

How will the circular economy enable sustainability in the utilization of trout farming waste?

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Abstract

The present study proposes a circular economy model for an aquaculture company to maximize the utilization of waste. The objective of the research was to evaluate the feasibility of converting rainbow trout processing residues into sustainable fish meal, thereby reducing environmental impacts and improving resource efficiency. The analysis of waste generated during evisceration revealed that approximately 40% of each trout corresponded to residues, thereby highlighting the inefficient use of available resources. The research adopted a documentary and exploratory approach, taking extant information on innovative subjects. A quantitative methodology was employed to collect numerical data to assess the potential increase in profits derived from waste valorization. The process entails the cooking, pressing, and drying of the residues, resulting in a dehydrated mass that is subsequently milled. This process has been devised to optimize the utilization of all materials in accordance with circularity principles. The indicators MCI, IC, and FIFO were estimated to measure circularity, biomass reincorporation, and nutrient retention efficiency. From a total of 4,000 kilograms of processed fish per month, 40% of by-products were obtained, yielding 25% of the total, resulting in 400 kilograms per month of sustainable fish meal, which served as the basis for calculating the system indicators. The results demonstrate adequate valorization, effective material reincorporation, and good nutrient retention, supporting the technical, environmental, and economic feasibility of the proposed model for the aquaculture industry.

Keywords: Circular economy, aquaculture, fish meal, evisceration, nutrients.

I. INTRODUCTION

The present study focuses on the evolution of aquaculture products consumption, with fish being the main representative of this sector. Currently, these products exhibit high global demand, which consequently results in the continuous exploitation of this resource [1]. However, when compared to the total number of existing species, only a fraction is suitable for human consumption, as detailed by [2] in a study focused on fry production and the strengthening of their productive chain.

The growing global demand for aquaculture and fisheries products, together with the need to ensure their supply in large volumes, has engendered sustainability challenges, particularly regarding the use of plant and marine proteins in aquafeed production [3]. It is well known that sustainability issues can lead to these practices; therefore, a model is proposed, aiming to reduce, repair, recycle, and valorize materials while minimizing waste generated during processing. Researchers [4] have further demonstrated in practical terms that the circular economy contributes to improving sustainability. However, they also note that significant barriers remain to its widespread integration.

In our country, there has been an exponential increase in the consumption of aquaculture products. Consequently, the use of tools designed to fortify aquaculture production systems is being assessed. Researchers [5] propose automating processes using artificial intelligence, addressing inefficiencies and reducing environmental impact through decision-making.

Studies conducted by researchers [6] indicate that evaluating the balanced feed provided to fish from the larval stage to adulthood can enhance growth performance compared to traditional feeding practices.

The circular economy is a production and consumption model that seeks to maintain resources within the economic cycle. This is achieved through strategies such as reduction, reuse, recycling, and material recovery. In the domain of aquaculture, this approach entails the utilization of by-products derived from species processing, which are then transformed into value-added inputs. As researchers have explained [7], the utilization of alternative sources, such as insect meal, reduces reliance on conventional raw materials and enhances resource-use efficiency. Furthermore, studies by [8] underscore the potential for viscera, heads, and spines of rainbow trout (*Oncorhynchus mykiss*) to serve as raw materials for the production of balanced feeds, provided that their nutritional quality and phosphorus release into the environment are properly controlled. These studies demonstrate that the valorization of fishery by-products constitutes a critical component of this paradigm, facilitating the closure of biological cycles and the optimization of material flows within productive systems.

Low-impact aquaculture integrates ecological, technological, and nutritional principles to reduce environmental impacts and improve efficiency in farming systems. According to the findings of studies conducted by [9], recirculation systems in aquaculture are defined as structures that reuse water and nutrients through biological and mechanical processes, thereby reducing the generation of solid waste. Concurrently, research conducted by [10] argues that supplementation with essential amino acids, such as lysine, in low-fishmeal-content diets promotes growth performance and protein conversion efficiency in triploid rainbow trout. Likewise, [11] conceptualizes the use of probiotics as a biotechnological tool that facilitates digestion, modulates intestinal microbiota, and fortifies the immune system of fish. When considered as a whole, these empirical foundations permit the comprehension of aquaculture valorization as an integrated system that combines the utilization of by-products, technological innovation, and environmental sustainability in the production of fishmeal from trout processing waste.

The production of fishmeal used in aquaculture hatcheries faces environmental limitations that directly affect fuel consumption and energy requirements. This issue has sparked a search for less harmful alternatives that do not compromise protein availability in the sector [12]. In this context, the regenerative economy provides a theoretical framework for reintroducing waste to generate value cycles and to reduce losses, thereby highlighting the value of agro-industrial by-products through different forms of reutilization that can be transferred within the aquaculture industry [13].

The most viable alternative focuses on transforming trout processing waste (i.e., heads, viscera, and spines) into fishmeal, thereby enhancing feed quality due to its high protein content while minimizing costs. Consequently, [14] underscores that the incorporation of meals derived from hydrolyzed viscera exerts a more substantial influence on weight gain, supporting their integration into aquafeeds. Furthermore, dietary regimens involving the substitution of traditional protein sources with protein powders have yielded positive results and economic advantages, reinforcing the feasibility of their inclusion in nutrition [15].

To ensure the sustainability of the proposed approach, it is essential to incorporate it into a systematic zero-waste framework, supported by standards, incentives, and intersectoral coordination, to facilitate the closure of material cycles within production chains [16]. In turn, waste reduction promotes changes in practices by fostering awareness of waste as a resource, thereby reinforcing the adaptation of training and management strategies to support the adoption of returnable models within aquaculture [17].

The development of this research is organized as follows: In Section 2, the methodology employed is presented, as well

as the research approach, the factors underlying the problem, and the procedure used to estimate and evaluate the proposal. Section 3 reports the calculation of by-products, the estimated yield of sustainable fishmeal, and the results obtained from the indicators (MCI, IC, and nFIFO). In Section 4, the results are interpreted and contrasted with existing literature, identifying contributions, potential benefits, limitations, and the scope of the study. Finally, Section 5 summarizes the most relevant findings and proposes recommendations and directions for future research.

