

Iaquis Conference Proceedings

*Fostering organizational transformation for a
sustainable future:
Enhancing synergies between quality, innovation and
sustainability*



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Viterbo, Italy

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Iaquis Conference 2024

**Fostering organizational transformation for a
sustainable future:**

**Enhancing synergies between quality, innovation and
sustainability**

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Foreward

The current economic, social, and environmental landscape is marked by a profound crisis, underscoring the urgent need for a paradigm shift in production and consumption patterns. The interconnectedness of these domains has become increasingly evident, with the effects of unsustainable practices rippling through economies, societies, and ecosystems.

Recent environmental and geopolitical events have further highlighted the fragility of the existing production system. Climate change, resource depletion, and geopolitical tensions have exposed the vulnerabilities of traditional economic models and the imperative for transformative action. Organizations must adapt to these challenges by embracing sustainable practices and innovating to create more resilient and equitable systems.

A synergistic contribution from academics, practitioners, and policymakers is essential to navigate this complex landscape. Academics can bring their research expertise to identify emerging trends, develop innovative solutions, and inform policy decisions. Practitioners can offer insights into the practical challenges and opportunities faced by organizations in their respective sectors. Policymakers can create enabling environments that support sustainable practices and incentivize innovation.

Academia, in particular, can play a pivotal role in driving the development of new ideas through research activities. The International Association of Quality, Innovation, and Sustainability (IAQUIS) can serve as a valuable platform for aggregating, coordinating, and mediating these efforts. By fostering collaboration among professors, researchers, doctoral students, and practitioners from around the world, IAQUIS can facilitate constructive discussions and knowledge sharing.

The choice of the main themes, "Quality, Innovation, and Sustainability," reflects the interconnected nature of these concepts and their critical importance for a sustainable future. Quality, as a cornerstone of excellence and customer satisfaction, is essential for long-term organizational success. Innovation, as the driving force behind progress and adaptation, is crucial for addressing emerging challenges and creating new opportunities. Sustainability, encompassing environmental, social, and economic dimensions, is a fundamental imperative for ensuring the well-being of future generations.

By adopting a cross-cutting and synergistic perspective, organizations can unlock the full potential of quality, innovation, and sustainability. This involves integrating these elements into all aspects of business operations, from product design and production to supply chain management and customer relationships.

The First IAQUIS Conference provides a unique opportunity to initiate a network of relationships and connections among key stakeholders from academia, industry, and policymaking. Through collaborative discussions and knowledge sharing, participants can explore innovative approaches, identify best practices, and develop strategies for fostering organizational transformation.

By focusing on quality, innovation, and sustainability, IAQUIS aims to contribute to a more equitable, resilient, and sustainable future for all.

Viterbo, Italy

Alessandro Ruggieri

Preface

The first Iaquis Conference was held in Viterbo (Italy) from 11th to 13th September 2024. It was promoted by the International Association for Quality, Innovation and Sustainability and hosted by the Department of Department of Economics, Engineering, Society and Business Organisation of University of Tuscia in Viterbo, Italy.

The objective of the Conference was to stimulate and foster collaboration and knowledge exchange in the areas of Quality, Innovation and Sustainability among researchers, educators, practitioners, and doctoral students hailing from diverse countries and backgrounds.

Over the course of the three-day Conference, the participants had the opportunity to present their research in both plenary and parallel sessions.

The central theme that permeated all discussions revolved around the synergies between Quality, Innovation, and Sustainability, embracing an interdisciplinary perspective and a cross-cutting approach.

A pre-conference Doctoral Consortium was held. During the Doctoral Consortium the PhD Students presented their research program and findings, and received suggestions by the mentors. Moreover a seminar on how to develop an impactful paper was held to provide young scholars with in-depth feedback from experienced lecturers on their ongoing research.

The Conference collected a total of 83 Papers from 15 countries. Some of the authors asked not to be publish their paper in these proceedings, thus some contributions will not appear, besides being counted.

The great number of papers and the variety of the topics allowed us to organize numerous parallel sessions, by dividing the papers into 18 tracks, plus the Doctoral Consortium:

- 1) Circularity
- 2) Healthcare
- 3) Sustainability in Tourism
- 4) Sustainability in Agri-Food
- 5) Sustainability
- 6) Life Cycle Assessment
- 7) Quality and Innovation in Food Sector
- 8) Innovation Industry 4.0
- 9) Quality Management
- 10) TQM and Sustainability
- 11) TQM and Employees
- 12) Quality Management and Improvement
- 13) Management Systems
- 14) Life Cycle Assessment
- 15) Sustainability and Service Innovation
- 16) Sustainability
- 17) Sustainability in Energy Sector
- 18) Innovation.

Due to the conspicuous number of the papers which fell under the topics of “Sustainability” and “Life Cycle Assessment”, each of these parallel sessions were split in two sessions, allowing all the authors to present their contribution.

