

Toward a Model for Characterizing the Aquaculture Sector: Integrating Economic, Environmental, Technological, and Commercial Dimensions in Norte de Santander, Colombia

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ABSTRACT:

The department of Norte de Santander lacks updated studies on the situation of its registered fish-farming units. This work aimed to characterize the departmental fish-farming sector across the economic, environmental, technological, and commercial dimensions, and to identify strategies for improving its development. The study followed a descriptive-analytical mixed-methods approach, combining a systematic literature review with a structured survey administered to 43 production units selected through probabilistic sampling from AUNAP and UMATA records, with data processed using descriptive statistics. The findings reveal consolidated basic financial management practices, alongside deficient production margins and unsatisfactory marketing channels, exposing a disconnect between productive effort and actual profitability. The environmental dimension received the lowest rating, particularly regarding waste utilization and renewable energy adoption, while incremental technological innovation emerged as the most favorably rated aspect. The study also identified a market conversion gap, whereby sustainable production attributes fail to translate into differentiated prices. The degree of associative organization was found to positively influence perceived performance across dimensions. The findings indicate that the sector requires coordinated interventions in infrastructure, financing, certification, and associative strengthening to overcome these structural limitations and secure long-term competitiveness.

Keywords: Fish farming, Species characterization, Aquaculture production, Regional economic development

1. Introduction

The department of Norte de Santander, located in northeastern Colombia, is a territory of marked economic and productive heterogeneity, whose sectoral structure has been transforming in a

sustained manner in response to the dynamics of the national and international market. In this transition scenario, fish farming has acquired increasing relevance as an activity capable of articulating food security, the generation of rural

employment and the diversification of regional income. The recognition of this activity as a vector of territorial development requires, however, rigorous analyses that go beyond mere quantitative description and move towards a comprehensive understanding of its structural dimensions, potentialities, and constraints (Mogrovejo et al., 2019).

In recent decades, continental aquaculture has experienced an unprecedented expansion on a global scale, a phenomenon that in Colombia has resulted in the progressive strengthening of fish farming as a strategic subsector. Norte de Santander has not been immune to this trend: the sustained increase in demand for protein of aquatic origin both in the domestic market and in export circuits has stimulated private investment and has motivated the formulation of public policies aimed at consolidating the sector's production chain. In particular, government promotion instruments have favoured the technification of production units and the expansion of the territorial coverage of fish farming activity (Araujo et al., 2022).

However, the growth of the sector has not been without tensions. The asymmetries in access to technology, financing and logistics infrastructure, added to the limitations in the transfer of technical knowledge to smaller-scale producers, make up a complex panorama that demands specific analytical attention.

In this sense, understanding the current structure of the fish farming sector in Norte de Santander implies identifying not only the distribution and magnitude of the productive units, but also the factors that condition their performance and their prospects for consolidation in the medium and long term.

Under this premise, this article develops a systematic analysis of the departmental fish farming sector, based on a methodological strategy that integrates the critical review of specialized literature with the processing and

analysis of primary information. The geospatial and socioeconomic characterization of the fish farming units reveals patterns of territorial concentration, identifies development gaps, and recognizes the enabling conditions that have favored or limited the progress of the activity in different subregions of the department.

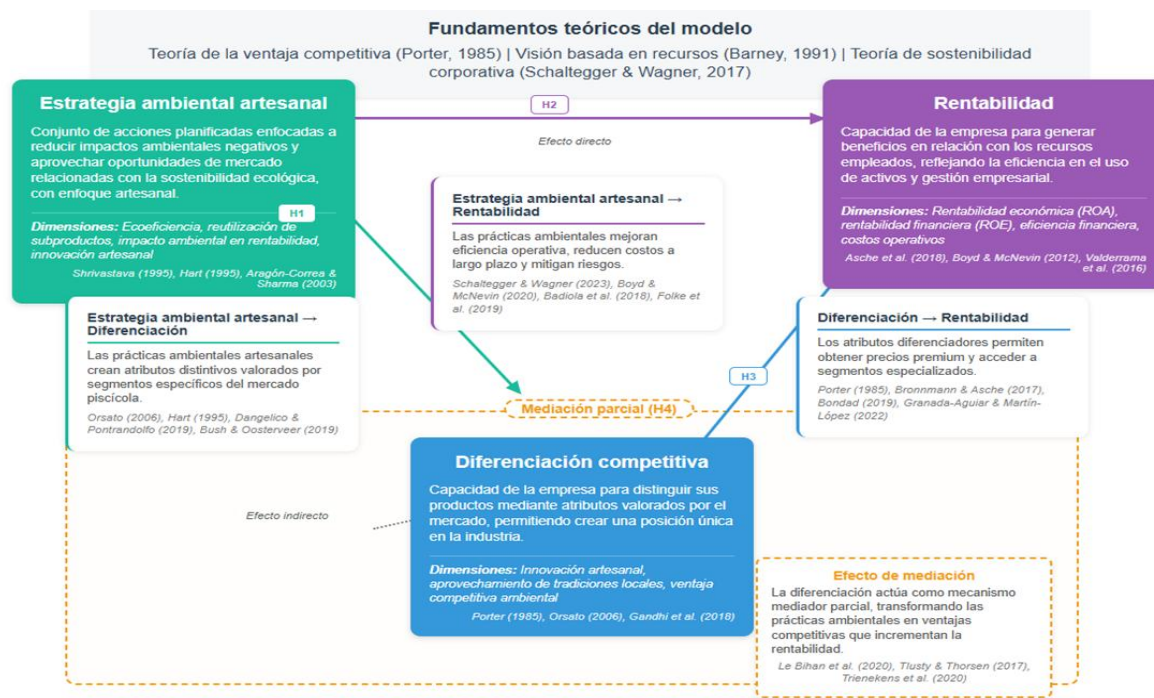
The results of this research exercise are aimed at offering concrete inputs for decision-making in the areas of sectoral policy, regional development planning and formulation of business strategies. It is expected that the evidence generated will contribute to the design of differentiated interventions that enhance the productive capacities of the sector, strengthen its articulation with other links in the food chain and promote conditions of sustainable economic development for communities linked to fish farming in Norte de Santander.

From the perspective of competitive advantage theory (Porter, 1985), resource-based vision (Barney, 1991), and corporate sustainability theory (Schaltegger and Wagner, 2017), environmental strategies can be a source of competitive advantage and improved business outcomes. In the context of fish farming, the adoption of artisanal environmental practices not only contributes to the reduction of ecological impacts, but can also promote the differentiation of establishments through attributes valued by the market.

Based on these approaches, a theoretical model is proposed that explains the relationship between the artisanal environmental strategy and the profitability of fish farming establishments in Norte de Santander, considering the mediating role of competitive differentiation.

The model states that environmental practices generate direct effects on profitability and, additionally, contribute to the creation of differentiating competitive advantages that strengthen the economic performance of productive units.

Figure 1 : Proposed theoretical model



Note: Authors' elaboration, referring to the theory of competitive advantage (Porter, 1985), resources and capabilities theory (Barney, 1991) Corporate sustainability theory (Schaltegger & Wagner, 2017)

Subsequently:

Based on the proposed model, the following hypotheses are formulated:

H1: The implementation of artisanal environmental strategies has a direct positive effect on the profitability of fish farming establishments.

H2: The implementation of artisanal environmental strategies positively influences the competitive differentiation of fish farming establishments.

H3: Competitive differentiation has a positive effect on the profitability of fish farms.

H4: Competitive differentiation partially mediates the relationship between artisanal environmental strategies and profitability.

2. Methodology

The study adopted a mixed approach of descriptive-analytical scope, integrating quantitative and qualitative methods to characterize the fish farming sector in the department of Norte de Santander (Creswell &

Creswell, 2018). The collection of information was structured in three complementary phases.

In the first phase, a systematic literature review was carried out in indexed databases Scopus, Redalyc and Google Scholar, as well as in technical publications of the FAO, AUNAP and the Ministry of Agriculture and Rural Development (MADR), prioritizing studies from the last ten years with direct empirical contributions to the subject.

In the second phase, a structured survey was applied to active fish farmers in the department, selected through simple random probability sampling from the records of AUNAP and the Municipal Units of Agricultural Technical Assistance (UMATA) and belonging to associative organizations of reference in the region. The instrument explored dimensions of the productive profile, economic conditions, access to support services, and perception of opportunities and limitations. The data were processed using descriptive statistics and represented through distribution tables.