Literature Review

The expansion of aquaculture has raised environmental concerns about nutrients, waste, and microplastics. One alternative is the integration of microalgae, which purify water and recycle nutrients. Researchers [18] indicate that their incorporation into aquaculture systems can reduce pollution and increase sustainability by 20%, aligning with initiatives related to trout production in Peru.

In aquaculture nutrition, the use of agricultural by-products is also being investigated. Researchers [19] reported a 20% improvement associated with the use of grape residues, due to their antioxidant properties, which enhance intestinal health, growth, and fish fillet quality, while also extending shelf life [19]. In the same vein, researchers [20] note that grape derivatives (polyphenols and bioactive compounds) strengthen metabolism, immunity, and oxidative stability, while valorizing their residues for use in aquaculture feed. The transition toward a closed-loop approach does not rely only on technology; it also requires institutional and business-driven support.

Researchers have documented a 35% enhancement in microalgae utilization [21], highlighting the effectiveness of augmenting the public sector and implementing viable initiatives to improve model performance, particularly in developing countries such as Peru, where economic, technological, and infrastructure limitations persist. In recirculating systems, the use of nutrients and CO₂ from effluents to cultivate microalgae has been proposed. An empirical demonstration showed that *Chlorella vulgaris* in RAS captured 98–100% of phosphate, 82–99% of nitrate, and 68–95% of total nitrogen, while generating biomass with lipid contents of 18% of dry weight and fatty acids that can be reused in fish feed [22].

This approach has also been discussed in other sectors. As researchers have noted [23], analyses of thermoelectric power plants emphasize that $\approx 80\%$ of global electricity generation still depends on fossil fuels—oil (4,497 Mt), coal (3,838 Mt), and natural gas (3,282 Mt). Their review indicates that this

model supports the modernization of these systems by reducing emissions and improving resource-use efficiency, and that it can be adapted to industries such as aquaculture production. To assess circularity, various tools and indicators have been proposed, taking the design of the Italian pasta supply chain model, which incorporates 51 indicators aligned with ISO 59020:2024, as a useful reference for developing equivalent metrics in trout by-product processing systems [24]. Within the context of supply chains, researchers [25] have demonstrated that emerging technologies, efficient logistics, and environmental regulation can enhance sustainability by >20%, thereby fortifying competitiveness and mitigating environmental impacts. With respect to effluent treatment, [26] have reported that RAS equipped with biochar filters can recover 35–55% of nitrogen and 45–65% of phosphorus. Furthermore, these systems have been shown to reduce emissions by $\approx 28\%$ (up to 55% when sequestration is considered), decrease eutrophication by 25–45%, conserve 8–15% of energy, and enable the reuse of >90% of water.

Research on sludge management conducted by [27] indicates that university entrepreneurship support enhances entrepreneurial intentions among students with low-to-moderate traits of proactive personality. This finding underscores the importance of applying resource valorization and recirculation approaches to waste generated in trout farming. A study involving 339 students from Malaysia and Ghana demonstrated that university support enhances entrepreneurial intentions among students with low proactivity, accounting for 60% of the variability in intentions among more proactive students. The valorization of organic waste through bioconversion using *Hermetia illucens* has been described in alignment with FAO estimates (one-third of global food production is wasted, amounting to 1.3 billion tons per year) [28]. The reported feeding regimens include diets with 22–28% dry matter, a uniform portion of 0.14 g DM/larva, and conditions of 28°C / 65% relative humidity over seven days. This method has been shown to efficiently convert into protein-rich biomass with lower emissions than conventional livestock systems. Additionally, researchers [29] in Bangladesh have emphasized the potential of BSF production to reduce costs, noting high male participation (98.3%), learning through YouTube (63.3%), motivation driven by cost reduction (35.1%), and utilization of in fish (50.7%) and poultry (46.4%) feeding, with market prices ranging from US\$ 0.42 to 4.19 per kilogram. However, technical and market barriers persist, and only 23.3% apply fermentation processes.

In terms of productive integration, researchers [30] conducted a nine-week evaluation of an aquaponic system (consisting of jade perch and lettuce). The application of mineral supplementation at a rate of 10% resulted in enhanced

plant growth; however, hydroponic systems exhibited higher values ($p < 0.05$). In contrast, fish growth remained comparable across various treatments ($p > 0.05$). Likewise, [31] developed an aquaponic system combining Japanese cucumber and hybrid catfish, and obtained 112 kg of fish and 3.2 kg of vegetables per production cycle over 14 weeks. Financial analysis showed a positive NPV, $B/C > 1$, and an IRR exceeding the cost of financing. Regarding water reuse, [32] tested bioretention systems with Canna (3,000 L/day) for domestic wastewater treatment, achieving reductions of 78.7% in BOD, 71.4% in COD, 85% in TSS, and 100% removal of parasite eggs. Additionally, phosphorus and ammonium were reduced by 65.5% and 74.7%, respectively, and the treated water was used for catfish and tilapia culture, resulting in better fish health compared to market-sourced fish.

Finally, to comprehend the ecological responses to contamination, the HeMHAS system exhibited avoidance behavior and displacement toward less toxic zones. This finding supports the notion that, beyond nutrient recycling, controlling environmental quality is essential when designing processes for the valorization of non-edible trout by-products [33].

A. Statement of the Problem

Currently, aquaculture faces numerous challenges in achieving a balance between productive activity and environmental sustainability. One of the most relevant challenges is the sustainable management of each type of waste generated during the evisceration of rainbow trout (viscera, heads, and spines). Despite their high protein value, these by-products are often discarded without leveraging their potential benefits. Valorization is a strategic alternative for transforming such waste into value-added inputs, promoting waste reduction and reuse within the production process. However, this tool is hindered by the necessity of technological infrastructure, specific regulatory frameworks, and technical expertise, which limit its effectiveness in the aquaculture industry. Consequently, a comprehensive analysis of the actual conditions of each company is imperative to incorporate this approach into the efficient production of trout meal. This analysis should encompass an examination of its technical, environmental, and economic feasibility. Accordingly, the following issues were identified to be addressed:

- How will the circular economy impact the process of transforming trout waste into sustainable fishmeal?
- What is the impact of trout by-product valorization on productive efficiency and environmental sustainability?
- Can waste reuse and reduction be considered effective circular practices for transforming trout by-products into fishmeal?

