Journal of Cleaner Production xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

From feed to fork – Life Cycle Assessment on an Italian rainbow trout (*Oncorhynchus mykiss*) supply chain

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ARTICLE INFO

Article history:
Received 3 June 2020
Received in revised form
30 September 2020
Accepted 14 November 2020
Available online xxx

Handling editor: Zhifu Mi

Keywords:
Environmental sustainability
Aquaculture
Feed
Fish processing
Fish by-products
Pet-food

ABSTRACT

The body of knowledge in trout farming sustainability is still not exhaustive, mainly due to the variability in the production system and in the methodological approach and partly to data quality issues. As such, Life Cycle Assessment (LCA) was applied to a trout supply chain located in Northern Italy, basing the inventory dataset almost entirely on primary data gathered from producers and extending the system boundaries beyond the conventional farm-gate, in order to include: phase 1. feed production; phase 2. trout grow-out in freshwater flow-through systems; phase 3. trout processing into foodstuff; phase 4. fish by-products processing into pet-food ingredients.

The results highlight that, while resource sharing in phase 3 is a winning practice and leads to decrease in environmental impacts, the other three phases present crucial aspects which require either technological or methodological improvements. Firstly, the relative contribution of feed ingredients is very high, with respect to all the impact categories considered. Secondly, despite on-farm effluents account alone for 92% of downstream river eutrophication (phase 2), data from rivers environmental monitoring prove this result to be an overestimation, due to the fact that LCA does not adequately cover proximate ecological concerns as yet. Finally, the energy demand for the recovery and recycling of the fish by-products (phase 4) is high, causing a high impact on global warming, terrestrial ecotoxicity, freshwater ecotoxicity and cumulative energy demand.

In order to improve the overall sustainability of the supply chain, changes are required mainly in the feed production and by-product processing phases. As far as the former is concerned, a winning strategy would be the formulation of feeds with more sustainable feed ingredients and further improvements in the feed quality (palatability, digestibility, nutritional content). In regard to the latter, more attention should be paid towards the source and amount of energy consumed. For instance, the use of renewable energy sources might be coupled with an improved insulation of the facilities and the use of less energivorous machineries/processes.

1. Introduction

The European Union boasts a relevant production of rainbow trout (*Oncorhynchus mykiss*), with 185 thousand tons valued at €615 million in 2016. Italy plays an important role in this context, accounting for 19% of the European production followed by Denmark and France (17% and 14%, respectively) (STECF - Scientific Technical and Economic Committee for Fisheries, 2018). Rainbow trout production in Italy steadily increased from the 1960s–1990s, reaching a peak of over 50,000 tons in 1997 (Iandoli and Trincanato, 2007). This positive trend was followed by a sharp decrease, due to market saturation and the consequent devaluation of the product (Roncarati and Melotti, 2007). In order to cope with this financial stress and thus to increase the value of the product (Iandoli and Trincanato, 2007), farmers began to sell processed fish (such as smoked fillets, hamburgers, fish skewers). As a consequence, nowadays only small-size fish (below 500 g) is sold as head-on-

Abbreviations: CED, Cumulative Energy Demand (characterization factor); FEP, Freshwater Eutrophication Potential (characterization factor); FETP, Freshwater Ecotoxicity Potential (characterization factor); GWP, Global Warming Potential (characterization factor); IC, Impact Category; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; TAP, Terrestrial Acidification Potential (characterization factor); TETP, Terrestrial Ecotoxicity Potential (characterization factor).

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https://doi.org/10.1016/j.jclepro.2020.125155
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gutted trout while larger fish (from 500 g up to 1–2 kg) is produced exclusively to be converted into processed products (Fabris, 2012). Thanks to this market strategy, the annual production became stable, and has always assumed values of around 40,000 tons in the last decade (Parisi et al., 2014; STECF - Scientific Technical and Economic Committee for Fisheries, 2018).

According to the last Italian census of aquaculture (PO FEAMP, 2014–2020), currently there are around 310 freshwater farming companies, most of which produce rainbow trout. Being an anadromous species (*i.e.* a species ascending rivers from the sea for breeding), trout tolerates a wide range of environmental conditions and live in headwaters, lakes and even seawater (Page and Burr, 2011). However, the optimum environmental conditions are represented by fast-flowing, well-oxygenated waters, with temperatures below 21 °C (Parisi et al., 2014). In Italy, these conditions are typical of mountainous watercourses on the Alps and Apennines and of karst springs (*i.e.* springs at the end of waterfilled cave systems), which are widespread in the northern Plain of the Po river. For this reason, 78% of trout companies are located in Northern Italy and in particular in Veneto, Friuli-Venezia Giulia and Trentino-Alto Adige (with 70, 68 and 58 companies respectively) (Fabris, 2012).

In Italy, trout production is generally carried out in monoculture flow-through systems (either concrete raceways or earthen ponds). Among Italian trout farms, around 20 entrepreneurial companies are large-sized and organized in a fully integrated supply chain. These companies account for a large share of the National production (60% in terms of volumes), and their products are sold on the national and international market both as whole fish and as processed products (ISMEA, 2009). However, they represent in number only 6% of the 310 existing companies. The remaining 94% is represented by medium-small size companies, either partially or totally family-run, with a yearly production lower than 200 tons per production site in 9 out of 10 cases (Iandoli and Trincanato, 2007) and a stocking density ranging, in the grow-out phase, from 30 to 80 kg m^{-3}, mainly depending on the water pH (Borroni, 2007).

The environmental performance of rainbow trout farming has already been investigated by means of several assessment tools, including Life Cycle Assessment (LCA). LCA represents an internationally standardised methodology which allows both to quantify the environmental impacts caused by the production, use and/or disposal of a good and to identify critical aspects along its supply chain (Wolf et al., 2012). The concept on which the analysis is based is that any good undergoes many changes (*i.e.* processes) all along its life cycle and each change is made possible by the consumption of matter/energy resources (inputs) and the creation of products and wastes (outputs). The LCA methodology provides for an inventory of all the input and output flows involved and then translated them into a range of environmental impacts by means of mathematical models. LCAs performed so far on trout production systems addressed the following topics: the impact assessment of rainbow trout aquafeeds produced in France (Papatryphon et al., 2004a), followed by two publications on rainbow trout rearing practices in the same country (D'Orbcastel et al., 2009; Papatryphon et al., 2004b); the environmental consequences of replacing fish meal and fish oil with plant-based sources in French salmonid feeds (Boissy et al., 2011); a statistical study based on the results of Boissy et al. (2011) and Papatryphon et al. (2004b), which combined the principal component analysis (PCA) and a non-parametric bootstrap technique to decrease the uncertainty in the results (Chen et al., 2015); a paper on rainbow trout rearing practices in Germany (Samuel-Fitwi et al., 2013); the comparison of three carnivorous fish species produced in Europe, including a rainbow trout flow-through system (Aubin et al., 2009); the environmental performances of commercial and artisanal feeds for trout and other freshwater species produced in Peru (Avadí et al., 2015); a study on rainbow trout rearing practices in Iran (Dekamin et al., 2015). Moreover, trout farming performances in terms of average contribution to climate change were summarized and compared with the sustainability performance of the other main food categories (Clune et al., 2017). Results proved farmed trout performance to be quite close to the one of farmed salmon and at least half of that of all other fish species, except for two farmed species (carp and seabass) and some caught species: mackerel, tuna and species from the Gadidae family (cod, haddock, pollock). According to the same study, the average impact of trout production on climate appears slightly higher than that of chicken but markedly lower than that of any mammalian livestock (especially lamb and beef).