3. Study variables

3.1. Fish farming in Colombia and Norte de Santander

The Colombian fish farming sector has progressively evolved from artisanal production practices to an activity of strategic relevance for the national economy, with tangible impacts on food security, employment in rural areas and the diversification of regional production structures. The hydrobiological wealth of the country, combined with the plurality of available farming systems, has allowed Colombia to position itself as one of the most dynamic actors in continental aquaculture in the Latin American context, contributing both to the growth of the Gross Domestic Product (GDP) and to the supply of quality animal protein for the population (Barragán et al., 2022; Rodríguez & Ruiz, 2021).

The structural relevance of the sector is confirmed by the most recent statistical evidence. According to the National Administrative Department of Statistics (DANE), fisheries and aquaculture registered an expansion of 18.2% during the first quarter of 2025 compared to the same period of the previous year, surpassing the performance of other agricultural activities such as forestry (11.4%), livestock (8.9%) and agricultural crops (2.4%), which positions the sector as the fastest growing within the national agricultural group (National Agricultural Authority of Aquaculture and Fisheries [AUNAP], 2025). This result is due, among other factors, to the sustained increase in the demand for fishery products in internal and external trade circuits, as well as to the implementation of public policy instruments aimed at strengthening the productive capacities of fishermen and aquaculturists, promoting their linkage to value chains and moving towards environmentally sustainable production schemes (AUNAP, 2025).

However, the sector's upward trajectory coexists with structural constraints that condition its competitiveness. Environmental and health constraints, barriers to access to credit, and fragmentation of marketing channels are recurrent obstacles, particularly for smaller-scale

producers. Despite this, the opening of new international markets, the gradual incorporation of more efficient production technologies, and the strengthening of the sector's regulatory framework are conducive to its future consolidation (Cardozo et al., 2022).

At the departmental level, Norte de Santander expresses these national dynamics with its own specificities associated with its territorial configuration, its water endowment and its socio-productive conditions. Fish farming has emerged in this department as a viable alternative for the generation of rural income and the rational use of available natural resources; however, there are still gaps in technification, financing and institutional support that demand rigorous territorial studies capable of guiding differentiated and relevant interventions.

3.2. Types of crops

In Colombia, geographic and climatic diversity has favored the cultivation of a wide variety of fish species, both freshwater and marine, which has contributed to the expansion and diversification of fish farming in the country. Among the most cultivated species are:

Tilapia: Tilapia is one of the most popular species in Colombian fish farming due to its high tolerance to different water conditions and its rapid growth. This species, native to Africa, adapts easily to pond and cage culture systems, making it an attractive option for producers (Debnath et al., 2023).

Trout: Trout is another widely farmed species in Colombia, especially in cold, mountainous climate regions such as the Andes mountain range. Its high-quality meat and its demand in the national and international market make it a profitable option for fish producers (Flórez and Roldán, 2021).

Cachama: Cachama is a species native to South America and one of the main farming options in Colombia. Known for its tasty meat and resistance to adverse conditions, cachama is grown in ponds and water recirculation systems in various regions of the country (Parés et al., 2023).

Bocachico: The bocachico is a freshwater fish that is highly appreciated in Colombian cuisine. Although its cultivation in commercial fish farming is still limited, efforts are being made to develop production techniques that allow its breeding in captivity in a sustainable way (Rojas et al., 2023).

Shrimp and Shrimp: In addition to freshwater species, Colombia also farms shrimp and shrimp in marine aquaculture systems, especially on the Caribbean and Pacific coasts. These species are in high demand in the international market and offer business opportunities for coastal producers (Stieglitz et al., 2023).

Producing regions

The main fish farming producing regions in Colombia are distributed throughout the country, each with geographical and climatic characteristics that influence the type of crops and production systems that predominate. Here are some of these regions:

Antioquia: Located in the northwestern region of Colombia, Antioquia is one of the main tilapia and trout producing areas in the country. Its many rivers and reservoirs offer ideal conditions for the cultivation of freshwater fish, and fish farming has become an important activity for the local economy (Valencia, 2020).

Valle del Cauca: This region, located in the western part of Colombia and crossed by the Cauca River, is known for its tilapia and shrimp production. Producers in Valle del Cauca have implemented advanced production technologies and intensive farming systems, which has allowed a significant increase in aquaculture production in recent years (Losada et al., 2021).

Huila: The department of Huila, in southwestern Colombia, is recognized for its production of rainbow trout in cold-water farming systems, taking advantage of its temperate climatic conditions and crystal clear water sources. The trout farmed in Huila stands out for its quality and flavor, being appreciated both in the national and international markets (Tobes et al., 2016).

Santander: In the department of Santander, located in the northeastern region of Colombia, fish farming focuses on the production of trout and tilapia. Its rivers and reservoirs provide a suitable habitat for freshwater fish farming, and fish farming contributes significantly to the local and regional economy (Durán et al., 2022).

Norte de Santander: Fish farming in Norte de Santander, Colombia, has experienced notable growth, highlighting the breeding of species such as tilapia, rainbow trout and cachama. It is developed in commercial aquaculture farms and small production units, supplying both the local market and exploring export opportunities. Although it faces challenges such as lack of infrastructure and access to credit, its growth potential is supported by investments in technology and training, offering employment and contributing to food security and regional economic development (Castellanos et al., 2023).

These producing regions represent only a part of the diverse and dynamic landscape of fish farming in Colombia. Each of them has its own characteristics and challenges, but they all contribute to the development of a solid and sustainable aquaculture industry in the country (García et al., 2019).

3.3. Economic importance

Fish farming plays a significant role in the Colombian economy, generating income and employment in different regions of the country. This activity not only boosts the local economy through the production and sale of fish, but also promotes the development of associated value chains, such as the commercialization of aquaculture inputs, production equipment, transportation, and processing of fish products (Muñiz et al., 2023).

In addition to its direct economic impact, fish farming makes an important contribution to the country's food security. Fish production provides a sustainable source of high-quality protein, which complements the diet of the population and contributes to meeting the nutritional needs of local communities. This is especially relevant in rural areas and remote areas where access to

other protein sources may be limited (Adah et al., 2022).

Fish farming also has the potential to improve food security at the national level by reducing dependence on fish and seafood imports. By increasing domestic fish production, Colombia can diversify its food base and reduce vulnerability to fluctuations in international prices of fishery products (Araujo et al., 2022).

In addition, sustainable fish farming can have environmental benefits by contributing to the conservation of native species, the restoration of aquatic ecosystems, and the reduction of pressure on wild fish populations. By adopting responsible and environmentally friendly production practices, producers can contribute to the conservation of biodiversity and the health of aquatic ecosystems in Colombia (Alleway et al., 2023).

On the other hand, fish farming in Norte de Santander plays a fundamental role in the regional economy, with significant impacts on several socioeconomic and environmental aspects. Firstly, this activity generates direct and indirect employment throughout the value chain, from production on aquaculture farms to the distribution and marketing of fish products. This employment not only benefits local producers, but also boosts the economy by increasing consumption and commercial activity in the region (Araujo et al., 2022).

In addition to employment, fish farming offers income opportunities for local producers, which can come from both selling on the local market and exporting to international markets. This diversification of income sources is crucial for the region's economic resilience, especially in rural areas where employment options are often limited (Adah et al., 2022).

In terms of environmental impact, well-managed fish farming can be a sustainable alternative for food production. By harnessing renewable natural resources such as water, and by adopting responsible farming practices, fish farming can contribute to food security without depleting

natural resources or degrading the environment (Kotta et al., 2023).

3.4. Challenges and opportunities

The sustained growth of Colombian fish farming has not been accompanied by a proportional resolution of the structural tensions that condition its competitiveness. Technical, environmental, and institutional constraints configure a complex scenario that demands responses articulated from multiple dimensions of sectoral policy and territorial management (Triana, 2023).

One of the most recurrent limitations identified in the literature is the insufficient incorporation of technology in production processes. The modernization of fish farming units through real-time monitoring tools, automated feeding systems and sanitary management protocols represents a necessary condition to increase productivity and reduce the environmental footprint of the sector; however, persistent gaps in access to specialized technical training and adequate financing schemes continue to hinder this technological transition in large areas of the country (Cheruiyot and Adhiaya, 2023). In this sense, the main challenges of the Colombian fish farming guild are currently concentrated in the areas of health, the adoption of new technologies, environmental sustainability, international certifications and, as a priority, the formalization of production (Colombian Federation of Aquaculturists [FEDEACUA], 2025).