- Which technical, economic, and environmental indicators are the most relevant for evaluating the feasibility of sustainable trout fishmeal production under a circular economy approach?

B. Objective

To evaluate the technical, environmental, and economic feasibility of implementing a circular economy model in the aquaculture industry through the valorization of waste generated from rainbow trout (heads, spines, and viscera) to transform these by-products into sustainable fishmeal. The proposed approach aims to mitigate environmental impacts by optimizing the utilization of natural resources and enhancing production efficiency. Furthermore, the objective is to establish criteria that enable the replication of this strategy in similar aquaculture systems under a sustainability-oriented framework.

C. Hypothesis

The integration of a closed-loop production model within the aquaculture industry facilitates the valorization of rainbow trout by-products by converting them into fishmeal, thereby augmenting the utilization of organic residues, enhancing operational efficiency, and substantially reducing the environmental impact of the production process. This approach is conducive to the sustainability of aquaculture systems by promoting the responsible use of resources and reducing dependence on conventional inputs.

II. METHODOLOGY

The present research was conducted using an empirical and documentary approach at Raracocha Lagoon, in the city of Cerro de Pasco, Peru. The evisceration process and its progression through the different stages of production were observed directly and continuously. The collection of data regarding the utilization of by-products in aquaculture—including viscera, process water, and derived meals—was grounded in the analysis and review of scientific sources addressing the application of return economy principles in aquaculture systems. Researchers [34] have demonstrated that this approach promotes the revalorization of fishery by-products through biotechnological processes that contribute to more sustainable production. Given its level of abstraction, the study is descriptive in nature, as data from various investigations on the utilization of aquaculture waste were conceptualized and explanatory analyses were conducted to examine cause-and-effect relationships between by-product management, environmental efficiency, and productive sustainability. This allowed the identification of the benefits associated with reducing environmental impacts [35]. Regarding the nature of the data, a quantitative approach was applied, employing measurements of protein yield and

substitution rates of conventional fishmeal. According to [36], quantitative analyses facilitate the estimation of the feasibility of replacing traditional meals with recovered protein sources. In terms of variable manipulation, the study is non-experimental, as environmental conditions were not altered. Concerning its purpose, it is applied research aimed at proposing sustainable solutions. The subsequent section conceptualizes the factors that directly affect aquaculture production processes.

Technology applied in aquaculture production

Technology applied in the aquaculture industry encompasses digital tools, smart sensors, and automated systems that optimize process efficiency and sustainability. In this context, [37] developed an Internet of Things (IoT)-based system to monitor critical water parameters in real time, including dissolved oxygen, ammonia, pH, and temperature. This system has been shown to achieve cost reductions of up to 85% and improve operational efficiency. Additionally, [38] argue that predictive models driven by artificial intelligence and deep learning can facilitate the anticipation of variations in dissolved oxygen (DO) concentrations, thereby enhancing environmental stability and productivity in culture ponds. In a similar vein, [39] underscores the significance of Biofloc Technology (BFT) as a pivotal innovation for nutrient recycling, thereby reducing water usage and curtailing the consumption of formulated feed by up to 30%. This, in turn, contributes to the sustainability of aquaculture systems. Consequently, this factor is a fundamental pillar of a return-oriented approach, as it promotes efficient resource use, automation, and the reduction of environmental impacts in aquaculture production. In this equation, the oxygen concentration is determined by identifying the variables that directly affect it.

$$DO_t = f(T_p, H, NH_3, Turbidity, Time, Temp) \quad (1)$$

Where:

DO_t: Dissolved oxygen concentration at time t (mg/L)

T: Water temperature (°C)

pH: Hydrogen potential of the water

NH₃: Ammonia concentration (mg/L)

Turbidity: Level of suspended solids (NTU)

Time: Time of day (h), which influences photosynthetic activity

Temp: Environmental temperature (°C)

H1: The use of intelligent technologies, such as IoT and Biofloc systems, improves the efficiency of transforming trout waste into fishmeal while promoting environmental sustainability.

Operational Efficiency of the System

Operational efficiency within recirculating aquaculture systems is defined as the relationship between the resources utilized (e.g., labor, energy, by-products, etc.) and the amount of final product recovered (i.e., fishmeal). The process's efficiency can be assessed by measuring the yield of converting organic residues into valuable products, allowing for an evaluation of its sustainability [40]. Likewise, [41] asserts that enhanced operational efficiency leads to reduced final waste, increased conversion rates, and decreased costs. The following equation was used to determine the yield of fishmeal production.

$$Y = A + B \cdot X \quad (2)$$

Where:

Y: Estimated yield of fishmeal production, expressed in kilograms.

A: Constant representing the baseline minimum yield (kilograms).

B: By-product conversion coefficient (percentage).

X: Amount of valorized by-product (kilograms).

H2: The estimated yield of fishmeal production depends on the amount of valorized by-products; that is, the coefficient B is greater than 0.

By-Product Circularity

By-product circularity is defined as the degree to which waste generated during a production process can be reintroduced into the economic cycle through transformation or reuse. Research by [42] underscores the significance of quantifying this factor and thus implements the Material Circularity Indicator (MCI) (see Equation 3). This indicator assesses the reduction of linear material flows and product durability compared to a similar market product. Consequently, the formula has been revised to encompass biological cycles, particularly related to zootechnics [43].

$$MCI = 1 - LFI \times F(X) \quad (3)$$

Where:

MCI: Material Circularity Indicator

LFI: Linear Flow Index (%)

F(X): Utility factor (%)

H3: The implementation of the by-product indicator increases the Material Circularity Index of the system compared to the initial situation.

Nutrient Fish-in–Fish-out ratio in Fish Production (nFIFO)

In the context of aquaculture, nFIFO is an indicator used to evaluate the efficiency of raw material use, focusing on assessing the amount of resources utilized and recovered within

farming systems. Empirical research by [44] establishes that nFIFO is a simple measure of the quantity of fish required to produce new farmed fish. To determine nFIFO, an inverse weight-to-weight relationship is applied between the marine-derived ingredients used in feed and the weight of fish produced (see Equation 4). The continuous updating of the data within the established formula to quantify nutrient flows of marine origin supports improved nutrient retention within aquaculture systems [45]. The following general formula is established in this study:

$$nFIFO = \frac{R_s}{R_{MI}} \quad (4)$$

Where:

Nfifo:

R_S: Nutrient retention in salmon (%)

R_{MI}: Nutrient retention in the marine ingredient (%)

H4: The incorporation of valorized trout by-products into the diet reduces the system's FIFO ratio compared to the baseline scenario without valorization.

