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Comparative life cycle assessment of rainbow trout (*Oncorhynchus mykiss*) farming at two stocking densities in a low-tech aquaponic system

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ABSTRACT

The present study assessed the effect of two fish stocking densities (Low, 3.81 kg m^{-3} vs High, 7.26 kg m^{-3}) on the environmental footprint associated with the production of rainbow trout (*Oncorhynchus mykiss*) and lettuce (*Lactuca sativa*) in an experimental low-tech aquaponic system. A gate-to-gate and a cradle-to-gate Life Cycle Assessment models were used. The functional unit was 1 kg increase of table-size rainbow trout (about 330 g body weight). Mass allocation, economic allocation, and system expansion were applied to resolve the multi-functionality of the tested system. The impact categories assessed were global warming (GWP, kg CO_2-eq), acidification (AP, g SO_2-eq) and eutrophication (EP, g PO_4-eq) potentials, cumulative energy demand (CED, MJ), freshwater ecotoxicity (ECO, CTUe), water depletion (WD, m^3 water equivalent). In the gate-to-gate model, considering mass allocation, the production of 1 kg increase of rainbow trout emitted on average 8.8 kg CO_2-eq (GWP), 56 g of SO_2-eq (AP) and 64 g of PO_4-eq (EP), while the CED was 161 MJ, the ECO was 186 CTUe, WD was 0.061 m^3. Global warming, cumulative energy demand and freshwater ecotoxicity were the impact categories mostly affected by the changes in fish stocking density. A high density was associated with a lower environmental impact per kg of fish produced both considering the gate-to-gate and cradle-to-gate approaches. Electricity was the dominant contributor in all the impact categories, ranging from 64% of EP to 93% of ECO while feed production accounted for 19% of WD and 10% of GWP. The change of the energy source from a common grid mix to a photovoltaic system substantially reduced global warming whereas the improvement of feed conversion ratio decreased eutrophication potential. Based on life cycle assessment, the farming of rainbow trout in aquaponics is a promising alternative to common flow-through systems, particularly in view of reducing water use.

1. Introduction

Fish production relies on the availability of finite resources such as fresh water, land, nutrients and fossil energy. Nowadays, the great expansion of aquaculture, one of the fastest-growing food sectors, is causing environmental pollution and exploitation of natural resources (Bohnes et al., 2019). Therefore, sustainable, reliable, and alternative production techniques have to be investigated and adopted. Aquaponics, a water-recirculating, nutrient-recycling, and soil-less farming technique that combines recirculating aquaculture with hydroponics, might provide part of the solution and will probably become one of the most used methods to produce food sustainably in the future (Hu et al., 2012), especially in non-arable and arid regions and in urban areas (Joyce et al., 2019). The main fish species used in aquaponics are low-value and easy-to-produce cyprinids and tilapias, due to their low environmental requirements and high adaptability to handling and farming conditions (Palm et al., 2019). However, the use of high-value species such as rainbow trout (*Oncorhynchus mykiss*) could improve the profitability and competitiveness of aquaponic productions (Bordignon et al., 2021).

To evaluate the environmental impact of a product throughout its life cycle, a commonly used method is Life Cycle Assessment (LCA) (ISO, 2006). Despite several LCA studies were performed in various aquaculture systems (Ghamkhar et al., 2021) and vegetable cultivations (Gruda et al., 2019; Parajuli et al., 2019), the application of LCA to

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aquaponics is still scarce (Wu et al., 2019; Greenfeld et al., 2022). In the last years, some experimental-based studies were published (Boxman et al., 2017; Hollmann, 2017; Jaeger et al., 2019), together with ones based on virtual farms (Forchino et al., 2017; Cohen et al., 2018) or very small-scale setups (Maucieri et al., 2018). The available studies showed a wide variety in terms of model settings, facility sizes and products (Wu et al., 2019).

Aquaponic set-ups show a high design plasticity (Maucieri et al., 2018). The implementation of a low-tech aquaponic system, built with low-cost materials and few technological features, simply designed, and easily maintainable with limited interventions, could produce fish and vegetables with moderate investment and maintenance costs. Moreover, such systems can be installed in marginal areas as well as in urban areas where short supply chains are encouraged. The adaptability and growth of various fish and vegetable species have been previously explored in these low-tech experimental aquaponic systems (Maucieri et al., 2018; Birolo et al., 2020; Bordignon et al., 2020; Bordignon et al., 2021), but to date no information is available on their environmental performance.