Still, as pointed out by Philis et al. (2019), a complete picture of trout farming sustainability is still lacking due to: (i) the variability in trout production systems (*e.g.* flow-through vs recirculating system; type of management practices); (ii) the lack of methodological standardization, as LCA results are sensitive to modelling choices such as the selection of system boundaries and the approaches to handle multi-functionality; (iii) data quality. With regard to the latter, the inability to access primary data may affect the reliability of the results. For example, to the authors' knowledge, only two among the published LCAs on salmonids managed to gather data on commercial aquafeed formulation directly from feed and farming companies (Aubin et al., 2009; Boissy et al., 2011), while the remaining literature has based the modelling of fish diet on data from experts in the field (Avadí et al., 2015; Papatryphon et al., 2004a, 2004b) or on previous publications (Chen et al., 2015; D'Orbcastel et al., 2009; Dekamin et al., 2015; Samuel-Fitwi et al., 2013).

Given this information gaps, this research aimed to enrich the body of knowledge in the field by assessing the environmental impacts of a rainbow trout supply chain located in Northern Italy. More specifically, we undertook this study in order to identify key aspects for improving the sustainability of this production and to offer various stimuli for reflection on the effectiveness of LCA methodology, in terms of databases and Impact Categories (ICs) used. In order to get results representative of the supply chain, the inventory dataset was based almost entirely on primary data gathered from the companies involved and verified by their R&D and/or Quality staff.

2. Materials and methods

LCA was performed according to the problem-oriented approach (attributional LCA), meaning that the analysis focused on the extent of existing impacts disregarding possible future production scenarios (Tillman, 2000). The four mandatory phases described in the guidelines of the International Standard Organisation (ISO, 2006a; 2006b) were included and are widely reported in the following sections: (i) statement of the purpose and methodological choices; (ii) list and quantification of the main input and output flows occurring along the studied process; (iii) translation of the flows into a range of environmental impacts by means of mathematical models; (iv) results interpretation and discussion. Calculations were made using the software SimaPro 8.5.2.0 (PRé, 2012).

2.1. Scope of the study

As explained above, most of the trout farms are medium-small size systems, partially or totally family-run, scattered throughout the north east of the Country. As such, the management practices and the local environmental conditions can markedly differ and may affect production quality and/or quantity. To give an idea of this variability, each farmer can resort to a quite wide set of commercial aquafeeds, can adopt different feed management practices, and can have unexpected reductions in fish appetite due to a decrease in water quality. Besides, the frequent lack of coordination and collaboration between the links in the supply chain (*e.g.* between the feed supplier and the fish farmer) makes it difficult to gather data on the production processes occurring upstream or downstream along the trout supply chain. These aspects are not negligible from a LCA perspective, since the inclusion within the system boundaries of a large part of the supply chain provides a better picture of the product sustainability and prevents the burden shifting between life cycle phases.

Given the complexity of the Italian supply chain, we opted for the analysis of a trout farms consortium, ASTRO (ASsociazione TROticoltori Trentini). ASTRO consists of 50 medium-small size companies and is located in the alpine belt of Trentino-Alto Adige, which is among the regions with the highest number of trout companies (as already mentioned in the Introduction section) (Fig. 1). ASTRO provides its associated partners with consultancy services and partly processes the annual yield of 13 companies (25 production sites in total).

Despite being mainly focused on ASTRO trout production, this study extends the system boundary beyond the farm-gate and investigates the sustainability not only of trout processing into foodstuff but also of fish by-products processing into pet-food ingredients (Fig. 2). Fish production at hatchery was the only process left outside the system boundary. The environmental impacts of the feed production, fish grow-out and by-products processing phases were scaled on a mass-based functional unit, namely 1 ton of product. With regard to the fish processing phase (phase 3), LCA results were scaled on 1 ton of trout processed biomass, thus including food for human consumption and fish by-products.

2.2. Further details on the rainbow trout supply chain

The associated partners of ASTRO mainly produce rainbow trout, followed at a distance by other species such as Arctic char (*Salvelinus alpinus*), brown trout (*Salmo trutta*) and European grayling (*Thymallus thymallus*). Most production, which is carried out in concrete raceways built close to the water courses, is destined for human consumption, although recreational fisheries and restocking of natural waters do not play a marginal role.

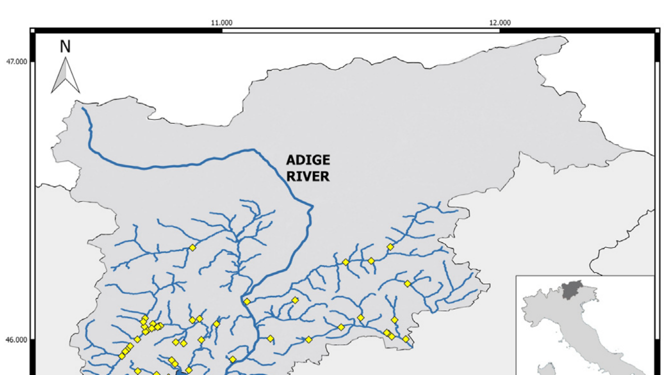

Fig. 1. Distribution of the trout production sites associated to the ASTRO consortium, in the Trentino-Alto Adige region, Italy.

As mentioned in section 2.1, 13 companies associated with ASTRO deliver to its processing plant 1300 tons per year of trout and char (38% of the fish they produced). These companies were used to carry out the LCA on phase 2. Despite having different production sizes (Table 1), they are homogeneous in terms of on-farm management and infrastructures. Indeed, since 2015 the consortium associates strictly adhere to a standardized production protocol, the Disciplinare di produzione “Trote del Trentino” (2015), which covers key aspects of farm management such as: feeding (*e.g.* only feeds with specific characteristics and ingredient formulations are used); stocking density (from 20 to 40 kg m^{-3}); quality of the water discharged in the drainage basin; quality of the final product (*e.g.* condition factor and flesh chemical-physical properties). The compliance with the protocol requirements is certified by a “Protected Geographical Indication” (PGI) label.