Reduction of Environmental Impact

Environmental sustainability reduces pollution from the main product and promotes the reuse of waste materials, leading to lower resource consumption in the operational cycle [46]. Consequently, the reuse of discarded materials for subsequent feed transformation and the valorization of by-products represent viable strategies for reducing the ecological footprint of our production [47]. The following equation is used to determine the circularity index associated with this impact.

$$Circularity\ Index\ (CI) = \frac{M_R}{M_T} \quad (5)$$

Where:

M_R: Recycled material (kilograms)

M_T: Total material input (kilograms)

H5: An increase in the Circularity Index reduces the intensity of the environmental impact associated with fishmeal production.

Implementation of the engineering tool in the study

The implementation of the proposed approach is structured into five sequential stages, designed to evaluate the feasibility of a return-oriented economy in fishmeal production from trout by-products. The sequence starts with applied documentary methodologies, incorporating criteria from Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI) to assess the extent of by-product utilization.

Phase 1: Identification of valorized by-products

The by-products generated from trout processing (spines, heads, and viscera) were identified to determine the average volume produced per ton of processed fish, which represents approximately 40% waste per unit processed. This allowed for the classification of the transformation potential that could be obtained from these materials.

Phase 2: Selection of technical indicators:

Valorization indicators were applied, such as the Material Circularity Indicator (MCI), assessing the proportion of waste that can be reintegrated into the production system. In addition, the operational efficiency indicator was used to determine the percentage of valorized by-products compared to the total generated. A predictive formula for process yield was also incorporated.

Phase 3: Analysis of the technological process

A production system process flow model was created, starting from raw material collection to the finished product. Technologies such as Biofloc and IoT-based sensors were incorporated into the conceptual process schemes (see Fig. 1).

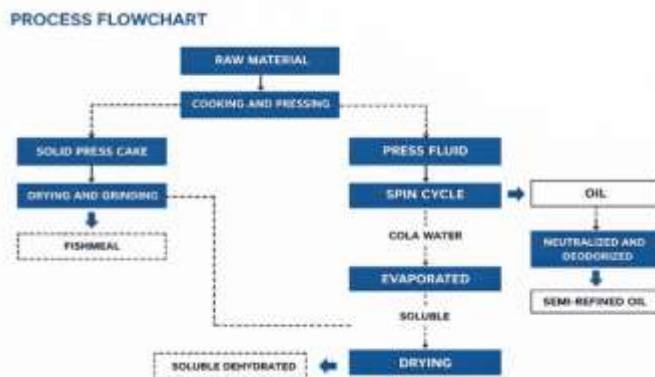


Fig. 1: Process flowchart

Phase 4: Application of the MCI model

The MCI was calculated using reference data for the Linear Flow Index (LFI) and the utility factor (F(x)). The resulting value was then interpreted to determine the degree of circularity of the process.

Phase 5: Evaluation and discussion of expected results

The estimated impacts related to the reduction of organic residues, substitution of conventional fishmeal, and projected operational costs were analyzed and evaluated. Accordingly, an assessment was conducted to determine the viability of replicating the proposed model.

III. RESULTS

Table 1 quantifies the by-products generated from trout processing. This information serves as the basis for Tables 2 and 3.

Table 1: By-product production

Concept	% of live weight	Kilograms per 1 ton of trout	Kilograms per month for 4 tons of trout
Processed weight	100%	1 000	4 000
Total by-products (waste)	40%	400	1 600
Heads	16%	160	640
Spines	12%	120	480
Viscera	12%	120	480

The company processes 4,000 kilograms of trout and generates approximately 1,600 kilograms of by-products, which constitute the baseline for their subsequent valorization.

At the initial stage, 4,000 kilograms of fish are processed each month, with 40% representing processing losses. Based on this information, Equation 2 was applied, and the results are summarized in Table 2.

Table 2: Total production and yield of sustainable fishmeal

Concept	Value
Fish processed per month	4,000 kilograms
By-products generated (40%)	1,600 kilograms
Fishmeal yield (25%)	400 kilograms/month

With a fishmeal yield of 25%, a total of 400 kilograms of sustainable fishmeal are recovered per month.

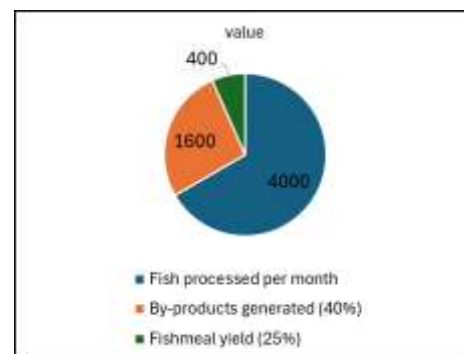


Fig. 2: Monthly distribution of processed fish, valorized waste, and recovered protein-rich fishmeal.

From a monthly volume of 4,000 kilograms of processed trout, approximately 1,600 kilograms of usable residual fraction are generated (40% of the total). The available mass is then subjected to a series of processing steps, including cooking, pressing, and drying, which collectively yield 400 kilograms of

protein-rich fishmeal per month, corresponding to a 25% yield. Table 2 summarizes these values, and Fig. 2 visually represents the relative proportions of processed fish, usable waste, and recovered sustainable fishmeal. As demonstrated in Table 2 and Figure 2, a substantial portion of previously discarded biomass can be converted into a reusable protein input within the aquaculture system.

In Table 3, Equations 3, 4, and 5 were utilized to calculate the system's circularity and efficiency indicators. These calculations were based on the valorization of 400 kilograms (kg) of sustainable fishmeal per month, as indicated in Table 2.