Water resource management is another critical axis for the long-term viability of the sector. Rigorous control of physicochemical parameters such as pH, concentration of ammonia, nitrites and nitrates is decisive to guarantee adequate cultivation conditions, reduce health risks and optimize the feed conversion of the species produced (Khanjani et al., 2023). Faced with this challenge, technological advances in continuous monitoring of water quality have made it possible to record essential variables such as dissolved oxygen and temperature in real time, which enables immediate adjustments in the management of production systems and contributes to reducing losses associated with

adverse environmental conditions (MBR Ingredients, 2025). This problem is especially relevant in Norte de Santander, where fish farming competes for water resources with larger-scale agricultural and industrial sectors, and where the accumulation of organic waste represents specific risks to the environmental quality of the territory (Cardozo et al., 2022).

In regulatory and institutional matters, the sector is going through a significant transition moment in 2026. The adoption of the Aquaculture Productive Management Plan (POP) by the Rural Agricultural Planning Unit (UPRA), articulated with AUNAP, provides the sector for the first time with an evidence-based technical framework that establishes guidelines for production, management, zoning and sustainability; however, priority gaps persist in biosafety, traceability, and regulatory compliance that limit access to international markets with increasingly stringent health requirements (TSI Group, 2026).

The climate dimension adds an additional layer of complexity to the sectoral landscape. Growing environmental variability demands the incorporation of adaptation strategies in production systems, among which the implementation of recirculating aquaculture systems (RAS) and precision aquaculture stand out for their ability to reduce dependence on external conditions and strengthen productive resilience to increasingly unstable climate scenarios (AllAquaculture, 2026). Strengthening applied research in animal genetics, nutrition and health is also essential to provide the sector with tools to respond to these emerging challenges (Glencross et al., 2020).

In the face of this set of constraints, the opportunities for development are equally significant. Colombia was the first country to gain recognition for tilapia under the Global Aquaculture Alliance's Best Aquaculture Practices (BAP) certification program, and the domestic aquaculture market is projected to register a CAGR growth rate of 5.70% between 2026 and 2035, driven by the adoption of more efficient production technologies. the advancement of sustainable practices and

innovations in the breeding of species of high commercial value (Expert Market Research, 2026). Taking advantage of this potential in Norte de Santander requires comprehensive strategies that articulate investment in productive infrastructure, equitable access to credit, continuous technical support for producers, and effective environmental regulation (Mogrovejo et al., 2019; Aguilar et al., 2021).

3.5. Sustainability and the environment

Concern about the environmental impact of fish farming has led to a growing interest in implementing more sustainable practices in the Colombian aquaculture industry. Authors such as Laktuka et al. (2023) have highlighted the importance of addressing the environmental challenges associated with fish farming, such as water pollution, habitat degradation, and biodiversity loss.

One of the main aspects of sustainability in fish farming is the proper management of the waste generated during production. According to studies such as that of Alvarado et al. (2023), organic and chemical waste produced by fish farming operations can have negative impacts on water quality and surrounding aquatic ecosystems. Therefore, it is crucial to implement waste management practices that minimize its environmental impact and promote the recovery of nutrients for reuse.

In this sense, organic farming has become an increasingly popular option among fish farmers looking to reduce their environmental footprint. Authors such as Elvines et al. (2024) have highlighted the environmental benefits of organic farming, which include reducing the use of synthetic chemicals, conserving biodiversity, and improving water quality.

In addition to waste management, the sustainable use of water resources is another crucial aspect of sustainable fish farming. Since water is a limited resource in many regions of Colombia, it is critical to adopt technologies and practices that maximize efficiency in its use. In this sense, water recirculation systems have gained popularity as a way to reduce freshwater consumption and

minimize the discharge of contaminated effluents into the environment (Sampathkumar et al., 2023).

4. Growth of the sector in Norte de Santander

The Colombian fish farming sector has consolidated a trajectory of sustained expansion in recent decades, a phenomenon that results from the convergence of multiple structural and conjunctural factors. This dynamic has been the subject of study by national and international researchers, who have rigorously analyzed the variables that explain this trend, and whose validity is confirmed in the most recent figures of the sector.

One of the main drivers of this process has been the strengthening of domestic demand. Transformations in the food consumption patterns of the Colombian population, accompanied by greater purchasing power, have led to a progressive increase in the consumption of aquatic protein (Mialon et al., 2020). Per capita consumption of fish in Colombia currently stands at 9.6 kg per person per year, with aquaculture contributing around 200,000 tonnes per year to supply this demand (Sectorial, 2024). However, the Colombian Federation of Aquaculturists points out that this indicator is still the lowest among animal proteins, which represents a strategic opportunity to increase national production and encourage domestic consumption (Fedeaqua, 2025). Accordingly, the National Aquaculture and Fisheries Authority reported that the fisheries and aquaculture sector grew by 18.2% in the first quarter of 2025 compared to the same period of the previous year, positioning itself as the most dynamic activity within the national agricultural set, above forestry (11.4%), livestock (8.9%) and agricultural crops (2.4%) (Presidency of the Republic of Colombia, 2025).

In terms of external markets, the expansion of fish exports has been another fundamental pillar of sectoral growth. Although authors such as Muñiz et al. (2022) had already documented progress in access to new commercial destinations, the most recent figures show an

unprecedented quantitative leap. During the first half of 2025, Colombia exported about 29.5 million kilograms of fish for consumption worth US\$200 million, which represented a growth of 52.45% compared to the same period in 2024 (AUNAP, 2025b). Tilapia consolidated its position as the leading export species with 17.1 million kilograms and a value of US\$134.9 million, followed by canned tuna, trout and farmed shrimp, species that also registered favorable performances in international markets (AUNAP, 2025b). This behavior reaffirms Colombia's position as a competitive and reliable supplier at the global level (Muñiz et al., 2022).

The incorporation of new technologies in production processes has also been decisive. Researchers such as Pandey et al. (2023) had previously pointed to the adoption of intensive farming systems, water recirculation, and genetic improvement as factors of competitiveness. This trend has deepened in the most recent period, with the incorporation of automation and data analysis technologies. Biofloc technology, articulated with artificial intelligence systems and the Internet of Things, has emerged as one of the most relevant innovations for precision aquaculture, allowing water consumption to be reduced by up to 90% and feed costs by 30%, while optimizing the feed conversion ratio (AquaHoy, 2026). On a national scale, recent research has explored the automation of fish farming systems through programmable logic controllers that regulate oxygenation and water recirculation in real time, contributing to the energy and operational efficiency of production units (León Ruiz et al., 2025).

Finally, the diversification of cultivated species and the commitment to applied research have been key elements in guaranteeing the sustainability of sectoral growth. Beyond what was pointed out by Bunting et al. (2023), national aquaculture production reached 215,090 tons in 2023, with fish farming as the main contributor with 209,976 tons; tilapia led with 121,786 tons, followed by cachama with 39,895 tons and trout with 33,596 tons (Universidad de La Salle, 2024). Likewise, with the adoption of the Aquaculture Productive Management Plan by the Rural

Agricultural Planning Unit, the sector has since 2023 a technical framework that establishes production, zoning and sustainability guidelines based on scientific evidence, guiding research and

development towards priority gaps such as biosecurity, traceability and regulatory compliance for access to more demanding international markets (TSI Group, 2026).

Table 1 : Fish farming industry in Colombia

Concept	Data
Fish production in 2025	240,163 tons
Most cultivated species	Tilapia (58%), Cachama (17%), Trout (15%)
Main producer	Huila (37% of national production)
Tilapia Exports (2025)	16,877 tons (~US\$104.2 million)
Trout Exports (2025)	1,376 tons (~US\$12 million)
GDP growth fisheries and aquaculture (2025)	11,2%

Note: The export data for tilapia and trout for 2025 correspond to projected annual figures based on the trend of the first half of the year reported by AUNAP (2025b) and the official figures of the Ministry of Agriculture, given that the definitive end of the year is still in the process of institutional consolidation.