In fish farming, stocking density is a key aspect, as it directly affects the amount and quality of nutrients, gases, and wastes released in the water (Palm et al., 2019) and, therefore, the environmental footprint of aquaponic products. Despite the effects of the stocking density and production intensity on the environmental impact were evaluated through LCA in other animal productions (Bhatt and Abbassi, 2021; Lorenz et al., 2019; Ross et al., 2017; de Vries et al., 2015) and conventional aquaculture systems (Mungkung et al., 2013; Yacout et al., 2016), to our knowledge, no LCA studies have been performed in aquaponics focusing on this aspect.

Thus, based on the feasibility of rainbow trout farming in the tested system evaluated in terms of fish growth performance, health, and quality, and vegetable productions (Birolo et al., 2020; Bordignon et al., 2021), the present study aimed to assess the environmental footprint of the rainbow trout production in a low-tech aquaponic system at two fish stocking densities.

2. Materials and methods

The environmental footprint was assessed by using an attributional life cycle assessment model. The environmental footprint was computed by applying the ILCD Handbook protocol for attributional LCA (EC, 2010). The construction and application of the LCA model followed the scheme described by ISO standards 14,040 and 14,044 (ISO, 2006): goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of the results.

2.1. Goal and scope definition

The LCA model settings were defined to evaluate the environmental footprint associated with the rainbow trout production in the experimental low-tech aquaponic system described by Birolo et al. (2020), with the scope of analysing the effect of two fish stocking densities (Low, 3.81 kg m^{-3} vs High, 7.26 kg m^{-3}). In this aquaponic system, the production of rainbow trout was associated with the production of lettuce. On these bases, a gate-to-gate model was used, considering the inputs, outputs and processes associated with the period from the start to the end of the trial. The system boundaries set to include the impacts related to the fish rearing, the production of the fish feedstuffs and the input needed to set (tanks, water, initial nutrients, expanded clay, pumps, aerators) and maintain (electricity, refilling water due to evapotranspiration) the trout-lettuce aquaponic system (Fig. 1). The functional unit was 1 kg increase of rainbow trout during the trial (from the initial weight of 145 g to the final weight of 333 g for the low stocking density and from 140 g to 329 g for the high stocking density). As the aquaponic system produced more than one product (fish plus lettuce leaves), the need to resolve how to allocate the whole impact to the animal and vegetable products emerged. Following the ISO guidelines (ISO, 2006), three methods to resolve the multifunctionality of the analysed system were applied:

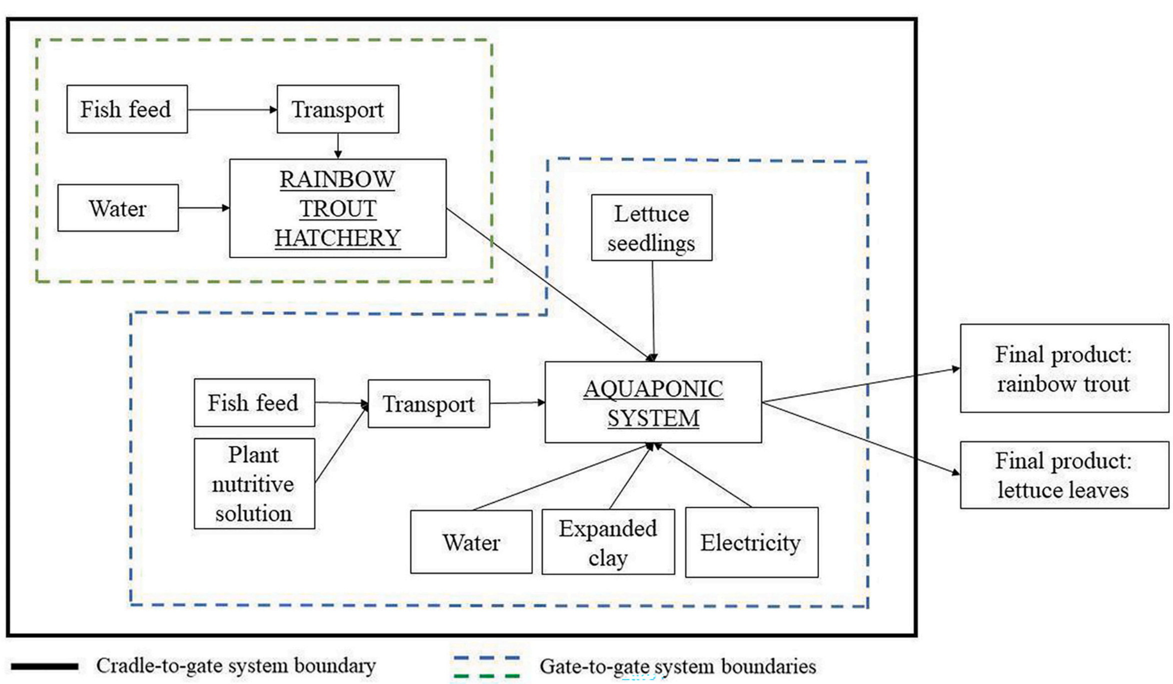

Fig. 1. System boundaries of the Life Cycle Assessment models (blue dotted line: gate-to-gate model for the low-tech aquaponic system, with rainbow trout from 142 g to 330 g of mean body weight; green dotted line: rainbow trout hatchery phase, with rainbow trout from 0 g to 142 g of mean body weight; black bold line: cradle-to-gate model, with rainbow trout from 0 g to 330 g). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1. mass allocation (whole impact allocated on the basis of the weight of fish and lettuce produced during the experiment). Data to compute mass allocation factors were derived from the trial by Birolo et al. (2020) (Tables 1 and 2);
2. economic allocation (whole impact allocated on the basis of the relative economic value of the fish and lettuce leaves produced). Mean market prices to compute economic allocation factors were obtained from ISMEA (2021) and BMTI (2021);
3. system expansion (the impact due to lettuce leaves produced in the aquaponic system was deducted from the whole impact by subtracting the impact computed by considering an alternative system to produce them). Data from the trial by Birolo et al. (2020) were used to compute the environmental footprint of the lettuce leaves produced in the hydroponic system, with the same configuration of the aquaponic system and with an equivalent production of lettuce leaves (the total amounts of lettuce leaves produced in the two cycles were equal in the aquaponic and hydroponic systems). The inventory and impact category values for 1 kg lettuce leaves in the hydroponic system are reported in supplementary Table S1.

Allocation factors for fish and lettuce leaves with respect to mass and economic allocations and system expansion are reported in Table 3.

The impact categories assessed were as follows:

1. global warming potential (GWP, kg CO_2-eq), associated with compounds contributing to the increase in the global tropospheric temperature (IPCC, 2021);
2. acidification potential (AP, g SO_2-eq), associated with change in an environment's natural chemical balance caused by an increase in the concentration of acidic elements (EEA, 2022);
3. eutrophication potential (EP, g PO_4-eq), associated with compounds having fertilizing effects on water bodies and soils matrix (Correl, 1998; Bennett et al., 2001);
4. cumulative energy demand (CED, MJ), associated with the energy demanded to produce a good or service (Frischknecht et al., 2003);
5. freshwater ecotoxicity (ECO, CTUe), associated with toxicological effects of the compounds released in the freshwater ecosystems (Rosenbaum et al., 2008);
6. water depletion (WD, m^3 water equivalent), associated with the reduction in the water availability for human and natural activities in a region (Brauman et al., 2016).

Table 1
Production performance of rainbow trout and lettuce farmed in the experimental low-tech aquaponic system at two different fish stocking densities (Birolo et al., 2020).

Variable	Stocking density		Hydroponic system	*P*-value
	Low	High		
Stocking density, kg m^{-3}				
Initial	3.81 ± 0.21	7.26 ± 0.65	–	<0.001
Final	8.86 ± 0.21	16.9 ± 0.68	–	<0.001
Fish weight, g				
Initial, 0 days	143 ± 34	140 ± 36	–	0.657
Final, 117 days	333 ± 71	329 ± 81	–	0.871
Feed conversion ratio	1.65 ± 0.21	1.51 ± 0.06	–	0.323
Lettuce leaves, kg m^{-2}				
First cycle, 77 days	2.69 ± 0.63	2.74 ± 0.84	2.89 ± 0.49	0.926
Second cycle, 44 days	2.00^b ± 0.10	1.96^b ± 0.10	1.71^a ± 0.19	<0.01

Data are expressed as means ± standard deviation.

Table 2
Life cycle inventory (gate-to-gate: low-tech aquaponic system, with rainbow trout from 142 g to 330 g) of rainbow trout farming at two initial fish stocking densities (Low: 3.81 kg m^{-3} vs. High: 7.26 kg m^{-3}) and of lettuce produced in the hydroponic system.