Table 3: Circularity and efficiency indicators

Indicator	Parameters used	Result
MCI (Material Circularity Indicator)	LFI = 0.60; F(X) = 0.30	0.82
CI (Circularity Index)	MR = 400 kg; MT = 4000 kg	0.10 (10%)
nFIFO (nutrient efficiency)	RS = 0.65; RMI = 0.80	0.81

The resulting MCI value is 0.82, indicating a high degree of resource utilization within the process. The Circularity Index (CI) indicates that 10% of the total processed biomass is reincorporated as sustainable fishmeal. An nFIFO < 1 has been shown to demonstrate high nutrient retention efficiency. This, in turn, indicates that a greater proportion of nutrients derived from marine ingredients is effectively transferred to the final product.

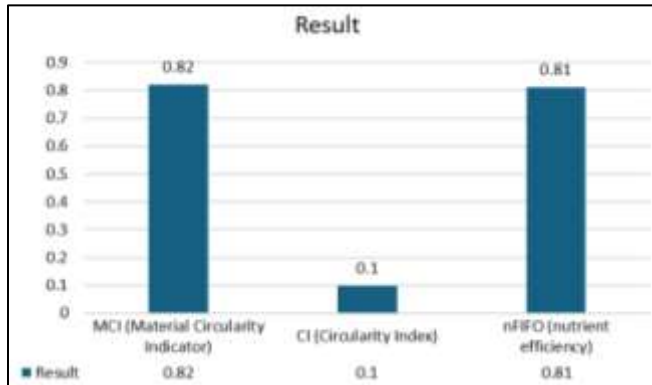


Fig. 3. Comparison of the MCI, CI, and nFIFO indicators of the trout by-product valorization system.

Based on the values summarized in Table 3, Fig. 3 illustrates the behavior of the three indicators applied to the case study. The MCI value of 0.82 indicates a high level of material utilization, and the nFIFO of 0.81 is associated with high nutrient-use efficiency. Conversely, the Circularity Index (CI) is only 0.10, indicating that although the system recovers a significant fraction of biomass, there is great potential to enhance resource recirculation within the production system.

IV. DISCUSSION

The objective of this research is to evaluate the technical, environmental, and economic feasibility of trout fishmeal by developing a return-oriented economy model within the aquaculture industry. This approach uses waste generated during rainbow trout processing (viscera, heads, and spines) to produce sustainable fishmeal. The objective of the present study is to demonstrate that by-product valorization reduces processing losses, improves productive efficiency, and contributes to the sustainability of aquaculture systems through the responsible use of natural resources.

As illustrated in Table 1, a total of 4,000 kilograms of fish are processed monthly, generating 1,600 kilograms of by-products, which corresponds to 40% of the live weight. In this waste, 16% is comprised of heads, 12% of spines, and an additional 12% of viscera. As demonstrated in Table 2, this amount yields a fishmeal production of 25%, equivalent to 400 kilograms of sustainable fishmeal per month. Finally, Table 3 presents the system's valorization and efficiency indicators: the MCI is 0.82, the CI is 0.10, and the nFIFO is 0.81. These findings demonstrate a strong capacity to utilize residual materials and effectively retain nutrients.

The values reported in Tables 1, 2, and 3 indicate that the applied return economy model enables the recovery of a significant proportion of process by-products. The MCI value of 0.82 means that over 80% of the materials are retained within the productive cycle, reflecting a high level of resource utilization. The IC value of 0.10 indicates that 10% of the total processed biomass is reintroduced as sustainable fish meal, thereby generating greater effective utility from the residues. Similarly, the nFIFO value of 0.81 indicates a strong efficiency in retaining nutrients from marine sources. Overall, these findings suggest that adopting a sustainability-oriented system can decrease reliance on external raw materials and the process environmental impact.

The results obtained in this study are closely aligned with those reported by [7], who demonstrated that incorporating sustainable meals produced from *Hermetia illucens* reduces environmental impacts in rainbow trout farming systems. Furthermore, researchers [14] have shown that incorporating hydrolyzed viscera into the diet of *Oncorhynchus mykiss* improves feed conversion and growth performance, thus supporting the proposed by-product valorization in this study. In a similar vein, [26] demonstrated that the implementation of recirculating systems equipped with biocarbon filters facilitates the recovery of up to 55% of nitrogen and 45% of phosphorus. This helps close nutrient cycles and enhances environmental efficiency. Furthermore, [28] highlighted that the

bioconversion of organic waste through black soldier fly larvae reduces waste mass by more than 60% while generating high-value protein biomass, in line with the principles of the proposed model. Finally, [48] emphasized that the combined application of Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI) yields both direct and indirect environmental benefits, consistent with the results of this research.

In this regard, it has been confirmed that the model applied to the valorization of rainbow trout processing residues represents a viable alternative for enhancing sustainability in fish meal production. Utilizing by-products can help reduce waste, improve resource efficiency, and lower operational costs. However, implementing this approach requires investment in technology, skilled personnel, and environmental management policies that promote its adoption. The findings suggest that the system can be replicated in other aquaculture facilities, thereby contributing to achieving the Sustainable Development Goals related to responsible production and environmental protection.

IV. CONCLUSION

The main objective of this research was to evaluate the technical, environmental, and economic feasibility of implementing the return economy model in the aquaculture industry by transforming rainbow trout cleaning residues into fish meal for reuse within the production process. The study aimed at demonstrating that the valorization of processing losses enables waste reduction and productivity improvement throughout the process, thereby contributing to the sustainability of the aquaculture system through more efficient use of resources.

The selection of this topic was driven by its practical applications in the production domain. A potential enhancement of the company was identified, characterized by an increase in real productivity, concurrent with waste reprocessing, as evidenced by Table 3. This analysis revealed that the waste circularity percentage equaled 10% of the initial input percentage. This reduces costs, making processes cheaper, obtaining greater profits, and reducing waste. As indicated in the initial table, trout waste accounted for 40% of the original product, which was then utilized as the foundation for the subsequent treatment process. This by-product can then be used to produce fish meal, thereby reducing food costs.

In contrast, the second table illustrates a waste utilization rate of 25%, equivalent to 400 kilograms of fishmeal per month. This indicates that food purchases will not be required. In this regard, efficiency and valorization indicators were calculated,

yielding a score of 0.82, which shows a high degree of resource utilization. Consequently, this implementation can be executed, as it engenders short- and medium-term benefits.