The consolidated data in Table 1 reveal a Colombian fish farming industry in clear expansion, whose recent performance shows the cumulative result of policies of promotion, productive technification and trade liberalization sustained over the last decade. In terms of total production, the sector recorded 240,163 tonnes in 2025, which represents a significant increase compared to the 210,516 tonnes reached in 2024, equivalent to an approximate growth of 14% in a single year (Ministry of Agriculture and Rural Development, 2026). This result positions Colombia among the benchmarks of Latin American aquaculture and confirms the structural growth trend of 6% average annual growth documented by the Rural Agricultural Planning Unit over the last decade (UPRA, 2025).

Regarding the composition by species, the national production structure shows a marked concentration around three main species. Tilapia leads with a share of 58% of the total produced, consolidating itself as the backbone of Colombian aquaculture thanks to its high

adaptability, sustained domestic demand and competitiveness in foreign markets. It is followed by cachama with 17% and trout with 15%, species that have progressively expanded their relevance both in the domestic market and in export chains (ICEX, 2026). This distribution reflects not only consumer preferences, but also the ecosystem conditions and differentiated investment in each production chain.

In terms of territorial concentration of production, the department of Huila maintains its historical leadership by concentrating 37% of national production with 87,864 tons in 2025, well above Meta (11%), Tolima (8%), Córdoba (6%) and Casanare (6%) (Ministry of Agriculture and Rural Development, 2026). This regional hegemony responds to the conjunction of favorable water conditions, the early adoption of technified systems such as integrated recirculating production systems (IPRS) and the consolidation of an internationally certified export chain, with 38 farms under the BAP standard and 6 under the ASC standard (Gobernación del Huila, 2025).

The export performance reinforces the positive reading of the sector. During 2025, tilapia exports grew by 22% in volume compared to 2024, reaching around 16,877 tons with an estimated value of US\$104.2 million, of which more than 90% were contributed by Huila (Ministry of

Agriculture and Rural Development, 2026). Trout, on the other hand, registered a more moderate growth of 2% in volume with approximately 1,376 tons and about US\$12 million in foreign currency. These results are part of the country's global export trend, which during the first half of 2025 registered a growth of 52.45% compared to the same period in 2024, consolidating Colombia as a reliable and competitive supplier in markets such as the United States and Asia (AUNAP, 2025b).

Finally, the GDP growth of the fisheries and aquaculture sector of 11.2% in 2025 is perhaps the most eloquent indicator of sectoral dynamism, far surpassing the performance of other agricultural activities such as livestock (8.9%) and agricultural crops (2.4%) (Presidency of the Republic of Colombia, 2025). This behavior not only reflects the increase in the volumes produced, but also the greater operational efficiency derived from technification, the progressive formalization of producers and the strengthening of value chains, factors that together make up a sector with solid foundations to sustain its growth in the medium term.

5. Fish production and marketing

Fish production and marketing comprises an articulated set of activities that ranges from the cultivation and breeding of aquatic organisms under controlled conditions to their transformation, distribution and positioning in local, national and international markets. This network of processes has become increasingly relevant in the context of global food security, as aquaculture has come to represent more than 50% of the total production of aquatic animals for human consumption, having exceeded the volume of wild extractive fishing for the first time in 2022 with 94.4 million tonnes compared to 91 million (Business Research Insights, 2025). This historic milestone reaffirms the structural role of aquaculture activity as the central axis of protein supply on a planetary scale (Chiquito et al., 2022).

In the field of production systems, the specialized literature distinguishes three main technological modalities: extensive, semi-intensive and

intensive, the adoption of which directly determines the levels of productivity, the degree of environmental control and the impact on the surrounding ecosystems (Khanal and Thapa, 2023). While extensive systems are characterized by low planting densities, dependence on natural food supply and reduced yields ranging between 50 and 300 kg/ha/year, intensive systems operate in environments of greater technological control with high densities and rigorous management of production parameters. In the current context, the global trend points towards the integration of automation, artificial intelligence and connectivity technologies in cultivation processes, with the aim of optimizing the use of resources, reducing losses and improving product traceability throughout the chain (Mordor Intelligence, 2026).

The commercial dimension of the sector exhibits, for its part, a dynamic of sustained expansion. The global aquaculture market is estimated to be worth \$42.09 billion by 2026, with growth projected to reach \$93.07 billion by 2035, driven by innovation in compound feeds, the incorporation of alternative protein sources, and the increasing export orientation of producers (Business Research Insights, 2026). However, this growth faces headwinds from persistent inflation, the readjustment of global tariff policies, and competitive pressure on smallholders, who are compelled to consolidate or establish contractual alliances to remain in place in supply chains that are increasingly demanding in terms of quality, traceability, and certification (Food and Agriculture Organization of the United Nations [FAO], 2025; Mordor Intelligence, 2026).

In terms of processing and the value chain, vertical integration emerges as a decisive strategy to improve the competitiveness of the sector's players. This approach allows companies to optimize their operations, reduce costs, maintain product traceability, and exert greater control over its quality from primary production to final sale (Business Research Insights, 2025). In international markets, certifications of good aquaculture practices and verifiable labelling of origin and production method are no longer

differentiating factors but entry requirements for higher-value trade circuits (Kolonchin and Cherdantsev, 2023; TSI Group, 2026). This reality poses particular challenges for smaller-scale producers, who must strengthen their organizational and technical capacities to respond to the growing demands of international buyers and premium distribution chains.

6. Gaps related to technological, productive, environmental and social capacities

The consolidation of the fish farming sector as a sustainable and competitive economic activity is conditioned by a set of structural gaps that affect the different actors in the production chain in a differentiated way. These disparities operate in an interrelated manner and demand comprehensive responses that transcend fragmented sectoral interventions.

On the technological level, inequality in access to modern cultivation, processing, and conservation tools continues to be one of the factors that most limit the productivity and competitiveness of producers, particularly in rural communities with less infrastructure (Laktuka et al., 2023). This situation is aggravated by the persistence of obsolete or technologically lagging equipment in a significant percentage of small and medium-scale production units worldwide, which are incompatible with modern data acquisition and management tools (Global Growth Insights, 2025). At the same time, the weak articulation between national agricultural innovation systems and actors in the fish farming sector has perpetuated the use of production methods with high consumption of water and energy resources, and poor management of the waste generated (Ainsworth et al., 2023). Against this backdrop, precision aquaculture and recirculating aquaculture systems (RAS) have demonstrated the ability to improve productivity by more than 60% and reduce feed waste by half, demonstrating the transformative potential of technification when accompanied by adequate transfer and appropriation processes (Global Growth Insights, 2025).

Productive gaps, on the other hand, express the existing asymmetries between production units of different scales. Differences in yield levels between small and large producers are due to inequalities in access to quality inputs, specialized technical knowledge, and economies of scale that only larger operators can take advantage of (Boye et al., 2022). Added to these internal constraints are deficiencies in logistics infrastructure for transport and distribution, which increase operating costs, generate post-harvest losses, and reduce the ability of producers to access larger and better-paid markets (Spasojević-Brkić et al., 2019). In the Colombian context, these gaps are particularly relevant given that, by 2026, compliance with regulatory requirements in terms of traceability, biosafety and international certification has become a basic technical requirement to access export markets, a condition that most small producers are not yet able to meet (TSI Group, 2026).

In the environmental dimension, the unplanned expansion of fish farming activity has led to negative impacts on water ecosystems, including nutrient pollution and eutrophication from uneaten food and organic waste, the escape of farmed species with possible genetic effects on wild populations, and the alteration of natural habitats (Jiang et al., 2022; Fish Farm Feeder, 2025). The insufficient adoption of responsible aquaculture practices reflects both the absence of adequate incentives and limitations in access to specialized technical assistance (Md Noor and Harun, 2022). However, advances in production systems such as aquaponics, biofloc culture (BFT) and integrated multi-traffic systems (IMTA) have shown that it is possible to significantly reduce polluting effluents, recycle nutrients and improve local biodiversity, reframing aquaculture as an activity compatible with environmental conservation when properly managed (MBR Ingredients, 2025; Venezuelan Aquaculture Society, 2025).