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Track 6: Life Cycle Assessment

A preliminary LCA of rainbow trout farming: a Case Study on freshwater aquaculture in Italy

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Abstract

Marine and freshwater fish aquaculture plays a significant role globally in ensuring food security. In 2020, marine fish accounted for 39% of the total aquatic animal production, while freshwater fish constituted 33% of total aquatic animal production. This trend is particularly notable in Europe, where species like rainbow trout, seabass and seabream are extensively farmed. Among them, rainbow trout is one of Europe’s top five farmed species in terms of production and in Italy it is the main breeding species. However, despite the sector’s significance, there is a gap in the literature concerning the potential environmental impacts generated by farmed rainbow trout (e.g., nutrient discharge, use of non-renewable resources, overexploitation of fish stocks). To cover this gap, this study aims to assess the potential environmental impacts of the rainbow trout production process, accounting a cradle to gate approach: from egg to grown fishes, ready for market. These are assessed applying the Life Cycle Assessment (LCA) method, in order to identify the main hotspots of process. The case study is conducted on trout farming using primary data provided by an Italian company that encompasses the entire production process. The data are collected through questionnaires and site visits, focusing on feed consumption, natural resource utilization, and emissions generated. The main findings of this study allow to identify the key environmental hotspots along the different stages of trout production, providing a basis for informing decision-making on which processes could be optimize and improved to mitigate environmental impacts effectively.

Keywords: LCA, rainbow trout, freshwater aquaculture.

Introduction

In recent decades, global aquaculture has grown significantly to meet rising food demand. From 2000 to 2022, global production of farmed animals increased by 204 per cent to 87.9 million tonnes. Finfish, in particular freshwater species, dominate this sector, with their share increasing from 20 per cent in 1961 to 55 per cent in 2021 (FAO, 2024). European aquaculture growth by more than 70.7 per cent from 2001 to 2022, with freshwater finfish being the most farmed group.

Salmonids, especially trout, are among the most valuable traded aquatic species. In 2020, Europe produced 183 thousand tonnes of rainbow trout, with Italy being the third largest producer with 33.8 thousand tonnes (STEFEC, 2023). However, the rapid growth of the aquaculture sector has raised a number of sustainability concerns. These include emissions leading to climate change, eutrophication, toxic and ecotoxic effects, use of antibiotics, land and water requirements for feed production, biodiversity loss, introduction of non-native species, spread of parasites and diseases, genetic pollution, reliance on capture fisheries and socio-economic issues (Kok *et al.*, 2020; Ghamkhar *et al.*, 2021). Sustainable strategies intensification is essential to address these issues. Among the different tools available to assess environmental impacts, there is a growing interest in the literature towards life cycle assessment (LCA) as a holistic method. LCA is one of the environmental accounting tools that can provide critical information needed to improve the sustainability of aquaculture systems (Philis *et al.*, 2019). Indeed, LCA has been used in previous studies on salmonid and trout farming (Boissy *et al.*, 2011), as it is a valuable assessment method, standardised by ISO principles in ISO 14040 and 14044 (2006 a, b), to identify and monitor potential hotspots in aquaculture (Aubin *et al.*, 2009; Jerbi *et al.*, 2012; Dekamin *et al.*, 2015). However, although rainbow trout is the main species produced in Italy (STEFEC, 2023) and aquaculture generates various environmental impacts (Laso *et al.*, 2022), there is only one study in the literature that applies LCA for assessing Italian trout farm environmental impacts (Maiolo *et al.*, 2021), and only nine LCA studies at global level on trout, seven of which are included in Philis' review (Philis *et al.*, 2019), with two additional papers published after the cited review and up to the first half of 2024 (Sanchez-Matos *et al.*, 2023; Pouil *et al.*, 2024). In detail, these studies used the LCA method to assess the potential environmental impacts of the pre-fattening and growing phases of trout, often neglecting the sowing and weaning phases, or aggregating the growing phases and including post-harvest activities. They primarily focused on the impacts of raw materials, particularly feed, with quantities typically estimated based on feed conversion ratios (Philis *et al.*, 2019) rather than directly collected for each trout growing phase. Furthermore, they overlooked detailed electricity consumption for each growth phase (Sanchez-Matos *et al.*, 2023), the distinction between grid and sustainable energy sources, and the environmental impact of packaging. Various studies have compared the environmental impacts of trout farming in different systems, such as conventional versus land-based closed recirculating systems, focusing on differences in feed conversion rates (Aubin *et al.*, 2009) or oxygen consumption (D'Orbcastel, Blancheton and Aubin, 2009), with environmental flows often limited to nutrient balances (Henriksson *et al.*, 2012). Other LCA studies have compared production scenarios using conventional feeds with innovative feeds based on plant ingredients, recycled fish industry by-products or insecticides (Dekamin *et al.*, 2015).

