesh, retain particles as water flows through, while sand filters filter water through granular layers. Countries like Egypt and Germany have led applied research in this area, reporting approximate removal efficiencies for various systems: hydrocyclones (27.4–57.8%), rotary drum filters (15.5–57.7%), and sand and screen filters (up to 71%) [2, 33].

Note: This method primarily targets total suspended solids (TSS) and particulate organic matter (POM), improving water quality and reducing nutrient load in recirculating aquaculture systems (RAS).

6.1.2.4.2. Biofiltration

Biofiltration employs nitrifying bacteria that convert toxic compounds such as ammonia and nitrites into less harmful nitrates. It is implemented using fixed-bed biofilters (rocks or plastic media) or moving-bed biofilters (floating particles). This method improves water quality and protects receiving ecosystems, with removal efficiencies of up to 99% for ammonia and 97% for nitrites. Biofiltration is widely applied in Norway, Denmark, China, and more recently in Chile and Brazil [12, 16, 49].

6.1.2.4.3. Disinfection

Disinfection aims to eliminate pathogens from water using physical technologies (e.g., ultraviolet light, which damages microbial DNA) or chemical methods (e.g., ozone, which oxidizes organic compounds and microorganisms). These methods significantly reduce the risk of diseases in aquaculture systems [5].

6.1.2.5. Use of Renewable Energy

The use of renewable energy sources, such as solar and wind power, is gaining increasing importance in modern aquaculture. These clean energy sources reduce energy consumption in activities such as water pumping and treatment. The installation of solar panels and wind turbines contributes to lowering the carbon footprint of aquaculture operations, enhancing sustainability, and reducing long-term operational costs. To ensure their effectiveness, renewable energy systems must be properly integrated with existing infrastructure and maintained regularly [2, 49, 50].

Table 6.
Summary of Strategies Applicable in Colombia for the Optimization of Fish Farms.

Strategy	Description	Actions	Impact
Improved Feed Management	Optimizing fish feeding to reduce waste, improve feed efficiency, and prevent eutrophication in water bodies.	Diet Formulation: Develop nutritious diets using local ingredients. Feeding Monitoring: Adjust feed rations through simple monitoring based on fish requirements.	Reduces feed costs and minimizes water pollution from excess nutrients.
Efficient Water Management	Implementing practices to conserve and efficiently manage water in fish farms.	Recirculating Systems: Implement basic recirculation. Rainwater Harvesting: Capture rainwater for reuse and to supply fish farm water needs.	Minimizes freshwater consumption and reduces operational costs associated with water supply.
Improved Waste Management	Implementing practices to properly manage waste generated by fish farms.	Use of Sludge as Fertilizer: Treat and use generated sludge as organic fertilizer in nearby agricultural crops. Composting of Waste: Compost leftover feed and other organic waste to reduce environmental contamination.	Improves resource efficiency and reduces negative environmental impact.
Training and Technical Assistance	Providing training and technical support to fish farmers to improve management and production practices.	Training Programs: Organize workshops and informational sessions on sustainable and efficient practices. Local Technical Support: Establish local support networks to share knowledge and address common issues.	Enhances the technical capacity of fish farmers and promotes the adoption of sustainable practices.

Source: FAO [5]; Béné, et al. [8]; Partelow, et al. [24]; El Bilali, et al. [25] and Kamal and Mair [51].

7. Final Analysis

Aquaculture is a high-value economic and social activity, but it faces significant environmental challenges, particularly due to its impact on aquatic ecosystems and competition for water. Its expansion has caused the loss of habitats such as wetlands, mangroves, and riparian areas, affecting biodiversity and ecosystem services. Cases such as the wetlands of Bogotá and the Ciénaga Grande de Santa Marta reflect the effects of poor management, aggravated by exotic species and alterations in water flows.

In basins with limited access to water, such as some in the Cauca region, intensive use of the resource by aquaculture generates tensions with other activities and with the basic needs of local communities. This underscores the urgency of participatory and integrated water governance that respects traditional uses.

In response to these challenges, technologies such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), aquaponics, constructed wetlands, and automated monitoring have been implemented, reducing water consumption and pollution while improving production efficiency.

Colombia, and particularly the Cauca region, can adopt these technologies as part of a sustainable aquaculture strategy, strengthening technical capacities, promoting incentives, and coordinating efforts among communities, academia, and public institutions.

8. Conclusions

In this way, it can be concluded that, according to information obtained through a literature review, the efficient management of water through the implementation of Recirculating Aquaculture Systems (RAS) and the use of alternative sources such as rainwater represents a key strategy to conserve water resources and reduce dependence on external sources, thereby contributing to the environmental sustainability of fish farming operations. Likewise, proper management of waste, such as uneaten feed and excreta, is essential to prevent water pollution and protect aquatic ecosystems.

Aquaculture has established itself as one of the fastest-growing productive activities worldwide; according to [9], more than 50% of the fish consumed by humans comes from farming systems.

In Colombia, this sector has shown sustained growth, driven by food demand, rural development, and the use of continental water resources. However, despite its benefits, such as employment generation, food security, and economic diversification, it also poses environmental challenges, including eutrophication, alteration of natural habitats, and competition for water resources.

Therefore, in the Colombian context, it is a priority to implement sustainable strategies such as the use of clean technologies, water recirculation, selection of adapted species, and comprehensive waste management. These actions not only minimize environmental impact but also improve the long-term profitability and viability of aquaculture as a sustainable activity.

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