Once delivered to the consortium fish processing plant, fish are converted into food for human consumption, packed and finally sold on large-scale retail trade. The consortium produces 4 main categories of foodstuff (Table 2). Fish average yield is 55% of the live weight, with a higher yield for the degutted fish (81%) and lower yield for the other products (43–51%). All by-products (a mix of viscera, heads and frames) are eventually sold to a company which processes them into pet-food ingredients.

This last phase requires some additional comments. The valorisation of fish viscera, heads and frames avoids somewhere else the impacts related to the production of conventional pet-food ingredients from whole animals (Table 3). Thus, the environmental sustainability of phase 4 was evaluated by including in the assessment also the avoided products.

2.3. Life cycle inventory (LCI) and main assumptions

Most of the foreground data were provided by the companies involved in this study: (i) the most important feed supplier of the consortium, which is one of the main aquafeed Italian producers (AIA - Agricola Italiana Alimentare S.p.A. - Unipersonale. San Martino Buon Albergo, province of Verona, Italy); (ii) three types of trout farm (Table 1), (iii) the industrial manufacturing plant of *ASTRO* consortium, converting the whole fish in several processed products for human consumption (Table 2); (iv) the industrial plant which collects all fish by-products from the consortium and converts them into ingredients for the pet-food industry (Table 3). The data provided by the companies are representative of the average resource consumption and of products and emissions generation in a timespan of one year and are shown in Table 4 as already scaled on 1 ton of the main product. Only inputs coming from outside each system were considered in the inventory list while self-produced resources, such as solar self-consumption in several trout farms, are not included.

Gaps in the inventory were filled on the basis of the assumptions reported in Table 5. Data on background activities, such as raw materials production, transportation modes and energy generation (electricity, diesel fuel, etc.) were taken from *Ecoinvent v 3.4* LCI database (Ecoinvent, 2017). The only exceptions are data on the aquafeed ingredients and data on the conventional pet-food ingredients used as avoided products (see Table 3), which were taken from *Agribalyse® v 1.3* (Koch et al., 2016). Both databases are grounded on the recommendations in international standards (Wolf et al., 2012). Their combined use was a forced choice, since the former is one of the richest and most frequently used databases, but it is poor concerning animal and crop production, while the latter was specifically created to address this problem.

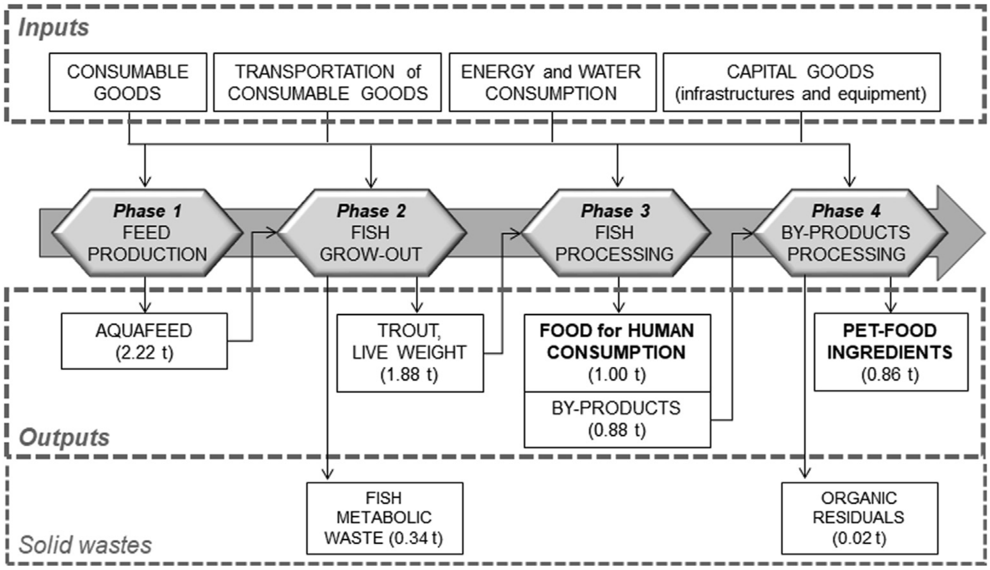

Fig. 2. System boundaries. The two final outputs of the supply chain (*i.e.* Food for Human Consumption and Pet-Food Ingredients) are highlighted in bold. The mass balance is here scaled on 1 ton of food for human consumption, as it is the main output of the supply chain.

Table 1
Types of trout farms. FCR=Feed Conversion Ratio, calculated as the ratio of feed intake to fish weight gain.

	TYPE 1	TYPE 2	TYPE 3
Yield (t year^{-1})	60	170	300
FCR	1.1	1.2	1.2
Water source	River	River	Well
Energy source	Country energy grid	Self-consumption (solar and/or hydroelectric power)	Country energy grid + Self-consumption (solar power)
No. production sites	10	8	7
Cumulative production (t year^{-1})	800	1000	1600
Cumulative production (%)	24%	29%	47%

Table 2
Details on fish processing.

Foodstuff category	Relative abundance(in terms of biomass)	Size (live weight) ofthe processed trout
Head-on-gutted trout	20.2%	<500 g
Fillet	51.5%	500–800 g
Smoked fillet	5.4%	>800 g
Other products(*e.g.* burgers, fish skewers)	22.9%	>800 g

Table 3
LCA on phase 4: avoided products included in the model. The recycle of 1 ton of fish by-products avoids the production of similar pet-food ingredients. PAP: processed animal proteins.

By-product valorisation			Avoided Products		
Material	Amount	Unit	Material	Amount	Unit
Animal grade hydrolysates (liquid) + fat (semi-solid)	0.26 + 0.04	t	Fish hydrolysate from whole fishes in Chile	0.30	t
Frozen minced fish	0.70	t	PAP & fat, from broiler	0.70	t
Total	1.00	t	Total	1.00	t

2.4. Life cycle impact assessment (LCIA)

The impact assessment was performed using ReCiPe 2016 Midpoint (H) V1.02 (Huijbregts et al., 2016). ReCiPe is based on the Eco-indicator and CML methodologies: according to the European Commission/JRC (2010), it represents the most recent and harmonized indicator approach available in life cycle impact assessment.

Table 6 details the five midpoint Impact Categories selected from ReCiPe (Climate change, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity), plus the single issue method Cumulative Energy Demand (Frischknecht et al., 2007). According to the literature (Aubin, 2013; Cao et al., 2013; Henriksson et al., 2012; Philis et al., 2019), these ICs are the best proxies of aquaculture impacts.

Finally, CML-IA baseline V3.05 (Guinée et al., 2002) was used as an alternative to the ReCiPe approach in order to facilitate the comparison with previous LCA studies on trout production systems. Since the CML characterisation factor for freshwater eutrophication

Table 4
Life Cycle Inventory. The inputs and outputs data of each phase are scaled on 1000 kg of product. TRSP: Transportation.