Therefore, considering that to date, no LCA studies have comprehensively addressed all stages of rainbow trout production, from embryonic eggs to commercially sized fish (Philis *et al.*, 2019). Thus, by examining the potential impacts generated at each stage of the production process, this study provides a novel insight into the environmental impacts of rainbow trout (*Oncorhynchus mykiss*) farming, highlighting the different contributions of the same inputs at different stages of production. This aspect of carrying out a contribution analysis has been largely neglected in the literature. While Silvenius (2017) carried out a contribution analysis, it focused on the environmental impact contribution of clusters of national trout farms producing adult fish of different sizes, with impacts determined based on the weight of the final product at the farm gate. In contrast, this study captures, within a single production cycle, the specific impacts that contribute most to each of the three main impact categories presented, providing an innovative and comprehensive approach to understanding the environmental dynamics of rainbow trout (trout) farming.

Methods

This paper uses the LCA method to identify environmental hotspots in rainbow trout farming, providing insights into resource use and emissions. Following the ISO 14040-44 standards (ISO, 2006b, 2006a, 2020a, 2020b), this section includes four sub-sections to describe assumptions, approaches and choices made for goal and scope definition, including a brief description of case study (2.1), inventory analysis (2.2), impact assessment (2.3) and results and discussion (3) phases. This study provides a contribution analysis of how factors from the three different growth phases of the fish impact on the environment.

Goal and scope definition

The aim of this study is to assess the potential environmental impacts of trout production in a freshwater flow-through system (FWFT) fed by natural karst spring water in Italy. A contribution analysis allows for identifying potential environmental hotspots. To achieve this, a trout farm in the Triveneto region of Italy is selected as a case study (CS) and the potential environmental impacts throughout the entire growth cycle of the trout are assessed. Indeed, the farm manages the entire life cycle of trout, from embryonated eggs to market size fish. The farming process is investigated according to three main phases: i) hatchery, where eggs are incubated and fry are reared for approximately two months; ii) pre-fattening, where fish grow to 220-250 grams over eleven months; and iii) on-growing, where adult fish reach a final size of around 1,000 grams in approximately seven months. Strict protocols for feeding, cleaning and water management are followed to ensure fish health and growth. Data collection occurred in the first quarter of 2024, covering the period 2022-2023, as the trout life cycle is about 20 months. This preliminary assessment of the environmental performance of the system suggests potential improvements to help farmers reduce the environmental impact of aquaculture processes. The functional unit (FU) selected for the study is 1 tonnes of live weight (LW) rainbow trout, as it is the most commonly used in literature (Dekamin *et al.*, 2015; Philis *et al.*, 2019; Maiolo *et al.*, 2021; Sanchez-Matos *et*

al., 2023; Pouil *et al.*, 2024). The system boundaries, shown schematically in Figure 1, follow a cradle-to-gate approach, encompassing three main growth phases of trout reared in freshwater under continuous flow conditions.