The subject of return economy will be explored in greater depth. However, there are initiatives to research Systematic Layout Planning (SLP) focused on the company and on companies with inadequate work organization. According to researchers [50], this tool facilitates the more efficient use of a productive area. In addition, as a complementary line of research into the utilization of by-products, researchers [51] assessed the composting of sludge from recirculation systems in salmon farming, demonstrating that it is viable to transform this waste (food scraps and feces) into a soil amendment with a high content of organic matter and phosphorus, with maturity and safety conditions evaluated through technical tests. Furthermore, we are interested in conducting future research on RCM (Reliability-Centered Maintenance) applied to fish manufacturing processes. According to [4], the use of this tool prevents unplanned downtime due to machinery problems.

REFERENCES

- [1] Méndez-Martínez Y., Reyes-Pérez J., Cárdenas-Zea M., & Moncayo-Carreño O. (2025). Proactividad y competencias profesionales: Aporte a la formación del Ingeniero en Acuicultura. *Revista De Ciencias Sociales*, 31(2), 310-324, 1-16. <https://doi.org/10.31876/rcs.v31i2.43768>
- [2] Burgos-Cañas D., Correa-Núñez A., & Piza-Jerez A. (2024). Fingerling market study for the Department of Arauca as a plan to strengthen the aquaculture. *e2726*, 1-11. <https://scopus.bibliotecaupn.elogim.com/inward/record.uri?eid=2-s2.0-85214435499&doi=10.31910%2fprudca.v27.n2.2024.2726&partnerID=40&md5=d3815796e0017e7ce49e1d977c098cdb>
- [3] Cooney R., de Sousa D., Fernández-Ríos A., Mellett S., Rowan N., Morse A., ..., & Clifford E. (2023). A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability. *Journal of Cleaner Production*. Elsevier Ltd, 1-15. <https://doi.org/10.1016/j.jclepro.2023.136283>
- [4] Bermejo-Campos D., & García-Avila F. (2025). A scientometric and systematic analysis of circular economy research focused on wastewater treatment from a sustainability perspective. *Green Technologies and Sustainability*. KeAi Communications Co. 1-15. <https://doi.org/10.1016/j.grets.2025.100259>
- [5] Roy D., Padhiary M., Roy P., & Barbhuiya J. (2024). Artificial Intelligence-Driven Smart Aquaculture: Revolutionizing Sustainability through Automation and Machine Learning. *LatIA*, 2, 116,1-8. <https://doi.org/10.62486/latia2024116>
- [6] Amaru Chambilla G., Yujra Flores E., & Cahui Suaña D. (2024). Evaluación de consentimiento de alimento balanceado sobre el crecimiento de la especie endémica *Trichomycterus dispar* (mauri) viable para la acuicultura. *Revista De Investigaciones Veterinarias Del Perú*, 35(2), e26008, 1-9. <https://doi.org/10.15381/rivep.v35i2.26008>
- [7] Bordignon F., Trocino A., Gasco L., Bellezza Oddon S., Xiccato G., & Berton M. (2024). Towards circularity in aquaculture systems: Environmental impact of *Hermetia illucens* meal inclusion in diets for rainbow trout reared in aquaponics. *Journal of Cleaner Production*, 466, 10-12. <https://www.sciencedirect.com/science/article/pii/S0959652624023503>
- [8] Toomey L., Gesto M., Alfonso S., Lund I., Jokumsen A., Lembo G., & Carbonara P. (2024). Monitoring welfare indicators of rainbow trout (*Oncorhynchus mykiss*) in a commercial organic farm: Effects of an innovative diet and accelerometer tag implantation. *Aquaculture*, 582, 1-12. <https://www.sciencedirect.com/science/article/pii/S0044848624000103>