		PHASE 1 – FEED PRODUCTION	unit	quantity		
INPUTS	Consumable goods	Fish ingredients (South America)	kg	320.00		
		Other animal ingredients (European Union)	kg	310.00		
		Plant ingredients (European Union)	kg	370.00		
	TRSP.	Road transport of feed ingredients	kg km	622,960.00		
		Ocean transport of feed ingredients	kg km	3,739,520.00		
	Capital goods	Not considered				
	Energy consump.	Electricity (Country energy grid)	kwh	148.00		
		Natural gas	m3	18.00		
	Water consump.	Water (from water supply system)	m3	0.32		
OUTPUTS	Product	Aquafeed	kg	1000.00		
	Emissions in water	Not considered				
	Wastes and other emissions	Steam (in the atmosphere)	m3	0.32		
		Feed production scrap (incinerated)	kg	1.02		
		PHASE 2 – FISH GROW-OUT	**unit**	**TYPE 1 quantity**	**TYPE 2 quantity**	**TYPE 3 quantity**
INPUTS	Consumable goods	Aquafeed	kg	1100.00	1200.00	1200.00
		Chemicals	kg	5.92	0.60	3.39
	TRSP.	Road transport of inputs (aquafeed, chemicals)	kg km	294,800.00	337,200.00	338,400.00
	Capital goods	Raceways (concrete)	kg	615.43	466.20	229.56
		Nets (nylon)	kg	0.28	0.24	0.11
	Energy consump.	Electricity (Country energy grid)	kwh	300.00	0.00	1500.00
		Diesel	l	28.63	13.33	28.62
	Water consump.	Water (T1, T2: from river; T3: from well)	m3	213,725.61	189,216.0	111,322.82
OUTPUTS	Product	Trout at marketable size (live weight)	kg	1000.00	1000.00	1000.00
	Emissions in water	Water (back to river)	m3	213,725.61	189,216.0	111,322.82
		Chemicals (in river)	kg	5.92	0.60	3.39
		Nitrogen (in river)	kg	110.50	56.76	33.40
		Phosphorus (in river)	kg	36.83	18.92	11.13
	Wastes and other emissions	Dead biomass (incinerated)	kg	226.99	226.99	226.99
		PHASE 3 – FISH PROCESSING	**unit**	**quantity**		
INPUTS	Consumable goods	Trout at marketable size (live weight)	kg	1877.61		
		Packaging	kg	67.66		
		Ingredients added to fish	kg	26.43		
	TRSP.	Road transport of trout	kg km	93,880.39		
		Road transport of the other inputs	kg km	24,387.69		
	Capital goods	Processing machines (stainless steel)	kg	0.32		
	Energy consump.	Electricity (Country energy grid)	kwh	766.06		
		Electricity, self-production	kwh	139.08		
	Water consump.	Water (from water supply system)	m3	30.60		
OUTPUTS	Product	Food for human consumption	kg	1000.00		
		By-products	kg	880.00		
	Emissions in water	Water (back to river)	m3	30.60		
		Phosphorus (in river)	kg	0.01		
		Semi-solid organic residuals collected from water (compost)	kg	333.80		
	Wastes and other emissions	Wasted packaging (recycled)	kg	8.35		
		PHASE 4 – BY-PRODUCT PROCESSING	**unit**	**quantity**		
INPUTS	Consumable goods	By-products (viscera, heads, frames)	kg	1024.67		
		Hydrolysis enzymes	kg	2.62		
		Chemicals	kg	7.39		
	TRSP.	Road transport of by-products	kg km	245,920.84		
		Road transport of the other inputs	kg km	628.60		
	Capital goods	Processing machines (stainless steel)	kg	0.32		

(*continued on next page*)

Table 4 (*continued*)

		PHASE 1 — FEED PRODUCTION	unit	quantity
	Energy consump.	Electricity (Country energy grid)	kwh	7903.50
		Natural gas	m3	294.64
	Water consump.	Water (from water supply system)	m3	7.78
OUTPUTS	Product	Pet-food ingredients	kg	1000.00
	Emissions in water	Water (sewerage)	m3	6.78
		Phosphorus (in river)	kg	0.07
	Wastes and other emissions	Semi-solid organic residuals collected from water (compost)	kg	3.25
		Steam (in the atmosphere)	m3	0.92
		Scraps from hydrolysis (incinerated)	kg	64.27
		Scraps from freezing (incinerated)	kg	37.85
		Chemicals (sewerage)	kg	7.39

Table 5
Assumptions made to fill inventory gaps.

TOPIC	DETAILS
Emissions in water	*Phase 1* — Emissions were not considered. *Phase 2* — Average values provided by the consortium: Total nitrogen = 0.3 mg of N L^{-1}; Total phosphorous = 0.1 mg of P L^{-1}. *Phase 3* — Average values provided by the consortium: Total phosphorous = 0.33 mg of P L^{-1}. *Phase 4* — Emissions were modelled according to the worst-case scenario, that is the concentration limits for surface water stated by the Italian legislation (Decreto Legislativo 3 aprile 2006, n. 152): Total phosphorous = 10 mg of P L^{-1}.
Wastewater treatment	*Phase 2* — Disease-free production sites have a mortality equal to 10%, while production sites with a disease outbreak have a mortality equal to 27%. Thus, an average mortality of 18.5% was considered. *Phase 3 and 4* — Wastewater treatments lead to the separation of semi-solid organic residuals from the main stream. Being 100% organic, they are assumed to be disposed of as compost and applied to field as a planting bed amendment.
Lifespan of infrastructures	Adoption of the average lifespan (assuming only ordinary maintenance): stainless steel machineries = 25 years; nylon nets = 5 years; concrete raceways = 50 year.
Infrastructures weight	Raceways — Data provided by farmers were cross-references with Google Maps measurements. The worst scenario was adopted, always considering the concrete walls of the raceways to be 1.5 m deep and 0.2 m thick (although some facilities have 0.6–0.7 m deep raceways). Concrete density was considered equal to 2250 kg m^{-3}.
Transport distances	Road distances were calculated from Google Maps; ocean distances (transport of aquafeed ingredients from South America to a Dutch harbour) were assessed from marinetraffic.com

applies not only to phosphorous but also to nitrogen content in water, the total nitrogen concentration in farms water outflow (phase 2) was considered as well in the inventory (Table 4).

3. Results

The result of the contribution analysis, shown in Fig. 3, provides an overview of the sustainability of the whole supply chain. Within each column of the bar chart, the main inputs used in phases 2, 3 and 4 (namely the aquafeed, live-weight trout, trout by-products) are not considered. Indeed, the segments of phases 2, 3 and 4 only include processing activities, while input production is already accounted for in the segment that precedes them. The impacts of each sub-category are detailed in Tables 7—10, which allow one to gain a thorough understanding of the key issue in each phase. With specific regard to Table 8, the reported values are the weighted averages of LCAs performed on the 3 types of trout farms (and which are detailed in Table A.1 in

Table 6
Characteristics of the Impact Categories chosen.