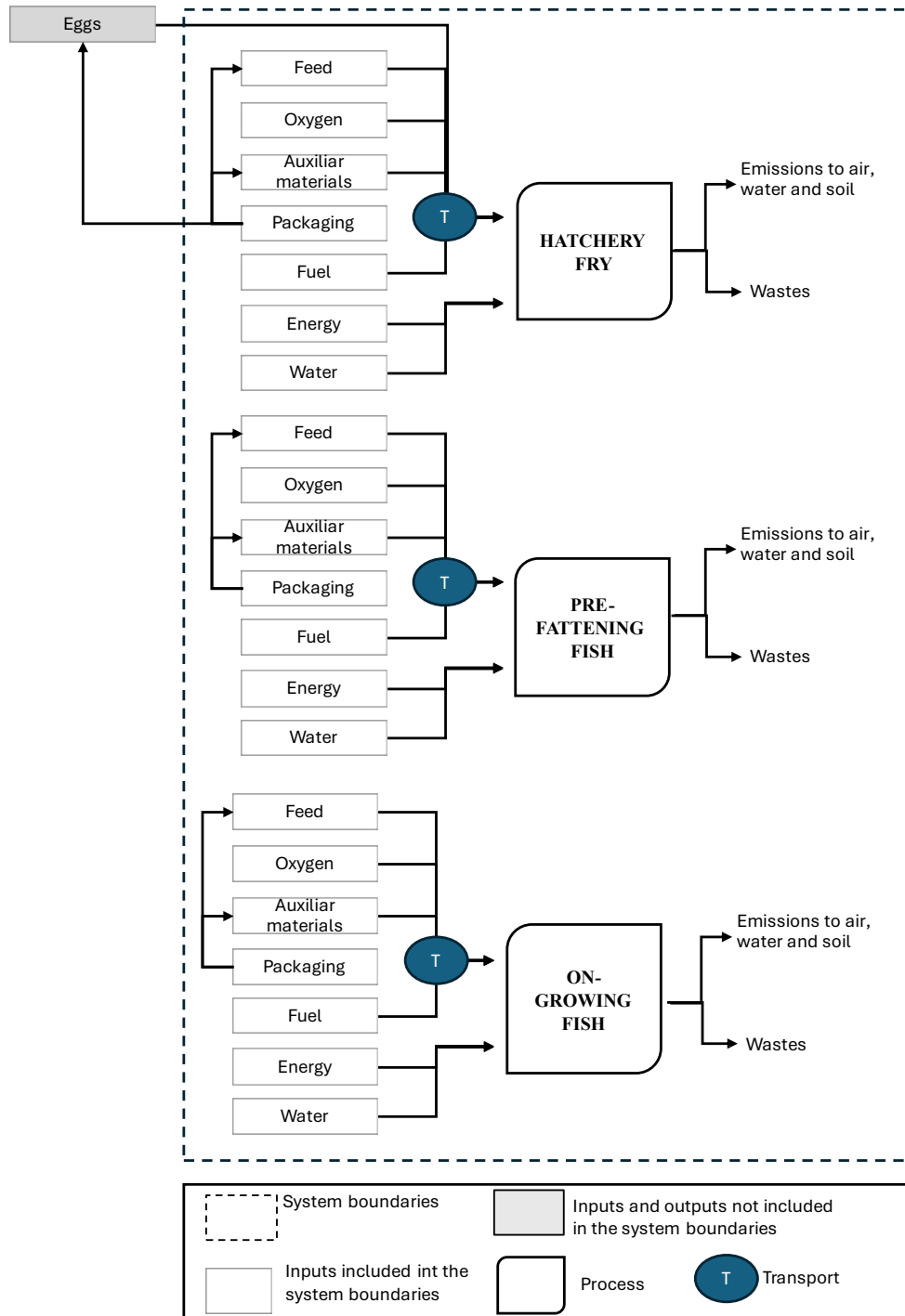


Figure 1: System boundaries of the case study on rainbow trout production

As highlighted in Figure 1, the study includes all the impacts linked to resource production, energy consumptions and water use, as well as all the contributes of internal transportation from one phase to another.

Instead, the production of embryonated eggs is excluded from the system due to missing data, but their transport from suppliers is included. Additionally, some other processes are excluded: a) the transport of market-ready fish to customers, b) the disposal of dead fish by an authorised company that uses them for processing into animal feed, c) the sludge produced by the farm that is generally used for agricultural purposes and whose contribution is excluded from the analysis based on previous studies (Besson *et al.*, 2016), and d) infrastructure, due to the significant time required to calculate their total input relative to their minimal impact (Ayer and Tyedmers, 2009, 2010). However, the energy and the fuel consumed at each stage are included. Both primary and secondary data are used. Primary data are collected through interviews with key managers. The farm provided data managed through its internal management system, which tracks the quantities of raw materials, energy and fuel consumed through supplier invoices. The farm provides data on the production batch because it has an in-house traceability system that keeps a daily log of all information relating to the farmed fish in each tank. Thus, all data are collected for the two calendar years covered and related to the production batch covered by this CS.

Secondary data are used when some data is missing, e.g., the amounts of direct emissions to water generated by feed. In this case, technical sheets of feeds are used. Other secondary data are related to the estimation of the background processes, obtained from the Ecoinvent 3.8 database (Moreno Ruiz *et al.*, 2021). The LCA study is performed using the SimaPro v. 9 software.

Inventory analysis

The inventory analysis involved the collection of data to quantify the inputs and outputs associated with the production of one tonne of LW rainbow trout (FU). As mentioned above, both primary and secondary data are used for the study. The first are collected through questionnaires, site visits and interviews with the production manager, owner and veterinarian of the organisation. The inventory includes information about feed, energy, water, oxygen and other resources used from the production from fingerling to adult fish and the release of farm emissions to the environment. Table 1 shows the input and output data included in the analysis in relation to each stage of growth to produce 1 tonne of LW trout.

Inputs were specific to the batch analysed, corresponding to the actual duration of each growing phase. The use of water from river was calculated from tank volumes and cross-checked with the farm's annual water flow analyses. The water entering the farm had an average flow rate of 0.4 m³/s. The water from river is equal to the water back to river, as the farm uses a continuous water flow system, as commonly assumed in the literature (Maiolo *et al.*, 2021). Therefore, in the case of trout, water drawn from the river to supply the raceways for trout production was not taken into account because this water was returned to the river and thus reusable (Boissy *et al.*, 2011).

The feed data are based on the actual amounts used throughout the rearing period. The feed production process is modelled using Ecoinvent datasets (Moreno Ruiz *et al.*, 2021). Unlike typical LCA studies of rainbow trout

and salmonids, which often rely on estimates using feed conversion ratio (FCR), this study provides accurate feed data. The accuracy of the reported quantities was verified by estimating the FCR (FCR = kg of feed distributed / kg of live weight fish produced) for each stage of production. Feeding rates were monitored from hatching to pre-fattening, with later phases estimated from the farm's recorded FCR and compared with supplier rates and literature values (Philis *et al.*, 2019).

Table 2: Life Cycle Inventory: Input and output data for each phase is scaled to 1 tonne of live weight rainbow trout.