- [9] Malinovskiy O., Profant V., Kučera V., Pěnka T., & Policar T. (2024). Aplicación práctica de la siembra bicultural y sus efectos sobre el crecimiento de los peces, la bioquímica sanguínea y la eliminación de residuos sólidos en sistemas de acuicultura de recirculación. *Animal*, 18, 1-4. <https://www.sciencedirect.com/science/article/pii/S1751731124001241>
- [10] Zhang S., Wang C., Liu S., Wang Y., Lu S., Han S., Jiang H., Liu H., & Yang Y. (2024). Impact of dietary lysine on growth, nutrient utilization, and intestinal health in triploid rainbow trout (*Oncorhynchus mykiss*) fed low fish meal diets. *Aquaculture Reports*, 39, 1-11. <https://www.sciencedirect.com/science/article/pii/S2352513424004903>
- [11] Ghosh T. (2025). Recent advances in the potential and multifaceted role of probiotics in the development of sustainable aquaculture: Its current form and future perspectives. *Microbial Pathogenesis*, 7, 1-8. <https://www.sciencedirect.com/science/article/pii/S2950194625000858>
- [12] Deville A., Vázquez-Rowe I., Avadí A., Miranda F., & Kahhat R. (2025). Identifying current trends in the environmental impacts linked to fishmeal and fish oil production in Peru. *Aquaculture*, 600, 742239, 1-15. <https://doi.org/10.1016/j.aquaculture.2025.742239>
- [13] Heredia Martín J., Ramírez D., & Camargo A. (2025). Overview of garlic waste management, circular economy, and upcycling. *Revista de la Facultad de Ciencias Agrarias*, 57(1), 215–231. <https://scopus.bibliotecaupn.elogim.com/pages/home?display=basic&zona=header&origin=#basic>
- [14] López-Macías J., & Salas-Benavides J. (2021). Efecto de harina de hidrolizado de vísceras en el crecimiento de trucha arcoiris (*Oncorhynchus mykiss*). *Revista MVZ Córdoba*, 26(1), e1989, 1-9. <https://doi.org/10.21897/rmvz.1989>
- [15] Tefal E., Peñaranda D., Martínez-Llorens S., Tomás-Vidal A., Jauralde I., Lagos L., Moyano F., & Jover-Cerdá M. (2024). Feeding of rainbow trout (*Oncorhynchus mykiss*) with organic ingredients replacing fish meal. *Aquaculture*, 592, 741257, 1-17. <https://doi.org/10.1016/j.aquaculture.2024.741257>
- [16] Li Y., Shan G., Hao S., Li J., & Li J. (2025). Systemic governance and circular economy synergies: A multidimensional analysis of China's "Zero-waste Cities" initiative. *Circular Economy*, 4, 100153, 1-7. <https://doi.org/10.1016/j.cec.2025.100153>
- [17] Li Y., Liang Y., Yu D., Xu L., & Song Q. (2025). Reducing food waste behaviors from the viewpoint of university students through the E-TPB model. *Circular Economy*, 4, 100154, 1-11. <https://doi.org/10.1016/j.cec.2025.100154>
- [18] Dasari D., Dong C., Singhania R., Tambat V., Piechota G., & Patel A. (2025). Harnessing microalgae for sustainable aquaculture and mariculture: Marine pollution mitigation and circular economy strategies. *Marine Pollution Bulletin*, 219, 1-15. <https://doi.org/10.1016/j.marpolbul.2025.118292>
- [19] Quagliardi M., Frapiccini E., Marini M., Panfili M., Santanatoglia A., Nguefang M., Roncarati A., Vittori S., & Borsetta G. (2024). Use of grape by-products in aquaculture: New frontiers for a circular economy application. *Heliyon*, 10(5), e27443, 1-14. <https://doi.org/10.1016/j.heliyon.2024.e27443>
- [20] Amin M., Quagliardi M., Frapiccini E., Marini M., Panfili M., Santanatoglia A., Nguefang M., Roncarati A., Vittori S., & Borsetta G. (2024). Use of grape by-products in aquaculture: New frontiers for a circular economy application. *Heliyon*, 10(5), e27443, 1-14. <https://doi.org/10.1016/j.heliyon.2024.e27443>
- [21] Borsetta G., Frapiccini E., Roncarati A., Quagliardi M., Marini M., Panfili M., & Vittori S. (2024). Agri-fiSh: sustainable and innovative feeds from agricultural wastes for a resilient and high-quality aquaculture. *Detritus*, 28, 97-101. <https://doi.org/10.31025/2611-4135/2024.19398>
- [22] Rajpal M., Singh B., Chatterjee S., & Sivarajah U. (2025). Public sector development and entrepreneurial initiatives for improving circular economy performance: Government policy and digital transformation initiatives as moderators. *Technological Forecasting And Social Change*, 221, 1-13. <https://doi.org/10.1016/j.techfore.2025.124333>
- [23] Hiltunen M., Kannangara R., Nakandalage B., Söderena O., Timilsina H., Pirhonen J., & Pulkkinen K. (2025). Growth and biomass composition of *Chlorella vulgaris* using nutrient-rich water and CO₂ from a recirculating aquaculture system. *Aquaculture*, 742956, 1-11. <https://doi.org/10.1016/j.aquaculture.2025.742956>
- [24] Da Silva Fonseca A., Diniz F., Gehrke C., Nunes A., Júnior E., & Coelho L., Jr. (2025). Thermal power plants in the energy transition and circular economy: A review. *Sustainable Futures*, 10, 101302, 1-15. <https://doi.org/10.1016/j.sfsr.2025.101302>
- [25] Esposito B., Notarnicola B., Renzulli P., & Di Capua R. (2025). Circularity in the Pasta Supply Chain: Developing a Multi-Indicator Framework for Circular Economy Assessment. *Cleaner Environmental Systems*, 100327, 1-14. <https://doi.org/10.1016/j.cesys.2025.100327>
- [26] Kumari S., Qalati S., Shaikh R., & Badwy H. (2025). Connecting emerging technologies with sustainability in the circular economy: The role of efficiency in logistics systems and regulatory pressure. *Sustainable Futures*, 10, 101297, 1-10. <https://doi.org/10.1016/j.sfsr.2025.101297>
- [27] Behjat M., Svanström M., Peters G., & Wennberg N. (2025). Life Cycle Assessment of recirculating aquaculture systems with innovative biochar filter for enhanced nutrient recirculation. *Resources, Environment And Sustainability*, 100233, 1-12. <https://doi.org/10.1016/j.resenv.2025.100233>
- [28] Mustafa M., Chin J., Nungsari M., & Morris K. (2023). Do proactive students benefit more from university support for entrepreneurship when it comes to choosing entrepreneurship as a career choice? An examination of Ghanaian and Malaysian students. *The International Journal of Management Education*, 21(3), Article 100868. <https://doi.org/10.1016/j.ijme.2023.100868>
- [29] Franco A., Pucciarelli V., Hosseini S., Schmitt E., Bovera F., Scieuzo C., & Falabella P. (2025). Bioconversion of Meat and Fish-Based Former Foodstuffs by Black Soldier Fly Larvae: A Sustainable Pathway for Reducing Food Waste, Enhancing Nutrient Recovery, with a Circular Economy Approach. *Insects*, 16(5), 508, 1-20. <https://doi.org/10.3390/insects16050508>
- [30] Akanda M., Hashem S., Roy P., Haque M., & Salam M. (2025). Black soldier fly farming in Bangladesh: current practices, farmers' challenges and future opportunities. *Journal Of Insects As Food And Feed*, 1-15. <https://scopus.bibliotecaupn.elogim.com/inward/record.uri?eid=2-s2.0-85217769325&doi=10.1163%2f23524588-00001450&partnerID=40&md5=f9e5f2f18fa1ab0532a01b7df4d429fe>
- [31] Emerenciano M., Slinger J., Koster G., Aland J., Lima P., Arsic M., & O'Sullivan C. (2025). Mineral Supplementation in Jade Perch (*Scortum barcoo*) Aquaponics with Lettuce: A Comparison with Hydroponics and RAS. *Animals*, 15(3), 317, 1-18. <https://doi.org/10.3390/ani15030317>
- [32] Worawut K., Tokhun N., Noppawan P., & Phungpis B. (2024). Integrated Aquaponics System by Combining Japanese Cucumber Cultivation with Efficient Hybrid Catfish Farming for Enhanced Farmer Quality of Life. *ASEAN Journal Of Scientific And Technological Reports*, 27(5), 1-12. <https://doi.org/10.55164/ajstr.v27i5.254067>
- [33] Muduli M., Swain B., Choudhary M., Verma P., & Ray S. (2024). Environmental Contaminants Remediation from Real Domestic Wastewater through a Canna-Based Bioretention Engineered System. *Water Conservation Science And Engineering*, 9(2), 1-14. <https://doi.org/10.1007/s41101-024-00277-5>
- [34] Salvatierra D., Islam M., González M., Blasco J., & Araújo C. (2025). The Heterogeneous Multi-Habitat Assay System (HeMHAS): A non-forced ecotoxicology test system to study contamination-driven habitat selection behavior from landscape and stress ecology perspectives. *Environmental Pollution*, 368, 125818, 1-15. <https://doi.org/10.1016/j.envpol.2025.125818>
- [35] Fraga-Corral M., Ronza P., Garcia-Oliveira P., Pereira A., Losada A., Prieto M., Quiroga M., & Simal-Gandara J. (2022). Aquaculture as a circular bio-economy model with Galicia as a study case: How to transform waste into revalorized by-products. *Science of the Total Environment*, 119, 1-13. <https://www.sciencedirect.com/science/article/pii/S0924224421006397>