Impact Category	Short name (acronym of the midpoint characterisation factor)	Unit of measure	Accounting for:
Climate change	GWP (Global Warming Potential)	kg CO_2 eq. to air	the contribution of greenhouse gases to climate change.
Terrestrial Acidification	TAP (Terrestrial Acidification Potential)	kg SO_2 eq. to air	changes in acidity in the soil due to a change in acid deposition, which in turn is a consequence of changes in air emission of NO_x, NH_3 and SO_2.
Freshwater Eutrophication	FEP (Freshwater Eutrophication Potentials)	kg P eq. to freshwater	a change in the levels of phosphorous in freshwater caused by emissions of nutrients into water and soil.
Terrestrial Ecotoxicity	TETP (Terrestrial Ecotoxicity Potential)	kg 1,4-DCB eq. to industrial soil	a change in the levels of toxic chemicals caused by emissions into the soil.
Freshwater Ecotoxicity	FETP (Freshwater Ecotoxicity Potential)	kg 1,4-DCB eq. to freshwater	a change in the levels of toxic chemicals caused by emissions into the water.
Cumulative Energy Demand	CED	MJ	the direct and indirect consumption of energy.

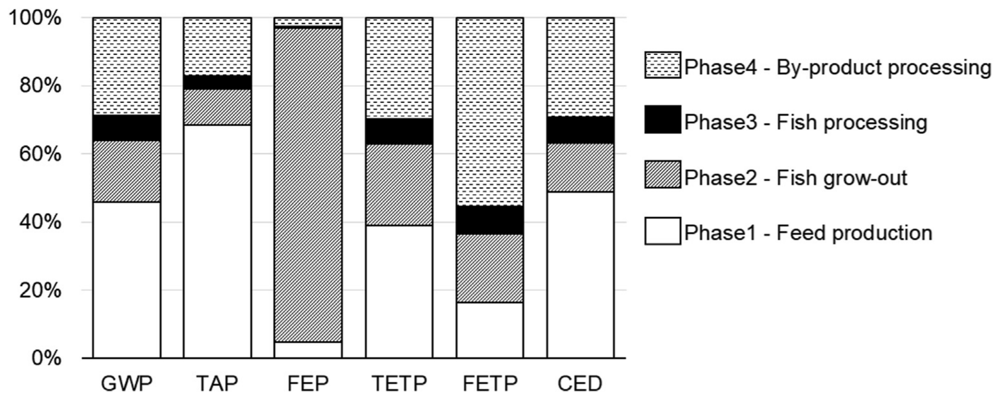

Fig. 3. Contribution analysis. Each column represents the contribution of the four phases to one of the six impact categories.

the Appendix). These weighted averages are based on the percentages reported in Table 1.

The impacts of the whole supply chain, scaled to 1 ton of food for human consumption and 0.86 tons of pet-food ingredients are: 16,330.34 kg CO_2 eq. to air (GWP), 114.66 kg SO_2 eq. to air (TAP), 39.36 kg P eq. to fresh water (FEP), 19,978.36 kg 1,4-DCB eq. to industrial soil (TETP), 401.57 kg 1,4-DCB eq. to fresh water (FETP), 154,685.53 MJ (CED). These estimates are obtained on the basis of the mass balance given in Fig. 2, by adding 0.86 tons of processed by-product (Table 10) to 1.88 tons of processed fish (Table 9).

The overview of the whole supply chain (Fig. 3) highlights the critical aspects of each production phase. First, it is evident the key role of the aquafeed (phase 1), accounting for 46, 68, 39 and 49% of the whole GWP, TAP, TETP and CED respectively. The activities carried out during fish grow-out phase (phase 2) are the main contributors to the eutrophication impact (accounting for 92% of the total FEP) but affect other ICs as well (18, 24 and 20% of GWP, TETP and FETP respectively). The impacts contribution produced by phase 3 (live weight trout processing) never exceed 8%, while the environmental burdens caused by phase 4 (trout by-products processing) are quite high, accounting for 29, 30, 56 and 29% of GWP, TETP, FETP and CED respectively.

A closer examination of each phase revealed other interesting aspects. Within phase 1 (Table 7), the cumulative impact contribution of ingredients production (fish, plant and other animal ingredients) ranges from 60% to 96% of the total impact in all ICs considered. With regard to ingredients production, the main hotspot is represented by the production of *'plant ingredients'* and of *'other animal ingredients'* (*i.e.* poultry and livestock by-product meals), while *'fish ingredients'* contribution is much lower and never exceeds 21%. In phase 2 (Table 8), the *'emissions in water'* sub-category stands out as the main contributor to freshwater eutrophication (FEP), which is the most critical IC of this phase (Fig. 3). Indeed, *'emissions in water'* accounts alone for 94% of the impact (19.48 kg of P eq. over the total 20.70 kg emitted). Another important sub-category of this phase is that of *'energy consumption'* since it accounts for 16–19% of GWP, TETP and CED and about 40% of FETP (Table 8). As already said, phase 3 impact contribution to the sustainability of the whole supply chain is very low and, within this phase (Table 9), most of the share is due to the main raw material used (that is, trout at marketable size), while the cumulative impact contribution from the processing activities accounts for less than 18% of the total impacts in all the 6 ICs considered. Finally, in phase 4 (Table 10), the high values observed in the four critical ICs (GWP, TETP, FETP, CED) are mainly due to the *'energy consumption'* sub-category.

The results presented in Tables 7–10 cannot be compared with those presented in previous LCA publications, which were obtained with the CML-IA method. Thus, the environmental impacts of the trout supply chain were assessed using also the CML-IA methodology and compared with literature (Table 11).

Overall, our results on phases 1 and 2 are consistent with those found in literature except for the two ecotoxicity impacts, which are more than 3 times bigger than those assessed in previous researches. As regards to phases 3, the only data found in literature is the global warming impact provided by Silvenius et al. (2017), which is similar to the value assessed by the present study (5470 kg CO_2 eq. per ton of processed fish against our 3057 kg CO_2 eq.).

4. Discussion

4.1. Comparison with literature

A literature comparison (Table 11) corroborated our findings on the impacts in phases 1 and 2 and on the global warming impact found in phase 3. Indeed, the value ranges provided for the ICs Global warming, Acidification, Eutrophication and CED are consistent with our results and were obtained by putting together the data of different publications.

Table 7
LCIA on Feed Production (phase 1). The impacts, assessed with the ReCiPe H method and with CED indicator, are scaled on 1 ton of aquafeed produced.