Category	Unit	Phase		
		Hatchery Fry	Pre-Fatty Fish	On-Growing Fish
INPUT				
Feed	kg	7,56E-01	5,50E+02	5,18E+02
Disinfectant	l	2,98E-02	1,31E-01	1,31E-01
Diesel	MJ	3,45E+00	2,73E+01	5,14E+01
Electricity	kWh	3,00E+01	9,88E+00	2,43E+01
Electricity (pv)	kWh		5,37E+01	1,79E+01
Water (from river)	m ³	7,29E+02	2,37E+04	5,50E+04
Mixed petrol	kg	8,87E-03	1,95E-01	1,31E+00
Oxygen	kg	8,40E-03	1,47E+00	5,51E-01
Packaging (hdpe)	kg	9,95E-04	1,19E-02	1,19E-02
Packaging (ldpe)	kg	1,51E-02	6,45E+00	6,06E+00
Packaging (ps)	kg	3,98E-03		
Transport	kgkm	2,76E+04	7,79E+05	8,22E+05
OUTPUT				
1° phase hatchery	kg	2,87E+01		
2° phase pre-fattening	kg		4,24E+02	
3° phase on-growing	kg			1,00E+03
Water (back to river)	m ³	7,29E+02	2,37E+04	5,50E+04
Emissions to water (N)	kg	5,11E-01	1,51E+01	4,23E+01
Emissions to water (P)	kg	1,75E-02	2,23E+00	3,57E+00
Waste incineration (organic waste, PE, PS, PP, PB)	kg	4,37E-01	3,04E+01	2,89E+00
Waste recycling (PE)	kg	1,51E-02	6,45E+00	6,06E+00

Also the production of liquid oxygen from the cryogenic air separation process was considered, following the methodology used in other LCA studies on rainbow trout (Pouil *et al.*, 2024). Oxygen consumption was provided by the farm based on the quantities purchased for the batch. The quantity for each phase was allocated according to the fish movements, as oxygen is used in all phases for transport and in the hatchery and pre-fattening phases to enrich the water input.

Auxiliary materials use, such as disinfectants, was calculated according to the farm's internal hygiene and safety procedures. Packaging data refers to consumables and raw materials purchased by the company, as farmed fish arrive and leave the farm unpacked.

Fuel and energy consumption has been calculated based on the hours of use and power ratings of machinery and equipment, validated by electricity bills and fuel purchase records.

Transport was calculated based on the number of kilometers travelled annually by the farm's own truck, considering the real number of trips made exclusively for the batch analysed. Transport of raw materials has been calculated using supplier invoices for 2022-2023, estimating the kilometers attributable to the batch by knowing the distances between the suppliers and farm sites and the number of trips made.

Outputs included resource use within the system. Dead fish waste was calculated based on mortality rates provided by the farm and cross-checked with records from the authorised fish waste disposal company. Packaging waste from feed sacks, medicated feed, disinfectants and egg transport frames was weighed and calculated for each farming phase, categorised for accurate disposal tracking (recycling or incineration) and validated against company waste management records. Transport also includes the kilometers travelled to approve the fuel used in vehicles and equipment. In this case, the farm reported the number of approvals, assuming that the average distance to the supplier was always around 5 km. Emissions were calculated from feed technical sheets and compared with the farm's bi-annual chemical-physical analyses to ensure data accuracy for this analysis, using secondary Ecoinvent data.

Impact assessment.

For the impact assessment phase, the CML-IA baseline method (Guinée *et al.*, 2002) is selected according to the findings of Philis *et al.* (2019), which indicate this method as the most employed in salmonid LCA studies. For this preliminary study, only three key impact categories are selected, in line with the evidence presented in the existing literature (Grönroos *et al.*, 2006; Philis *et al.*, 2019), namely: climate change (GWP) (Aubin *et al.*, 2009; D'Orbcastel, Blancheton and Aubin, 2009), acidification (AP) (Avadí and Fréon, 2013; Chen X. *et al.*, 2015), and eutrophication (EP) (Ayer and Tyedmers, 2009). These impact categories were chosen due to their scientifically established characterisation factors, which have been thoroughly validated and widely discussed in LCA studies on trout production (Philis *et al.*, 2019).

Results and Discussion

Table 2 reports the characterization results of analysis, showing the potential environmental impacts for the FU selected.

Table 3: Potential environmental impacts of the three rainbow trout farming stages for FU (characterization results)

Impact category	Unit	Hatchery fry	Pre-fattening fish	On-growing fish	TOTAL
GWP	kg CO ₂ eq	2.67E+01	1.15E+03	1.14E+03	2.32E+03
AP	kg SO ₂ eq	8.77E-02	3.98E+00	3.90E+00	7.97E+00
EP	kg PO ₄ ³⁻ eq	2.93E-01	1.61E+01	3.14E+01	4.78E+01

The table clearly shows that the greatest impacts in all categories are generated by the second and third phases. In particular, each phase contributes to each impact category as follows:

- hatchery fry phase contributes minimally to GWP (1.2%), AP (1.1%), and EP (0.6%);
- pre-fattening fish phase contributes significantly to GWP (49.6%), AP (49.9%), and EP (33.7%);
- on-growing fish phase contributes significantly to GWP (49.1%), AP (48.9%), and EP (65.7%).