- [36] Anokye K. (2025). Black soldier fly larvae as a circular solution for organic waste management and sustainable livestock feed in Ghana. *Nombre de la revista*, 12, 1-17 <https://www.sciencedirect.com/science/article/pii/S2772912525002143>
- [37] Hedén I., Forghani Targhi B., Baardsen G., Westereng B., Svendsen T., Jönsson E., Hasselberg Frank L., Undeland I., Sundell K., & Sundh H. (2023). Dietary replacement of fishmeal with marine proteins recovered from shrimp and herring process waters promising in Atlantic salmon aquaculture. *Aquaculture*, 574, 1-11. <https://www.sciencedirect.com/science/article/pii/S0044848623005094>
- [38] Zuhaer A., Khandoker A., Enayet N., Partha P., & Awal M. (2026). Sustainable aquaculture: An IoT-integrated system for real-time water quality monitoring featuring advanced DO and ammonia sensors. *Aquacultural Engineering*, 112, 102620,1-12. <https://doi.org/10.1016/j.aquaeng.2025.102620>
- [39] Yu M., Feng Y., Ouyang B., Wills P., & Tang Y. (2026). Dissolved oxygen in aquaculture ponds: Causal factors, predictive modeling, and intelligent monitoring. *Aquacultural Engineering*, 112, 1-19. <https://sciencedirect.bibliotecaupn.elogim.com/science/article/pii/S0144860925001232>
- [40] Lovejan M., Jayachandran P., Syanya F., Ntakirutimana R., Aneesa K., & Mujeeb Rahiman K. (2025). Biofloc technology toward sustainable aquaculture: Opportunities, constraints, and environmental perspectives. *Aquaculture*, 743285,1-17. <https://doi.org/10.1016/j.aquaculture.2025.743285>
- [41] Hasan M., & Halwart M. (2021). Fish as feed inputs for aquaculture: Practices, sustainability, and implications. *Aquaculture Reports*, 20, 1-10. <https://doi.org/10.1016/j.aqrep.2021.100742>
- [42] Gonçalves A., Ribeiro A., Almeida C., & Silva C. (2022). From waste to feed: A circular approach to aquaculture. *Journal of Environmental Management*, 308,1-15. <https://doi.org/10.1016/j.jenvman.2022.114598>
- [43] Sazdovski I., Battle-Bayer L., Bala A., Margallo M., Azarkamand S., Aldaco R., & Fullana-i-Palmer P. (2024). Comparative assessment of two circularity indicators for the case of reusable versus single-use secondary packages for fresh foods in Spain. *Heliyon*, 10(6), 1-12. <https://doi.org/10.1016/j.heliyon.2024.e27922>
- [44] Rocchi L., Paolotti L., Cortina C., Fagioli F., & Boggia A. (2021). Measuring circularity: an application of modified Material Circularity Indicator to agricultural systems. *Agricultural and Food Economics*, 9(1), 1-13. <https://doi.org/10.1186/s40100-021-00182-8>
- [45] Aas T., Åsgård T., & Ytrestøyl T. (2022). Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2020. *Aquaculture Reports*, 26, 1-11. <https://doi.org/10.1016/j.aqrep.2022.101316>
- [46] Newton R., Malcorps W., Robinson J., Kok B., Little D., Lofstedt A., de Roos B., & Willer D. (2025). Fish as Feed: Using the nutrient Fish In: Fish Out ratio (nFIFO) to enhance nutrient retention in aquaculture. *Aquaculture*, 602, 742332, 1-9. <https://doi.org/10.1016/j.aquaculture.2025.742332>
- [47] Torres-Hoyer R., Peña J., Millalén F., Picón R., Barreto W., Peña O., & Torres-Hoyer J. (2024). Reducción del Impacto Ambiental con Desechos Industriales en Pavimentos por Análisis del California Bearing Ratio. *Revista Politécnica*, 53(2), 1–10. <https://doi.org/10.33333/rp.vol53n2.04>
- [48] Arana Landín S. (2024). Tax measures to reduce food losses and waste in the United States and the European Union: a comparative analysis. *REVESCO. Revista de Estudios Cooperativos*, 146, e94850,1-15. <https://doi.org/10.5209/reve.94850>
- [49] Niero M., & Kalbar P. (2019). Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resources, Conservation and Recycling*, 140, 1–8. <https://doi.org/10.1016/j.resconrec.2018.10.002>
- [50] Saidani M., Yannou B., Leroy Y., Cluzel F., & Kendall A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, 234, 1–13. <https://doi.org/10.1016/j.jclepro.2019.06.243>
- [51] Torres K., Florez Peña L., Sánchez C., & Castañeda Peñaranda M. (2020). Metodología SLP para la distribución en planta de empresas productoras de Guadua Laminada Encolada (G.L.G). *Ingeniería*, 25(2), 1–14. <https://doi.org/10.14483/23448393.15378>
- [52] Martín A., Tortosa G., Bustamante M., González A., & Curaqueo G. (2025). Composting Salmon Farming Sludge: A Potential Soil Amendment with a Focus on the Circular Economy Approach. *Journal Of Soil Science And Plant Nutrition*, 25(2), 1-10. <https://doi.org/10.1007/s42729-025-02465-1>