SUB-CATEGORIES	GWP (kg CO_2 eq. to air)	TAP (kg SO_2 eq. to air)	FEP (kg P eq. to fresh water)	TETP (kg 1,4-DCB eq. to industrial soil)	FETP (kg 1,4-DCB eq. to fresh water)	CED (MJ)
Fish ingredients	358.36	1.23	0.02	281.40	1.40	5382.12
Other animal ingredients	603.78	9.50	0.19	1045.78	8.10	13,913.83
Plant ingredients	535.27	5.33	0.62	1055.68	12.55	15,177.01
Transportation	145.83	1.10	0.01	1434.18	1.87	2351.43
Energy consumption	75.20	0.29	0.02	139.88	4.67	2111.54
Water consumption	0.12	0.00	0.00	0.29	0.00	2.28
TOTAL	1718.57	17.46	0.86	3957.20	28.60	38,938.21

Table 8
LCIA on Fish Grow-out (phase 2). The impacts, assessed with the ReCiPe H method and with CED indicator, are scaled on 1 ton of trout (live weight) produced. The reported values are the average results of the three farm types.

SUB-CATEGORIES	GWP (kg CO_2 eq. to air)	TAP (kg SO_2 eq. to air)	FEP (kg P eq. to fresh water)	TETP (kg 1,4-DCB eq. to industrial soil)	FETP (kg 1,4-DCB eq. to fresh water)	CED (MJ)
	weighted average	weighted average	weighted average	weighted average	weighte daverage	weighted average
Aquafeed	2021.85	20.54	1.01	4655.53	33.64	45,809.66
Other consumable goods	5.95	0.04	0.00	13.86	0.38	119.99
Transportation	224.14	0.77	0.04	1456.37	9.86	3579.70
Capital goods	39.45	0.10	0.01	160.77	0.89	389.72
Energy consumption	528.75	2.28	0.16	1228.66	28.61	9424.93
Water consumption	0.00	0.00	0.00	0.00	0.00	0.00
Emissions in water	0.00	0.00	19.48	0.00	0.00	0.00
Dead biomass disposal	7.89	0.03	0.01	15.94	1.84	55.40
TOTAL	2828.02	23.75	20.70	7531.13	75.23	59,379.40

Table 9
LCIA on Fish Processing (phase 3). The impacts, assessed with the ReCiPe H method and with CED indicator, are scaled on 1 ton of processed fish, composed of 0,53 tons of food for human consumption plus 0,47 tons of by-products produced alongside.

SUB-CATEGORIES	GWP (kg CO_2 eq. to air)	TAP (kg SO_2 eq. to air)	FEP (kg P eq. to fresh water)	TETP (kg 1,4-DCB eq. to industrial soil)	FETP (kg 1,4-DCB eq. to fresh water)	CED (MJ)
Trout (whole fish)	2827.77	23.75	20.79	7529.86	75.23	59,369.46
Other consumable goods	104.16	0.28	0.01	129.58	1.04	2608.21
Transportation	28.99	0.10	0.00	193.55	1.07	459.72
Capital goods	0.91	0.00	0.00	15.65	0.05	11.93
Energy consumption	200.10	0.77	0.06	532.00	14.31	4279.92
Water consumption	5.95	0.02	0.00	11.44	0.29	91.64
Emissions in water	0.00	0.00	0.01	0.00	0.00	0.00
Solid wastes disposal	−15.02	−0.03	0.00	−1.58	−0.02	−360.42
TOTAL	3152.86	24.89	20.87	8410.49	91.97	66,460.46

Table 10
LCIA on By-product processing (phase 4). The impacts, assessed with the ReCiPe H method and with CED indicator, are scaled on 1 ton of pet-food ingredients produced. Being a recycled material, fish by-product is considered as a burden-free input and thus not included in the assessment.

SUB-CATEGORIES	GWP (kg CO_2 eq. to air)	TAP (kg SO_2 eq. to air)	FEP (kg P eq. to fresh water)	TETP (kg 1,4-DCB eq. to industrial soil)	FETP (kg 1,4-DCB eq. to fresh water)	CED (MJ)
Consumable goods (except for fish by-product)	42.05	0.29	0.10	170.55	1.63	852.66
Transportation	155.68	0.56	0.02	1121.77	5.53	2413.17
Capital goods	1.72	0.01	0.00	29.62	0.09	22.58
Energy consumption	4127.51	14.70	1.08	7390.59	248.25	83,065.46
Water consumption	2.84	0.01	0.00	5.46	0.14	43.74
Emissions in water	0.00	0.00	0.07	0.00	0.00	0.00
Solid wastes disposal	3.55	0.01	0.00	7.17	0.83	24.93
Avoided burdens contribution	−1561.81	−4.34	−0.08	−961.57	−5.18	−26,192.89
TOTAL	2771.54	11.25	1.19	7763.58	251.29	60,229.64

Table 11
Comparison of the results (assessed with the CML-IA method and with CED indicator) with literature data. Values for phase 1 were taken from: Pelletier et al. (2009); Boissy et al. (2011). Values for phase 2 were taken from: Papatryphon et al. (2004b); Samuel-Fitwi et al. (2013a); Chen et al. (2015); Aubin et al. (2009); Dekamin et al. (2015); supplementary materials of Boissy et al. (2011); supplementary materials of Avadí et al. (2015); D'Orbcastel et al. (2009). Impacts are scaled on 1 ton of feed and trout (live weight) respectively.

	CML-IA					
	Global warming (kg CO_2 eq. to air)	Acidification (kg SO_2 eq. to air)	Eutrophication (kg PO_4- eq. to fresh water)	Terrestrial ecotoxicity (kg 1,4-DCB eq. to industrial soil)	Freshwater ecotoxicity (kg 1,4-DCB eq. to fresh water)	CED (MJ)
PHASE 1						
This study	1655	17	12	142	860	38,938
Values in literature	1450−1590	9−15	6−8	6−8	//	18,070 −23,300
PHASE 2						
This study	2653	23	112	169	1290	59,379
Values in literature	1760−3561	10−33	29−76	12−29	340−392	30,000 −78,200

The two ecotoxicity ICs represent the only exceptions as they show a high discrepancy from the results provided in Boissy et al. (2011) and Avadí et al. (2015). The reason doesn't lie in the aquafeed formulation, which still cannot be entirely disclosed due to industrial secrecy. Indeed, fishmeal and fish oil content in the aquafeed is comparable to that of Boissy et al. (2011) and Avadí et al. (2015), and both resources are shipped from South America, as is the case with most of the aquafeed currently in use in Europe. Moreover, all the other animal and plant resources are produced in Europe in a conventional way and transported to the aquafeed plant by road transport.