In order to observe which is the main hotspot that affect each phase of growing of trout, a contribution analysis is conducted reporting the results in Figure 2. This detailed breakdown highlights the environmental inputs and outputs at each stage and provides insight into the main factors influencing the overall environmental footprint of the production system.

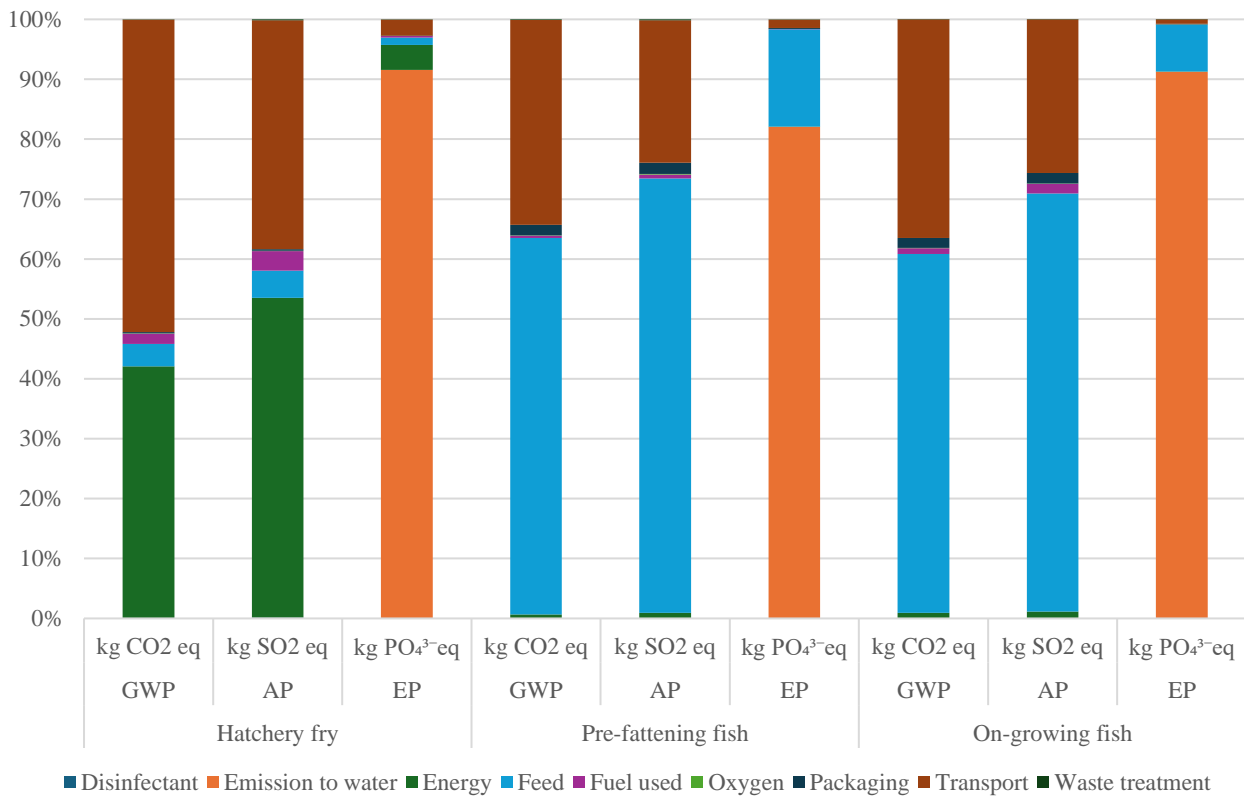


Figure 2: Contribution analysis for the three phases of the trout production system (characterization results).

According to the graph of figure 1, it could be noticed that some major differences between the hotspots in the hatchery fry phase compared to the subsequent phases of pre-fattening and on-growing to adult fish exist.

In the hatchery phase, the main contributors to the GWP are energy (around 42%) and transport (52.2%). For the AP, the main contributors are also the energy (53.4%) and transport (38%). For EP, emissions to water dominate (91.5%).

In the pre-fattening phase, feed is the main contributor to GWP (63%), followed by transport (34.2%). For AP, feed contributes 72.5% and transport 23.8%. For EP, emissions to water (82%) and feed (16.2%) are the main contributors, with transport having a minor impact (1.4%).

In the on-growing phase, feed is the dominant factor for GWP (60%) followed by transport (36.5%). For AP, feed (70%) and transport (25.6%) are significant, while packaging is minor hotspot (less of 2%). For EP, emissions to water are the main contributor (91.2%), with feed contributing around 8%, while the transport contributes with less than 0.7%.