Finally, social gaps express the inequities that persist within the sector in terms of participation and distribution of benefits. Public policies aimed at promoting aquaculture have tended to be designed from a predominantly productive logic,

without explicitly incorporating the sociocultural conditions or differentiated trajectories of rural territories, which has perpetuated structural barriers to access for small producers, rural women, and ethnic communities (Universidad de Concepción, 2025). Overcoming these disparities requires a comprehensive approach that combines investment in applied research, relevant technology transfer, strengthening local capacities, widespread adoption of good productive practices, and public policy frameworks that guarantee the effective inclusion of all actors in the chain, from primary producers to final consumers and the communities that inhabit the territories where the activity is carried out (Mogrovejo et al., 2019; Glencross et al., 2020).

7. Results

7.1. Characterization of the Experimental Productive Units in Norte de Santander

Within the framework of the Special Cooperation Agreement No. 00127 of 2021, signed between the Government of Norte de Santander, the Francisco de Paula Santander Ocaña Sectional University (UFPSO) and the University of Cartagena, three experimental continental aquaculture production units were established in the municipalities of El Zulia, Puerto Santander and Chinácota. These facilities operated as participatory research scenarios aimed at evaluating the zootechnical performance of native freshwater species introduced under controlled management conditions (Guevara et al., 2024).

The productive infrastructure of each unit was configured by means of geomembrane ponds, with stocking densities of 35 individuals·m⁻³ for red mojarra (*Oreochromis* spp.) and 15 individuals·m⁻³ for bocachico del Catatumbo (*Prochilodus reticulatus*). The total volume of sowing per farm amounted to 32,500 red mojarra fingerlings and 10,800 bocachico fingerlings. In order to establish systematic comparisons between production modalities, three experimental treatments were implemented: (a) monoculture in a biofloc system with a balanced

feed, (b) a polyculture in a biofloc system with a balanced diet, and (c) a monoculture in a traditional system with a balanced diet. This configuration made it possible to evaluate the effect of the production system on growth, feed efficiency, and mortality variables in both species (Guevara et al., 2024).

7.1.1. Physicochemical Parameters of Water

The systematic monitoring of the physicochemical parameters of the water throughout the production cycle evidenced interfarm variations with direct implications on the biological performance of the cultivated organisms. The El Zulia farm recorded an average dissolved oxygen concentration of 4.78 mg·L⁻¹ and an average temperature of 28.6 °C. At the Puerto Santander farm, the corresponding values were 6.13 mg·L⁻¹ and 30.2 °C, respectively. The Chinácota farm presented the most favorable conditions in terms of oxygenation, with an average of 7.12 mg·L⁻¹, and the lowest average temperature of the set, equivalent to 27.0 °C (Table 1).

These differences acquire physiological relevance considering that the red mojarra is a poikilothermal species whose metabolism, growth rate and immunological integrity depend on specific thermal ranges. According to Hernández et al. (2023), the optimal expression of these functions occurs between 27 and 31 °C; dietary intake ceases below 15 °C, and values below 12 °C compromise the viability of individuals. Consequently, the thermal conditions recorded in Chinácota, although within the acceptable range, constituted the limiting factor with the greatest impact on the productivity of that unit, as evidenced in the subsequent biometric records.

7.1.2. Weight Growth and Gain

Red Mojarra (Oreochromis spp.)

Biometric sampling carried out on 10% of the population with a periodicity of 21 days revealed differences in the weight performance of red mojarra both between farms and between treatments. At the end of the fattening period

(October 30, 2024), the Puerto Santander farm recorded the widest average weight range, with values ranging from 295 g to 510 g depending on the cultivation system, with monoculture in biofloc being the treatment with the highest yield. The El Zulia farm showed intermediate results, with weights ranging from 336 g in biofloc polyculture to 478 g in biofloc monoculture, values that exceeded the growth projections established by commercial suppliers for the same feeding period. The Chinácota farm presented the lowest weight records of the experimental set, with a range of 213 g to 299 g, a condition attributed to the restriction that water temperatures exerted on metabolic efficiency and feed utilization by the organisms.

7.1.3. Bocachico del Catatumbo (*Prochilodus reticulatus*)

In the case of bocachico, the Chinácota farm reported the highest individual weight at the end of the cycle, with a maximum of 221 g in biofloc monoculture, followed by the El Zulia farm with 181 g and the Puerto Santander farm with a maximum value of 174 g. Cross-sectional to the three units, treatments with the biofloc system exhibited a dynamic of compensatory weight gain in the phases after episodes of food restriction, suggesting that this system sustained the somatic development of organisms even under conditions of temporary undernourishment (Guevara et al., 2024).

7.1.4. Mortality and Aquaculture Health

The mortality dynamics recorded during the production cycle followed a differentiated temporal pattern, with the most critical rates concentrated in the initial months. During July 2024, total mortality reached its maximum value of the cycle, with a rate of 15.3%, as a result of the convergence of multiple factors: metabolic stress derived from the temporary suspension of the feed concentrated in biofloc treatments, instability in the physicochemical parameters of the water, particularly increases in the concentration of ammonia and abrupt thermal fluctuations, and the entry of fingerlings with pre-existing health compromise. In August 2024, microbiological analyses identified the presence

of gram-positive and gram-negative pathogenic bacteria, specifically *Aeromonas* spp. and *Streptococcus* spp., whose proliferation deteriorated water quality and weakened the immune response of fish, favoring the appearance of secondary infections. The therapeutic intervention with florfenicol, a broad-spectrum antibiotic administered in the concentrated feed using olive oil as an adherent agent, was effective in controlling bacterial outbreaks and promoting a progressive reduction in mortality.

As of September 2024, all three farms exhibited a sustained downward trend in mortality rates. The farms of El Zulia, Puerto Santander and Chinácota registered values of 2.2%, 2.1% and 2.3%, respectively, constituting this month the period of lowest incidence of the cycle. In October, the El Zulia farm consolidated the lowest rate with 0.3%, while Puerto Santander and Chinácota reported 2.5% and 1.5%, respectively. Microbiological analyses carried out in the biology laboratory of UFPSO confirmed the presence of *Aeromonas* spp., *Salmonella* spp., *Escherichia coli*, total coliforms and *Staphylococcus* spp. in gill, fin, stomach and liver tissues of the sampled individuals, with a differential bacterial distribution depending on the farm and the tissue of origin (Guevara et al., 2024).

7.2. Characterization of the productive units of Norte de Santander

The application of the characterization instrument called for the participation of 43 representatives of fish farming units in the department of Norte de Santander, belonging to associative organizations of reference in the region: the Association of Fish Farmers of the Municipality of Tarra (ASOPISTAR), with 52 active productive units in El Tarra (n = 12 respondents), and the Association of Fish Farmers of Teorama (ASOPISTEO). made up of 22 units in Teorama (n = 17 respondents). The remaining 14 participants corresponded to units from municipalities such as El Zulia, Mutiscua, San Cayetano and Cúcuta, included in the collection campaign. Regarding the profile of the

respondents, the most frequently declared functions were those of partner or associate ($n = 9$), owner ($n = 5$), manager ($n = 4$) and legal representative ($n = 2$), among others, which

indicates that the sample predominantly attracted people with direct decision-making power over the management of the productive units.

7.2.1. Economic Performance

Table 2 : Distribution of frequencies and averages by item — Economic performance dimension ($n = 43$)

Item	Statement	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)
Q1	Return on Assets Meets Expectations	9,3	9,3	30,2	20,9	30,2
Q2	Regular review of asset returns	4,7	16,3	18,6	20,9	39,5
Q3	Investment generating good returns	4,7	7,0	32,6	23,3	32,6
Q4	Improved Gains on Equity (ROE)	4,7	18,6	30,2	18,6	27,9
Q5	Profits proportional to total sales	9,3	2,3	25,6	32,6	30,2
Q6	Acceptable gross production margin	4,7	20,9	41,9	20,9	11,6
Q7	Cash flow control and monitoring	4,7	4,7	20,9	37,2	32,6
Q8	Sufficient liquidity for day-to-day trading	4,7	20,9	20,9	30,2	23,3
Q9	Competitive production costs in the market	7,0	25,6	20,9	23,3	23,3
Q10	Reducing costs without compromising quality	9,3	16,3	18,6	27,9	27,9
Q11	Sales prices cover costs with margin	11,6	14,0	25,6	32,6	16,3
Q12	Satisfaction with sales channels	16,3	9,3	25,6	27,9	20,9

Note. The scale ranges from 1 (strongly disagree/never) to 5 (strongly agree/always). M = arithmetic mean. Percentages may not add up to 100% by rounding. ROE = return on equity.