Variables	Unit	Aquaponic, fish stocking density	
		Low	High
Inputs			
Fish	n	42	81
Fish feed	kg	12.7	22.5
Nutrient solution			
H_2PO_4	kg	0.40	0.40
K_2SO_4	kg	0.59	0.59
$MgSO_4$	kg	0.82	0.82
Fe-ETDA	kg	0.03	0.03
Micronutrients	kg	0.02	0.02
Expanded clay	kg	4.05	4.05
Electricity	kWh	445	445
Transport	tkm	0.97	1.74
Water	L	3625	3625
Tank, PVC	kg	0.5	0.5
Greenhouse, plastic (90 m^2, use: 117 d, lifetime: 20 y)	m^2	1.4	1.4
Outputs			
Nutrient released in the water			
Ammonium	g	2.0	2.9
Nitrate	kg	1.14	1.51
Phosphate	kg	0.31	0.39
Rainbow trout	kg	7.7	14.7
Lettuce leaves	kg	13.1	13.1

In order to improve the understanding of the environmental footprint and the comparison of the results of this study with the literature, the system boundaries were expanded to also include the background phase of the fish production (hatchery phase), with a cradle-to-farm gate setting. The functional unit for the cradle-to-gate model was 1 kg of rainbow trout (from 0 g to 333 g for the low stocking density and from 0 g to 329 g for the high stocking density). The impacts related to the hatchery phase were entirely allocated to the rainbow trout fish.

2.2. Life cycle inventory

Data about the aquaponic facilities and experimental design were obtained from Birolo et al. (2020). Briefly, the trial was conducted at the experimental farm of the University of Padova, North-East Italy (45°20′N, 11°57′E, 6 m a.s.l.), inside a plastic greenhouse, during the winter season (November–February) for 117 days.

The experimental system was characterized by nine identical independent units: three hydroponic units without fish (considered in the LCA analysis for the system expansion method), three aquaponics units with a low stocking density, and three aquaponics units with a high stocking density. The system was designed according to the recommendations of Somerville et al. (2014), i.e. approximately 10 kg of fish biomass in a 500-L fish tank coupled with a biofilter having a minimum volume equal to 10–30% of the total fish tank volume. The system was designed to be a low-tech system, as no energy to regulate water temperature, no probe for the continuous evaluation of water quality or remote management, and no device for water sanitation were used.

Each of the experimental aquaponic units was characterized by: 1) a main tank (volume 500 L, height 0.80 m, diameter 0.90 m), in which the fish were kept; 2) two tanks for the cultivation of vegetables (volume 275 L each, height 0.35 m, diameter 1.00 m, total crop area 1.6 m^2) filled with 225 L of light expanded clay aggregates (LECA Laterlite, Solignano, Italy); the tanks for vegetable cultivation received water from the tank with fish and acted both as a biofilter and a substrate for plant growth; 3) a storage tank (volume 50 L, height 0.45 m) in which the water from the tanks with vegetables was collected before being pumped back into the

Table 3
Allocation factors (mass, economic and system expansion) to allocate the whole impact between rainbow trout and lettuce produced from the low-tech aquaponic system at two initial fish stocking densities (Low: 3.81 kg m^{-3} vs. High: 7.26 kg m^{-3}). Gate-to-gate model.

Multifunctionality resolution method	Fish stocking density					
	Low			High		
	Rainbow trout	Lettuce leaves	Allocation to rainbow trout (%)	Rainbow trout	Lettuce leaves	Allocation to rainbow trout (%)
Mass allocation						
Output, kg	7.7	13.1	37	14.7	13.1	53
Economic allocation						
Output, euro	37.1	9.2	80	70.8	9.2	88
System expansion[1]						
GWP,WD			69			69
AP			85			85
EP			58			58
CED, ECO			78			78

[1] Allocation factors based on the inventory and impacts obtained from the hydroponic system producing lettuce leaves; GWP: global warming potential, AP: acidification potential, EP: eutrophication potential, CED: cumulative energy demand; ECO: freshwater ecotoxicity; WD: water depletion.

main tank (Fig. 2).

Water flow through the system components was guaranteed by overflow. A single pump (Newa Jet 1700, NEWA TecnoIndustria Srl, Loreggia, Italy) returned the water from the storage tank to the main tank. The flow rate was 300 L h^{-1}, which corresponded to a complete recirculation of water every 2 h. The nine main tanks were aerated by a porous stone (Sweetwater® AS15S, Pentair, Cary, NC, USA) connected to an aerator (Scubla D100, Scubla Srl, Remanzacco, Italy).