Rather, the discrepancy is most likely due to methodological choices and its understanding requires a reflection on the shift from ReCiPe to CML-IA baseline method. In other terms, some of the environmental hotspots changed by changing the assessment methods. When assessed with ReCiPe, the ecotoxicity performances of phase 2 appear to be not only affected by the *'aquafeed'* (around 50%) but also by *'transportation'* and *'energy consumption'*, which together account for around 35% of total TETP and FETP impacts (Table 8). However, when using CML-IA baseline method, the same two impacts appear almost entirely due to the *'aquafeed'* used (over 80%). And the *'aquafeed'* impact assessed with CML-IA (phase 1) is in turn mainly affected by *'other animal ingredients'* and *'plant ingredients'*, each representing approximately 50% of Terrestrial ecotoxicity and around 25% and 65% respectively of Freshwater ecotoxicity (Table A.2 in the Appendix). In brief, when resorting to CML-IA baseline method, the key sub-categories affecting the ecotoxicity performances of phases 1 and 2 are reduced to two: livestock and crop feed ingredients. And here a second methodological difference comes in. The LCAs performed in Boissy et al. (2011) and Avadí et al. (2015) modelled the background inputs by resorting to government statistics, literature and Ecoinvent datasets, adapting the latter to local contexts whenever needed. On the opposite, our study combined *Ecoinvent v 3.4* and the younger *Agribalyse® v 1.3*, with the latter created paying particular attention to: (i) model the main emissions of potentially polluting substances directly associated with livestock and arable/horticultural production; (ii) review the characterization models for the eco toxicity impact assessment (Koch et al., 2016). This led to a far higher quantification of both the ecotoxicity impacts considered in this study.

4.2. Performances of the four phases

The results of this study are representative of 13 trout companies (*i.e.* 25 production sites out of a total of 50) in the Trentino province: this aspect is not frequent in trout LCA literature, as most of the studies published are limited to one production site (Philis et al., 2019).

With regard to phase 1, the most interesting result is that each of the three ingredients sub-categories (namely, *'fish ingredients', 'other animal ingredients', 'plant ingredients'*) accounts for around one third of the aquafeed in terms of biomass, but they affect the aquafeed environmental performances in a completely different way (Table 7). More specifically, the impacts of '*fish ingredients*' are markedly smaller than those of the *'other animal ingredients'* and of *'plant ingredients'* because of the methodological choices made. The *'fish ingredients'* are modelled by considering the infrastructures use, water and energy consumption and waste emissions along the fishing and processing activities: this means that the fish, which is actually the main input of this process, is not included within the LCA model as it is a self-regenerating natural resource. Moreover, the consequences of fishery activities on the marine ecosystem are here disregarded, although some scientific research groups already developed a few indicators to cope with this problem (*e.g.* Biotic Resource Depletion, Sea Use and Biodiversity Loss), and more detailed aquafeed LCAs were already published. Still, a deep focus on all the nuances of aquafeed sustainability assessment was not among the purpose of the present aquafeed model, which aimed at assessing the whole supply chain.

All the activities carried out in phase 2 (fish grow-out) were included in the analysis, with the only exception being the fish production at hatchery, as the biomass of a fry never exceeds 2.9% of that of an adult animal (10 g against a minimum weight of 350 g for the fish at a commercial size): thus, inputs and emissions related to this step were assumed to be negligible. The major environmental impact caused by phase 2, see Table 8, is freshwater eutrophication, which is almost entirely due to fish metabolic wastes. Although this finding is in accordance with the literature, it is worth mentioning that freshwater eutrophication is a local-scale IC and the actual negative effects on the environment depend on the assimilative capacity of the receiving water bodies. Indeed, according to the environmental mechanisms underlying the assessment of FEP impact, the addition of a considerable amount of nutrients in watercourses may affect the river vegetal community by favouring more nutrient-demanding species, with cascade effects on the whole aquatic ecosystem. However, river environmental monitoring in the *ASTRO* production sites did not show marked changes of the Extended Biotic Index (APAT-IRSA, 2003) neither upstream nor downstream, in line with the findings reported by scientific literature on Italian trout farms (Fabrizi et al., 2010; Mancini et al., 2010; Pontalti et al., 2006). This is probably linked to the low water temperatures in mountain farms, which causes: trout metabolism to be slower than that of trout farmed in plain lands (Kim et al., 2017) and a consequent reduced nutrients load; a high river flow, which further decreases the nutrient load in water; an increased oxygen concentration (available for the bacterial degradation of nutrients). Phase 2 has also some effects on global warming (GWP) and ecotoxicity (TETP and FETP) due to on-farm *'energy consumption'*.

With regard to the performances of phase 3, the impacts contribution due to fish processing activities is definitely low (Fig. 3). The reasons are several. Almost no fish delivered to the trout processing plant is discarded: all animals are in good sanitary conditions (fresh and free of parasites and/or diseases, affecting internal quality), and those in noncompliance with morphological quality standards (*e.g.* size, shape, colour) are used to get fish skewers and minced fish products (Table 2). Good practices (such as the recycle of part of the wasted packaging) and technical improvements (*e.g.* photovoltaic panels installed on the roof) further improve the environmental sustainability (Table 9).

In contrast to phase 3, by-product processing phase shows quite high impacts in four ICs over six (Fig. 3), due to the energy input (Table 10). Energy is required not only to keep trout by-products at a constant low temperature (from the initial grinding of the raw material to the packaging and labelling of the frozen minced fish) but also to feed the fully automated transport system and the machineries involved in the enzymatic hydrolysis. In order to see the whole picture, results of the LCA on phase 4 were compared with those of an incineration scenario (Table 12), which includes by-products transportation, municipal incineration (with fly ash extraction), and the avoided impacts linked to the conventional production of electric energy in Italy. LCI data were sourced from Ecoinvent database and the treatment of 1 ton of municipal solid waste in an incinerator was assumed to produce 564 kWh of energy (Mendes et al., 2004). Results indicate that the recycling of fish by-product into pet-food ingredients (Table 10) would be a viable alternative to

Table 12
LCIA on By-product processing (phase 4): hypothetical incineration scenario. The impacts, assessed with the ReCiPe H method and with CED indicator, are scaled on 1 ton of pet-food ingredients produced.

SUB-CATEGORIES	GWP (kg CO_2 eq. to air)	TAP (kg SO_2 eq. to air)	FEP (kg P eq. to fresh water)	TETP (kg 1,4-DCB eq. to industrial soil)	FETP (kg 1,4-DCB eq. to fresh water)	CED (MJ)
Transportation	106.81	0.39	0.01	771.28	3.79	1655.37
Municipal incineration (with fly ash extraction)	34.75	0.13	0.03	70.21	8.13	244.07
Avoided burdens (conventional production of electric energy)	−239.73	−1.01	−0.08	−524.51	−17.68	−4887.15
TOTAL	**−98.17**	**−0.49**	**−0.03**	**316.97**	**−5.76**	**−2987.71**

incineration (Table 12) only if the impacts due to energy consumption were markedly reduced.