The results corresponding to the economic performance dimension revealed an overall average rating of $M = 3.50$, which places all the surveyed units at a moderately favourable level of perception with respect to their financial and productive situation. However, this average masks considerable internal heterogeneity, both between items and between organizations, which deserves a disaggregated analysis.

The item with the highest score in the entire dimension was the one referring to the control and monitoring of cash flow (Q7; $M = 3.88$),

where 69.8% of the participants gave ratings of 4 or 5. This finding suggests that cash movement management is a relatively well-established practice in the surveyed units, possibly because it is an immediate operational need that does not require sophisticated accounting infrastructure. In a close position were the regular review of return on assets (Q2; $M = 3.74$) and the proportionality between total profits and sales (Q5; $M = 3.72$), items in which about 60% of the respondents concentrated on the highest levels of agreement (4 and 5).

At the opposite extreme, the gross margin of production (Q6; $M = 3.14$) turned out to be the indicator with the lowest value within the dimension. Interestingly, 41.9% of the

participants selected the intermediate option (3), while only 11.6% expressed a fully favorable perception (5). This pattern of response in which neutrality prevails over the agreement can be interpreted as a sign of structural uncertainty regarding the real profitability of the activity: fish farmers do not clearly perceive that what remains between the cost of production and the sale price is sufficient. Items related to cost

competitiveness (Q9; $M = 3.30$), cost coverage by sales prices (Q11; $M = 3.28$) and satisfaction with marketing channels (Q12; $M = 3.28$) configured a block of indicators with low valuations that point to weaknesses in the value chain: it is not enough to produce if market prices do not guarantee sustainable margins and distribution channels are not adequate.

7.2.2. Environmental Management

Table 3 : Distribution of frequencies and averages by item — Environmental management dimension (n = 43)

Item	Statement (abridged version)	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)
Q13	Reuse of pond water	18,6	7,0	18,6	20,9	34,9
Q14	Techniques to reduce water consumption	7,0	9,3	20,9	25,6	37,2
Q15	Regular measurement of water savings	9,3	16,3	25,6	20,9	27,9
Q16	Practices to reduce energy consumption	9,3	9,3	18,6	30,2	32,6
Q17	Use of alternative energy sources	37,2	16,3	18,6	11,6	16,3
Q18	Regular monitoring of energy expenditure	11,6	9,3	20,9	27,9	30,2
Q19	Fish waste harvesting	25,6	25,6	18,6	9,3	20,9
Q20	Use of scales and viscera for additional income	58,1	14,0	7,0	11,6	9,3
Q21	Formal by-product management plan	25,6	16,3	23,3	20,9	14,0
Q22	Reduction of expenses due to environmental practices	11,6	16,3	37,2	18,6	16,3
Q23	Positive trend of profits from environmental management	9,3	7,0	37,2	27,9	18,6
Q24	Reduction of pollution in the environment	9,3	4,7	25,6	34,9	25,6

Note. The scale ranges from 1 (strongly disagree/never) to 5 (strongly agree/always). M = arithmetic mean. Percentages may not add up to 100% by rounding.

The environmental management dimension registered the lowest mean of the instrument ($M = 3.18$), a result that alone reveals a significant gap between the demands of sustainable

aquaculture and the level of effective implementation of environmental practices in the surveyed units. However, a disaggregated analysis shows that this dimension is not homogeneously deficient: within it there are subgroups of items with relatively high ratings and others that concentrate the most critical scores of the entire instrument, which configures a bimodal

environmental profile that deserves differentiated interpretation.

7.2.3. Water and Energy Management: Relative Strength

The subgroup of items related to water and energy use presented the most favorable evaluations within the dimension. Reduction of water consumption through specific techniques (Q14; $M = 3.77$) led this block, with 62.8% of the participants concentrated in levels 4 and 5, also constituting the second best valued item of the entire environmental dimension. Reducing energy consumption through operational practices (Q16; $M = 3.67$) and the monitoring of energy expenditure (Q18; $M = 3.56$) completed this block with ratings that exceed the general average of the dimension, which indicates that the efficiency in the consumption of basic inputs water and energy has found greater adoption than other more complex environmental practices.

However, this positive trend is abruptly fractured when analyzing the item referring to the use of alternative or cleaner energy sources (Q17; $M = 2.53$). With 37.2% of respondents at the lowest level of the scale and only 16.3% at the highest level, this item revealed the lowest rating of the entire water-energy subgroup and the second lowest of the entire dimension.

The interpretation is clear: the fish farming units surveyed have incorporated energy-saving practices into their conventional systems, but the transition to solar, hydro or other renewable sources remains practically unexplored, possibly due to initial investment barriers, limited technological access or the absence of sectoral incentives.

7.2.4. Waste Recovery and Circular Economy: Critical Gap

The subgroup of items linked to the use of by-products of the production process concentrated the lowest scores not only in this dimension, but in the entire instrument.

The use of scales and viscera for the generation of complementary income (Q20) obtained a mean of only $M = 2.00$, with 58.1% of the

participants selecting the minimum level of the scale the highest percentage of negative response recorded in any item of the questionnaire. This result strongly indicates that the circular economy around fish processing waste is, in practice, non-existent in most of the units studied.

The general use of fish waste in other processes was also unfavorable (Q19; $M = 2.74$), where 51.2% of the responses were concentrated in the two lowest levels of the scale, and the existence of a formal plan for the management of by-products (Q21; $M = 2.81$), in which 41.9% declared total or almost total absence of said plan. Read together, these three items form a consistent pattern: not only do fish farmers not take advantage of the waste, but they have also not formalized any strategy to do so in the future, which shows a structural disconnection between productive activity and the principles of residual biomass valorization.

7.2.5. Environmental Impact Perception: An Ambiguous Signal

The items that evaluated the perception of the economic impact of environmental practices, that is, whether they generate cost savings or improved profits, obtained intermediate valuations. Reduction of operating expenses as a result of environmental practices (Q22; $M = 3.12$) presented the greatest weight in the neutral option (37.2 % in level 3), while the perception of a positive trend in profits associated with environmental management (Q23; $M = 3.40$) showed a more agreement-oriented distribution, although without reaching high levels of conviction. This ambiguity suggests that producers do not clearly perceive direct economic retribution from their environmental practices, which can act as a disincentive to deepen them. On the contrary, the reduction of pollution in the productive environment (Q24; $M = 3.63$) obtained the highest rating of the subgroup, with 60.5% of the respondents in levels 4 and 5, evidencing that awareness of the local environmental impact is greater than the link between environment and profitability.

7.2.6. Technological Innovation

Table 4 : Distribution of frequencies and averages by item — Technological innovation dimension (n = 43)

Item	Statement	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)
Q25	Built-in improvements over traditional techniques	9,3	7,0	11,6	37,2	34,9
Q26	New ways of manual work with better results	7,0	2,3	25,6	34,9	30,2
Q27	Adoption of new tools and equipment	11,6	11,6	20,9	16,3	39,5

Note. The scale ranges from 1 (strongly disagree/never) to 5 (strongly agree/always). *M* = arithmetic mean. Percentages may not add up to 100% by rounding. Examples of tools such as water pumps, nets, aerators, and oxygen and pH meters are included. The technological innovation dimension obtained the highest mean of the instrument at the total sample level (*M* = 3.74), a result that, read in the context of the previous dimensions, acquires a particular significance: the surveyed fish farming units perceive more clearly their progress in terms of operational innovation than in environmental management or economic competitiveness. This does not necessarily imply that innovation is the area of greatest objective strength, but rather that it is the domain where producers most clearly identify concrete and tangible changes in their way of working. The three items that make up this dimension presented a distribution of responses coherently oriented towards the upper levels of the scale. The incorporation of improvements over traditional production techniques (Q25; *M* = 3.81) led the block with 72.1% of the respondents located in levels 4 and

5, being also the best valued item of the entire questionnaire. This result suggests that the transformation of inherited practices in feeding, pond management or stocking densities has been perceived as a real and positive change by most producers. In a very close position was the implementation of new forms of manual work (Q26; *M* = 3.79), with 65.1% of the evaluations concentrated in the highest levels of agreement and a notably low percentage of negative response (levels 1 and 2) (9.3%), the second lowest of the entire instrument. The adoption of new tools and equipment (Q27; *M* = 3.60) completed the dimension with the lowest assessment of the block, although 55.8% of the participants were placed in levels 4 and 5. It is striking that 39.5% of the respondents chose the maximum level (5) for this item, the highest proportion of responses at that level for any item of the instrument, which indicates that for a significant part of the producers, the provision of equipment such as aerators, oxygen meters and specialized networks represents a substantial transformation with respect to their previous operating conditions.