Additionally, in order to analyse if the results obtained in this CS are accurate, each impact category for each phase is compared with the literature results and discussed more in-depth in the following paragraph. In particular, the GWP for 1 tonnes of trout in this CS appears significantly better than that reported in the literature. Specifically, the GWP impact for trout is 21% lower than the literature reference value of 2,613 kg

CO₂ equivalent for inland water trout farming systems with continuous flow rivers (Philis *et al.*, 2019). This improvement is attributed to innovations in feed, with the commercial feeds used by the company being less impactful and more efficient in terms of both fish growth and environmental emissions (Chen X. *et al.*, 2015). The feed represents the main hotspot in this preliminary assessment, especially in pre-fattening and on-growing phases. It affects all categories significantly. For GWP, it contributes 59.9% (on-growing) to 62.9% (pre-fattening). Therefore, the preliminary results confirm that the feed is the largest contributor to these impacts (Aubin *et al.*, 2019), and it is consistent with the literature where feed production in land-based flow-through systems accounts for 48% to 88% of the impact categories considered (Ayer and Tyedmers, 2009). In this CS, feed contributes to 61% of total GWP related to life cycle of trout production. This result could be attributed to two factors that characterise the feeding process: feed is distributed only when the feed operators visually detect that the rearing fish are hungry, combined with a gradual transition to feeds containing higher percentages of plant-based ingredients and recycled by-product animal feed.

In order to fully understand the contribution of each trout growth phase to the impact categories, the distribution of different contributors to GWP is analyzed. The GWP is almost equally distributed between the pre-growing phase (49.2%) and the growing phase (49.6%), with the weaning and hatchery phases having a negligible impact (1.2%). In this CS, the most significant contributors to GWP are the transport of embryonated eggs and the use of grid electricity, accounting for 52% and 42% of the impact respectively. In particular as a hotspot, the transport results significant in hatchery and pre-fattening p; in particular for GWP (34.2% in pre-fattening to 52.2% in hatchery) and AP (23.8% in pre-fattening to 38% in hatchery).

EP impact is notable in the pre-fattening phase (23.8%). The impact on freshwater ecosystems is primarily influenced by the use of grid electricity, which accounts for about 70% of the impact, while egg transport contributes about 25%. This distribution is likely to reflect the initial rearing phase, which in this CS lasts about 2 months to produce juveniles averaging 10-15 grams. In contrast, other studies indicate a longer larval period to produce juveniles of approximately 70 grams. The farm's decision to limit the use of feed in the rearing phase only when fish are visibly hungry has probably resulted in a low overall impact on acidification (AP) and eutrophication (EP), contributing less than 1.1% and 0.6% respectively to the total AP and EP for the entire rearing cycle. Both the pre-fattening phase and the growing phase of adult fish have a similar impact on AP (around 49%). However, there is a significant difference in the impact on EP between these phases. The growing phase accounts for approximately 66% of the total EP impact for the entire rearing cycle. Specifically, the final growing phase of adult fish contributes more than 90% of the EP due to emissions released to the freshwater environment when process water is returned to the river. In addition, 8% of the EP is attributed to the use of high protein feed during this phase, resulting in a feed conversion ratio (FCR) of 0.9%. In the present trout LCA, the AP impact was found to be 7.97 kg SO₂ eq per tonne of LW trout. This is significantly lower than reported in other studies. For example, Grönroos (Grönroos *et al.*, 2006) reported 8.8 kg SO₂ eq per tonne LW trout, while Ayer and Tyedmers (Ayer and Tyedmers, 2010) calculated up to 63.4 kg SO₂ eq for similar outputs. For freshwater trout land-based systems in tanks, the average AP is about 16.3 kg SO₂ eq. Although

the literature discusses whether there may be a correlation between AP and the FCR of the feeds used (Philis *et al.*, 2019), the AP in the present LCA is significantly lower than in previous studies. This could be due to an average FCR of 0.9-1, combined with the low average biomass density of less than 15 kg/m³ in the continuous flow water system that supports the entire aquaculture facility. Nevertheless, feed formulations can have a significant impact on AP values. In the present LCA, feed contributes to AP in the pre-growing phase (73%), followed by transport (24%). In the on-growing phase, AP is attributed to feed input (70%) and transport (26%). Acidification is strongly linked to fuel combustion and fuel consumption per kg of fish produced and can vary greatly depending on the region and fish species (Tyedmers, 2004; Pelletier *et al.*, 2007; Parker, 2012). In this LCA study, the EP is 47.5 kg PO₄³⁻-eq. The preliminary results of this study align with Boissy's findings on innovative feeds (Boissy *et al.*, 2011). EP seems to correlate with feed ingredient formulation and supports the view that feed is a major contributor to the environmental impact of fish farming (Boissy *et al.*, 2011). EP values range from 42.2 kg PO₄³⁻-eq with standard feed to 47.9 kg PO₄³⁻-eq with new formulations based on soy and other vegetable ingredients. This supports the transition to innovative feeds used on the farm and confirms that EP is strongly related to the feed formulation and the feeding protocols used on the farm. Specifically, in this CS, the 43% of EP is attributed to phosphorus (P) emissions, 40% to nitrogen (N) emissions and 16% to the type of feed used. The production phases that contribute most to the total EP value are the growing phase of the adult trout, which accounts for 51% of the emissions leading to EP, and the pre-fattening phase, which contributes 16%. In detail, EP in the growing phase was mainly related to emissions (P and N), accounting for about 91% of total EP, and less than 8% to feed. The preliminary results of this study confirm the diversity found in the literature on this topic. Indeed, the average EP for trout in LCAs was around 50.7 kg PO₄³⁻-eq (Philis *et al.*, 2019). Some researchers have investigated the replacement of fishmeal and fish oil with vegetable ingredients and found that the environmental impact of trout diets vary with the geographical origin of the fishmeal and fish oil (e.g. Peru or Norway) and the type of plant used (e.g. rapeseed or palm oil). In this study, the findings regarding EP highlight the heterogeneity of results reported in previous studies for this impact category. Thus, according to the preliminary results of this study, the EP seems to correlate with feed ingredient formulation and supports the view that feed is a major contributor to the environmental impact of fish farming (Boissy *et al.*, 2011). The preliminary results related to emissions that impact EP must be subjected to further analysis in future studies. It should be noted that the EP method is currently unable to assess other potential releases, such as dead fish, faeces production, and feed loss during distribution, as it only evaluates the feed. In a final assessment of these impacts, individual pollutant emissions of various elements not considered in this preliminary analysis could be calculated, as they might demonstrate different impacts on EP. This approach has been previously utilised in a study which employed mass-balance methods (Besson *et al.*, 2016).