4.3. Possible improvements in the supply chain and in the LCA method

The aquafeed — Over the past few years, the increased attention in Italy to the quality of fish flesh led to a markedly improved quality of the aquafeed ingredients used, in terms of both ingredients safety (see for instance Perugini et al., 2013) and zootechnical performances. However, this study confirms that feed is the largest contributor to all environmental impacts associated with phase 1, with cascade effects on the rest of the supply chain. These impacts can be reduced by using different strategies: in the feed production phase, ways to solve the problem are a shift toward novel and more sustainable feed ingredients, an improved production of the conventional ones and the formulation of feeds with further improved feed quality (palatability, digestibility, nutritional content); in the fish grow-out phase, the crucial aspects are to avoid the supply of an inadequate quantity of feed (which could be achieved by implementing more advance control methodologies) and to ensure fish welfare, which in turn affects the feeding response. With regard to the LCA method, the aquafeed formulation here used was based on primary data and the related impacts found were in line with those in literature but, as previously discussed, they were assessed by resorting to SimaPro databases and ICs, which still have room for improvement. In this regard, a joint research effort involving food industry professionals and several LCA practitioners is underway to develop a Seafood LCI database (Hognes et al., 2018) and other open inventories such as the Thai LCI database and the used here AGRIBALYSE database, while in parallel several fisheries LCA studies have already been carried out (Avadí et al., 2019; Ziegler et al., 2016) and characterization models capable to include impacts on the oceans ecosystems have already been suggested by previous literature in this field (Cashion et al., 2016). Thus, more comprehensive inventories and ICs are expected to be integrated within the International Life Cycle Data system (https://eplca.jrc.ec.europa.eu/ilcd.html) in the near future.

On-farm fish emissions and energy needs — Besides the aquafeed, on-farm fish emissions were already highlighted by previous literature as the second impact driver. Despite eutrophication due to trout farms effluents appeared as the main hotspot of phase 2, it should be borne in mind that proximate ecological concerns are still not adequately covered by LCA methodology. Thus, the quantification of the potentially altered area at the bottom of the river (as already suggested in Ford et al., 2012), coupled with further researches on trout emissions under different environmental and farming conditions, would certainly help gaining a more complete picture of the nutrients contribution to local scale effects. On-farm energy needs seem to play a quite important role too. However, today the energy consumption by trout farms is usually not markedly high, as most of the small mountain fish farms have little mechanization (*i.e.* low diesel consumption) and adequate availability of high-quality surface water (*i.e.* no pump and no oxygenator needed). In mountain farms with higher productions and thus with higher energy needs, the use of self-consumed electricity was proved to be a good solution (compare types 1—2 farms in Table 1 and in Table A.1 of the Appendix). However, this solution sometimes cannot be applied due to local conditions (logistical, orographic and climatic constraints). Thus, the biggest farms (type 3) — unable to self-produce all the energy they need — are forced to use the Country energy grid. Moreover, due to climate change, an increased variability in water availability/quality could cause an increase in energy needs in the near future. Thus, a complementary solution to that of renewable energy could be the use of improved control systems, since those used on farms were designed around 20 years ago (when the ability to collect data and process them was very limited). For instance, there could be wide scope for optimizing the oxygen supply by implementing more advanced control methodologies, based on the Precision Fish Farming approach.

Resource sharing and recycling — The result concerning phases 3 and 4 fills a gap concerning LCA of trout farming. The sale of processed fish in place of fish in the round appears as a winning strategy from both an economical and environmental point of view, since it increases the revenue while having a very limited contribution to the environmental impacts. Moreover, fish processing allows to collect all the fish by-products, which otherwise would have been generated separately through household food consumption. The fish by-products produced by the ASTRO consortium (more than 611 tons per year) represent 47% of the whole fish biomass and, if further processed, can be valorised and recycled into pet-food ingredients (Table 3). According to the EU Waste Framework Directive, recycling of materials has the preference over energy recovery (*i.e.* biomass incineration). However, phase 4 involves a high energy input probably linked to the high perishability of fish by-products, since a great amount of energy is required to maintain low temperatures and to swiftly process the biomass. Therefore, as already highlighted by previous studies (Schrijvers et al., 2016), it may not be the most environmentally friendly option when energy is sourced (as in this case) by fossil fuels. To improve this phase, the use of renewable energy sources could be coupled with an improved insulation of the facilities and to the use of less energivorous machineries.

5. Conclusions

This paper presents the results of an LCA study including the whole rainbow trout supply chain. In order to achieve this goal, the system boundaries were expanded beyond the conventional farm-gate and include all the main production phases: from aquafeed production up to the processing of live weight trout into foodstuff and of fish by-products into pet-food ingredients. Although our findings confirm that the environmental sustainability of aquafeed production remains a key issue, this approach allowed the identification of other critical aspects along the supply chain.

In phase 1 (aquafeed production), an increased aquafeed sustainability could be attained through an increased sustainability in ingredients production and through an improvement in feed nutritional properties, digestibility and palatability. Moreover, further research is needed to tailor LCA inventories and impact assessments methods capable of providing more precise and accurate measurements. With regard to phase 2 (fish grow-out), the surge in eutrophication values is definitely a key issue, which makes it urgent to improve/develop impact assessment methods capable to better describe the effects of an increased nutrient release on freshwater ecosystems. The contribution to impacts of on-farm energy consumption should not be underestimated, especially in type 3 fish farms (*i.e.* the biggest ones) and, above all, when considering the consequences of possible climatic variations in the near future. Further improvements in the renewable energy production and storage (*e.g.* higher efficiency and/or lower costs) complemented with a higher control over on-farm activities (Precision Fish Farming approach) can represent a viable solution.

Phase 3 (fish processing) appears as a highly efficient production system, which already optimizes the resources used. Indeed: (i) the environmental and economic burdens of the single processing plant are shared among the consortium associates; (ii) to minimize fish rejection rate, the harvested trout is delivered to the processing plant within a short period of time, thus guaranteeing the cold chain compliance (and the preservation of the fish); (iii) when fish is seen as not fit for market (due to odd shape or blemishes), still it is not discarded but simply processed into minced fish. Finally, the last phase of the supply chain provided a quite unexpected result, since the recycling of fish by-products into pet-food ingredients appears less sustainable than the incineration option. In this case, more attention must be paid towards the amount and source of energy used, since this aspect stands out as the most critical one.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express sincere thanks to Pierluigi Perantoni and Andrea Di Biase from AIA—Agricola Italiana Alimentare S.p.A. (http://www.aiafood.com/en), to Diego Coller and Massimo Manfrini from ASTRO – Associazione TROticoltori Trentini (https://www.troteastro.it/) and to Giovanni Baruchelli from Fondazione Edmund Mach (https://www.fmach.it/eng) for providing the raw data concerning the first three steps of the supply chain.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125155.

Funding information

The research leading to these results has received funding from the European Union's HORIZON 2020 Framework Programme under grant agreement no. 773330 (GAIN, Green Aquaculture Intensification in Europe).

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