7.2.7. Market Orientation

Table 5 : Distribution of frequencies and averages by item — Market orientation dimension (n = 43)

Item	Statement	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M
Q28	Customers value product sustainability	7,0	14,0	23,3	30,2	25,6	3,53
Q29	Customers willing to pay more for sustainable products	20,9	20,9	23,3	16,3	18,6	2,91
Q30	Sustainable practices improve the image of the business	4,7	7,0	32,6	30,2	25,6	3,65

Note. The scale ranges from 1 (strongly disagree/never) to 5 (strongly agree/always). *M* = arithmetic mean. Percentages may not add up to 100% by rounding.

The market-oriented dimension obtained an overall mean of $M = 3.36$, positioning itself as the second dimension with the lowest score after environmental management. However, as in this dimension, the aggregate mean hides an internal tension between items that is analytically more revealing than the average itself.

Improving the image of the business as a result of sustainable practices (Q30; $M = 3.65$) and the perception that customers value the sustainability of products (Q28; $M = 3.53$) obtained moderately favorable evaluations, with 55.8 % and 55.8 % of the respondents respectively located in levels 4 and 5. These results indicate that producers recognize, in general terms, that sustainability has a reputational value in the market: they perceive that their customers appreciate it and that it projects a positive image of their production units.

However, this favourable perception collapses significantly when it is transferred to the level of the actual willingness to pay. Item Q29 referring to whether customers actually pay more for environmentally responsible products obtained the lowest mean of this dimension ($M = 2.91$) and the third lowest of the entire instrument, with a remarkably dispersed distribution of responses: 41.8% of the participants were located in levels 1 and 2, 23.3% in the neutral level and only 34.9% in the levels of positive agreement. This fracture between the symbolic valuation of sustainability (Q28 and Q30) and its concrete translation into price differential (Q29) configures what can be called a market conversion gap: producers perceive that their customers appreciate sustainability, but fail to capture this attribute as a tangible competitive advantage in their sales prices.

Finally, technological innovation leads the global assessment because it is the domain in which changes are most perceptible and operationally immediate for producers: a new network, an aerator or an improved feeding technique produces observable effects in the short term. Economic performance is in second place, mainly supported by relative strength in basic financial control, although weakened by difficulties in

margins, costs and marketing. Market orientation and environmental management close the ranking with the lowest valuations, and they share a common characteristic between them: both demand transformations that transcend the scale of the individual productive unit, articulation with value chains, access to differentiated markets, investment in clean technologies and that cannot be solved solely from the internal management of the producer.

7.3. Difficulties for the Growth of the Fish Farming Sector

The fish farming sector of Norte de Santander, in line with the trends identified in other producing regions of the country and Latin America, faces a set of interrelated constraints that condition its expansion and compromise its long-term viability. These difficulties do not operate in isolation but as a system of mutually reinforcing constraints, which requires equally integrated policy approaches to overcome them.

Among the factors with the greatest impact on the economic stability of the sector is the impact of the COVID-19 pandemic, whose consequences on aquaculture value chains in developing countries resulted in severe contractions in demand, restrictions on the mobility of products and inputs, shortages of fingerlings and concentrates, and significant losses in marketing volumes (Alam et al., 2022; Prima et al., 2023). Comparative evidence in Latin American contexts indicates that small-scale production units, a category in which most fish farmers in Norte de Santander are enrolled, exhibit a higher structural vulnerability to systemic shocks of this nature, given their limited capacity to access credit, productive insurance, and formal mechanisms of articulation with the market (Alam et al., 2022). Added to this fragility is the persistent scarcity of updated and disaggregated sectoral information at the regional level, which restricts the capacity for timely diagnosis and hinders the design of evidence-based technical and policy interventions (Prima et al., 2023).

The management of water resources is another critical axis of the sectoral problem. Water

represents the fundamental input of fish farming activity, since the physicochemical quality of the aquatic environment directly determines the growth rates, feed conversion, susceptibility to pathogens and mortality of farmed species. The accumulation of toxic compounds such as ammonia, nitrite and hydrogen sulfide, together with conditions of hypoxia or proliferation of pathogenic bacteria, make up the main risk factors associated with water quality in low- and medium-tech aquaculture production systems (Yusoff et al., 2024). For fish farmers in the region, guaranteeing optimal water conditions in a sustained manner represents a challenge that is aggravated by the insufficient transfer of specialized technical knowledge: training in good production practices, systematic monitoring of physicochemical parameters and the efficient use of water resources continue to be aspects of low penetration in the sector. which limits both the individual productivity of the units and the environmental sustainability of the activity as a whole (Aljehani et al., 2023).

On the commercial level, the disarticulation between production and the markets of greater value represents perhaps the obstacle with the greatest impact on the profitability of the sector. The absence of effective marketing channels, the dependence on short sales circuits with little bargaining power for the producer and the competition of imported products at lower prices converge to generate a price structure that often does not cover the real costs of production, eroding margins and discouraging investment in productive improvement (Castellanos et al., 2023). The Ministry of Agriculture and Rural Development has recognized this limitation and implemented strategies aimed at improving producers' marketing conditions, including the delivery of storage infrastructure, cold rooms, and processing rooms, as well as training in good product handling practices. However, these interventions have not yet had an insufficient scope to transform the commercial structure of the sector at the departmental level. In this sense, the development of strategies for differentiating the regional fish product through quality certifications, designations of origin or

traceability schemes emerges as a priority line of action to strengthen the competitive position of local producers in the face of imported supply and improve their capacity to capture value in the chain.

In summary, the difficulties faced by fish farming in Norte de Santander respond to a complex articulation of exogenous factors such as the economic disturbances derived from the pandemic and endogenous factors such as weak technical training, poor management of water resources and commercial disarticulation, the overcoming of which requires a coordinated response between productive actors, sectoral support institutions and departmental and national public policy entities (Castellanos et al., 2023; Prima et al., 2023).

8. Discussion

The results obtained from the characterization of the fish farming units of the department of Norte de Santander allow the construction of a comprehensive sectoral diagnosis that articulates the economic, environmental, technological and commercial dimensions of the activity. Read together, the findings do not describe isolated realities but systemic patterns that cut across the sector, regardless of the municipality or the associative affiliation of the productive units, and that demand equally systemic policy responses.

The moderately favourable assessment of the economic dimension ($M = 3.50$) reflects a situation that can be characterised as operational sufficiency without competitive strength. The department's fish farming units have consolidated basic financial management practices, particularly cash flow monitoring (Q7; $M = 3.88$) and the revision of return on assets (Q2; $M = 3.74$) that allow them to sustain their daily operations. This capacity is not trivial in a sector composed mostly of small and medium-sized producers who operate with narrow margins and limited access to formal financial services; it represents, on the contrary, a management base on which it is possible to build interventions of greater complexity.

However, this operational strength coexists with structural weaknesses that compromise the long-term economic viability of the sector. The lowest indicators of the gross production margin dimension (Q6; $M = 3.14$), cost competitiveness (Q9; $M = 3.30$) and cost coverage through sales prices (Q11; $M = 3.28$) point to a problem that cannot be solved by the internal management of the production unit: producers in Norte de Santander are unable to translate their productive effort into sustained profitability because the prices they receive in the market do not adequately recognize their real production costs. Added to this is the dissatisfaction with the current marketing channels (Q12; $M = 3.28$), which limits access to higher-value markets and perpetuates dependence on short sales circuits with little bargaining power for the producer.

This combination of factors configures a competitiveness trap characteristic of agricultural sectors with low vertical integration: producers produce well, but sell poorly, and the margins that remain between cost and price are not enough to finance the investment necessary to produce better. Overcoming this trap requires interventions that act simultaneously on production costs through associative economies of scale, access to subsidized inputs or technical assistance, and on marketing channels, articulating producers with institutional markets, restaurant chains, processors, or fair trade platforms that recognize value differentials.

Environmental management registered the lowest mean of the instrument ($M = 3.18$), a result that in principle could be interpreted as environmental negligence of the sector. However, the disaggregated analysis reveals a more complex and nuanced reality that justifies a differentiated reading.