Conclusions

In conclusion, this LCA study of 1 tonne of LW trout farmed in northern FWFT Italy provides preliminary results on the impact categories of GWP, AP and EP, which are of significant interest to researchers. The study

identifies hotspots contributing to these impact categories, with the highest impacts associated with phases of pre-fattening and on-growing fish, particularly due to feed use. This study represents the first attempt to model an LCA analysis of Italian trout aquaculture using water from natural springs with a constant temperature of 13°C throughout the year. The results show that the AP is significantly lower than reported in the literature, reflecting the responsible and sustainable practices adopted by the farm. By controlling the average biomass density in the trout pond, which never exceeds 15 kg/m³, the company ensures the dilution of biomass production emissions in water volumes that also guarantee oxygenation rates above vital minimums. This practice maintains the well-being of the fish, as evidenced by the fact that medicated feed was only used for a few days during the weaning and pre-fattening phases (when the fish had an average weight of 15 grams). The environmental sustainability of farm is also linked to the feeding protocol, which includes commercial feeds based on both fish and vegetable meal. Semi-automated feeding is always supported by a feeding operator who adjusts the amount and timing of feeding based on constant observation of fish movements. This approach reduces uneaten and lost feed in the water leaving the farm. The pre-growing phase has a slightly higher impact across all three categories, except for EP, which is more significantly influenced by the on-growing phase of adult trout. This may be due to the higher energy ingredients used in the feed formulation during the later stages of the on-growing phase. In both the pre-fattening and the on-growing phases, feed is the main source of environmental impacts, followed by transport and the use of electricity from the national grid. The main hotspots generating environmental impacts in the continuous flow production cycle of trout at the Triveneto company are a) feed, the main source of environmental impacts in both the pre-fattening and fattening phases. b) transport, the second largest contributor to AP and GWP impacts. c) electricity use, a significant contributor in hatchery to all three impact categories, particularly due to the reliance on electricity from the national grid. As the sector is energy intensive, a comprehensive LCA should include the calculations of energy indicators to provide a more complete understanding with trout farming. Indeed, future research should focus more on the energy aspects of trout aquaculture, in particular exploring the potential impact of using solar energy during all three phases of the rearing cycle, rather than only during the pre-fattening and growing phases, as is currently the case. To evaluate these contributions, a solution could be including the calculation of Cumulative Energy Demand (CED), which quantifies the total energy required throughout the production, use and disposal of a product or service. Moreover, a limitation of the present study is the need for a more in-depth evaluation of feeds, especially medicated feeds. This limitation is due to the lack of datasets that better represent the different types of feed, especially medicated feed. To address this, future research should focus on developing comprehensive datasets that accurately reflect the environmental impacts of different types of feed used in aquaculture. Furthermore, the preliminary results related to emissions must be subjected to further analysis in future studies. It must be acknowledged that the EP impact category is currently unable to assess other potential releases, such as dead fish, faeces production and feed loss during distribution, as it only evaluates the feed. In the light of the preliminary results reported, among the solutions proposed for future investigation, it is suggested that the effects of producing more sustainable feeds, such as those based on algae, should be evaluated in more detail and that it should be understood if there are benefits to be gained from the use of

algae-based feeds. Similarly, the organic waste produced in aquaculture could be considered for its value in other sectors such as agriculture as bio-fertiliser, in the chemical and pharmaceutical industries for the extraction of valuable compounds. Finally, assessing the environmental impact of aquaculture infrastructure is crucial, especially in disadvantaged mountainous areas. Properly managed aquaculture can contribute to environmental conservation measure, helping to maintain the ecological state of the neighbouring area.

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