The fish farming units of Norte de Santander have made perceptible progress in practices of efficiency in the use of conventional resources. Reduction of water consumption through specific techniques (Q14; $M = 3.77$), the implementation of practices to reduce energy consumption (Q16; $M = 3.67$) and the monitoring of energy expenditure (Q18; $M =$

3.56) obtained valuations that exceed the general average of the dimension, evidencing that when environmental practices have a direct and visible translation into a reduction of operating costs, producers incorporate them relatively naturally. In these cases, environmental motivation and economic motivation converge, facilitating adoption without the need for additional external incentives.

The situation is radically different in the subgroup of items linked to waste recovery and the circular economy, which concentrated the most critical scores of the entire study. The use of scales and viscera to generate additional income (Q20; $M = 2.00$) was the item with the lowest rating in the entire instrument, with 58.1% of the producers located at the minimum level of the scale. In the same direction, the general use of waste from the production process (Q19; $M = 2.74$) and the existence of a formal by-product management plan (Q21; $M = 2.81$) confirmed that the circular economy around fish processing waste is practically non-existent in the departmental sector.

This gap does not reflect environmental disinterest but the absence of enabling conditions that no individual producer can generate autonomously. The use of fish by-products requires processing infrastructure, access to specialized markets for meal, oils or derived fertilizers, specific technical knowledge and articulation with other actors in the production chain, conditions that exceed the capacity of an isolated production unit and that require coordinated institutional intervention. The fact that awareness of the reduction of pollution in the environment (Q24; $M = 3.63$) was significantly higher than the perception of economic benefit derived from environmental practices (Q22; $M = 3.12$) confirms that producers are clear about their environmental impact but have not found the mechanism to convert that awareness into captureable economic value, which acts as a disincentive to deepen sustainable practices.

Special mention should be made of the item referring to the use of alternative energy sources

(Q17; $M = 2.53$), which with 37.2% of responses at the minimum level revealed the second deepest gap in the dimension. The department's fish farming units have optimized their consumption within conventional energy systems, but the transition to renewable sources remains largely unexplored, possibly due to initial investment barriers, limited access to technology appropriate for rural contexts, and the absence of sectoral incentive programs specific to inland aquaculture.

Technological innovation led the overall assessment of the instrument ($M = 3.74$), constituting the most encouraging finding of the sectoral diagnosis. The incorporation of improvements over traditional production techniques (Q25; $M = 3.81$) and the implementation of new forms of manual work (Q26; $M = 3.79$) obtained the two highest scores of the entire questionnaire, with more than 70% of producers placed in the highest levels of agreement in both cases. These results indicate that the fish farming sector in Norte de Santander has undergone a real and perceptible operational transformation in recent years, and that the producers themselves recognize and value this evolution.

However, this positive result calls for interpretative caution. The items capture incremental innovation, improvements over what exists in feeding, pond management, stocking densities that are valuable for the consolidation of the activity but that do not necessarily imply a leap towards production systems of greater efficiency, sustainability and scale. The adoption of new tools and equipment (Q27; $M = 3.60$), although favorably assessed, reveals that the incorporation of technology continues to be heterogeneous between units and that the provision of instruments such as aerators, oxygen meters and equipment for monitoring fundamental physicochemical parameters for intensive systems such as biofloc is not generalized in the departmental sector.

Technological innovation, then, represents the most solid asset on which to build the next phase of sectoral development, but its consolidation requires moving from adaptive innovation to

transformative innovation: from improving what is done to changing the fundamental way in which it is produced, incorporating recirculation systems, automated control of parameters and technologies with low environmental impact that simultaneously increase the productivity and sustainability of the companies' units.

The market-orientation dimension ($M = 3.36$) exposed the most significant strategic constraint of the sector in terms of future projection. Producers in Norte de Santander perceive that their customers value the sustainability of their products (Q28; $M = 3.53$) and that their environmental practices improve the image of their production units (Q30; $M = 3.65$), but this favorable perception collapses when it is transferred to the specific level of the willingness to pay: only 34.9% of the respondents considered that their customers effectively pay more for environmentally responsible products (Q29; $M = 2.91$), with 41.8% located in the levels of disagreement.

This fracture between symbolic valuation and economic translation of sustainability configures what can be called a market conversion gap, and is possibly the most important obstacle to the future competitiveness of the sector. The sustainable attributes of departmental fish production, rational use of water, improvement of techniques, reduction of pollution, exist in practice, but they are not being communicated, certified or positioned in a way that the market recognizes and pays for them. In the absence of differentiation mechanisms such as quality seals, environmental certifications, product traceability or fair trade schemes, sustainability remains an invisible attribute for the end consumer, incapable of generating the price differential that would justify its deepening.

The integration of the findings of the four dimensions allows us to draw a clear sectoral profile: the fish farming sector of Norte de Santander has a productive base with consolidated operational capacities and a positive incremental innovation trajectory, but faces structural limitations on three fronts that compromise its long-term sustainability — the

profitability of the value chain, waste management and market value capture by sustainable attributes.

Based on this diagnosis, improvement strategies must be organized into three articulated levels. At the production level, the priority should be to strengthen margins by reducing costs through associative economies of scale, subsidized access to strategic inputs such as fingerlings and concentrates, and technical assistance for the transition to systems of greater productive efficiency. At the environmental level, the most urgent intervention is the development of departmental infrastructure for the processing and marketing of fish by-products, complemented by incentive programs for the adoption of renewable energies adapted to rural aquaculture contexts. At the commercial level, the construction of market differentiation schemes, sustainability certifications, marketing routes with institutional markets and regional designation of origin programs constitutes the strategic lever with the greatest potential to transform the identified conversion gap into a real competitive advantage for producers in the department.

9. Conclusions

The present research aimed to characterize the fish farming sector of the department of Norte de Santander and identify improvement strategies aimed at strengthening its productive, environmental, technological and commercial performance. The findings obtained from the application of the characterization instrument to 43 productive units allow the following conclusions to be formulated, organized in correspondence with the dimensions analyzed and with the propositional horizon that guides the study.

The fish farming units of Norte de Santander have developed elementary financial management and operational control capacities that constitute a viable platform for more complex interventions. However, this operational strength does not translate into market competitiveness, given that the indicators of production margin, cost coverage and

satisfaction with marketing channels were systematically low. The sector produces with increasing efficiency, but sells under conditions that do not adequately recognize the value of its production, which generates a gap between productive effort and real profitability that compromises the long-term economic viability of the units studied.

The low valuation of the environmental dimension does not reflect a lack of interest on the part of producers in the sustainability of their activity, but rather the absence of institutional, technological and market conditions that allow environmental awareness to be translated into viable and economically profitable practices. The department's fish farming units have advanced in water and energy saving practices where environmental and economic motivation converge, but waste recovery and the energy transition to renewable sources remain critical gaps that no individual producer can close autonomously. Overcoming it requires coordinated institutional intervention in infrastructure, financing and specific sectoral incentives.

The departmental fish farming sector has undergone a genuine operational transformation recognized by its own actors, expressed in the improvement of traditional production techniques and the progressive incorporation of specialized tools and equipment. This incremental innovation represents the strongest asset identified in the study and forms the foundation on which the next stage of sectoral development must be built. However, the leap towards production systems of greater efficiency, sustainability and scale such as biofloc, water recirculation or automated monitoring of parameters requires overcoming adaptive innovation to achieve a transformative innovation that demands sustained technical, financial and institutional support.

One of the most significant findings of the study is the existence of a market conversion gap: producers in Norte de Santander implement practices with sustainable attributes recognized by their own customers, but they do not have the

necessary mechanisms for these attributes to translate into differentiated prices and concrete competitive advantages. The absence of environmental certifications, traceability schemes, regional quality seals and differentiated marketing channels keeps the sustainable value of departmental fish production invisible to the market, depriving the sector of a potential source of profitability that could finance its own transformation.

The comparative analysis among the participating organizations showed that the level of formalization and associative articulation has a

direct impact on the perceived performance in all the dimensions evaluated. The productive units with a higher degree of collective organization showed more favorable perceptions in economic management, innovation and market orientation, which suggests that the strengthening of the associative structures of the sector not only in terms of membership but also in terms of management, negotiation and representation capacity constitutes an enabling condition for any sectoral improvement strategy. and not an optional complement to productive and commercial interventions.

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