A total of 123 rainbow trout (initial live weight: 142 ± 35 g) obtained from a commercial farm were used. The three low-density units were stocked with 14 fish per tank (average initial stocking density of 3.81 kg m^{-3}), while the three high-density units received 27 fish per tank (average initial stocking density of 7.26 kg m^{-3}). Fish were manually fed once a day, until apparent satiation with a commercial diet (Skretting, Verona, Italy; composition: 40% crude protein, 11.5% crude fat, 4% crude fibre, 8% ash, 0.2% sodium, 1.5% calcium, and 0.8% phosphorus, as-fed basis). During the trial, two crop cycles of lettuce (*Lactuca sativa* L.) were cultivated in succession during 77 days for the first cycle and 44 days for the second one. At the beginning of each cycle, 20 plants per experimental unit (10 plants per tank, plant density 13 plants m^{-2}) were transplanted during the third true leaf stage. The first cycle began 3 days before fish addition in the systems; the second cycle was harvested the day after fish harvesting. Plants were obtained from an external supplier. The aquaponic units were added a nutrient solution formulated by the free software HydroBuddy based on optimal conditions for lettuce in hydroponics. Neither pesticides nor antibiotics were used.

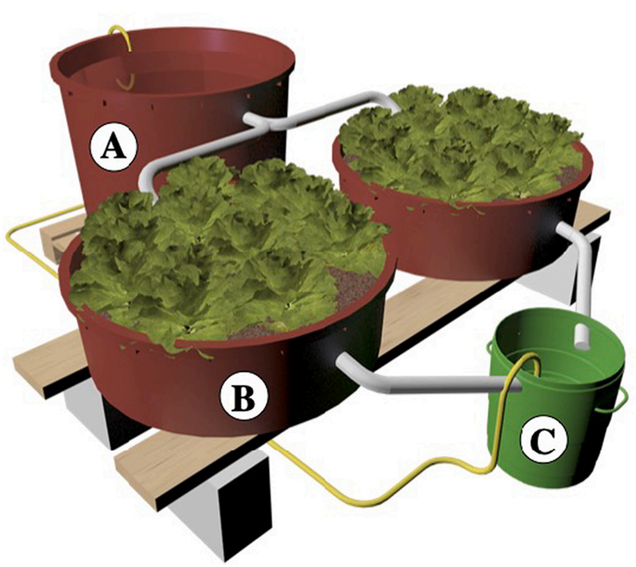

Fig. 2. Scheme of an aquaponic unit. A) main tank for fish rearing (500 L); B) tanks for vegetables/biofilters (275 L); C) storage tank (50 L) in which the water was collected before returning into the fish tank.

Table 1 summarizes production performance of rainbow trout and lettuce obtained in the tested aquaponics and hydroponic systems by Birolo et al. (2020). Briefly, trout production in aquaponics was not affected by fish stocking density and fish reached an average final weight of 331 ± 23 g, corresponding to a feed conversion ratio of 1.58 ± 0.16 and a mortality rate of 3%. Likewise, the average yield of lettuce during the two consecutive cycles was 2.4 ± 0.66 kg m^{-2} with no differences according to fish stocking density (Table 1). The water daily added to refill evapotranspiration losses was on average 2.45 L d^{-1}, equal to 0.41% of the total volume of each aquaponic unit.

The inventories about the aquaponics system at low and high stocking density and about the hydroponic system are reported in Table 2. At low stocking density nearly 13 kg of fish feed, 450 kWh of electricity and 3600 L of water were used to produce 7.7 kg of rainbow trout and 13 kg of lettuce leaves. At high stocking density about 23 kg of fish feed, 450 kWh of electricity and 3600 L of water were used to produce 14.7 kg of rainbow trout and 13 kg of lettuce leaves. On the other hand, in the hydroponic system 13 kg of lettuce leaves were produced by using 4.3 kg of nutrient solution, 140 kWh and 3600 L (see also supplementary Table S1). The average inputs required to produce 1 kg increase of table-size rainbow trout (from 140 to 330 g of live weight) at low and high stocking density are reported in supplementary Table S2.

The local emission of N and P due to fish input-output balance was estimated according to the procedure suggested by Cho and Kaushik (1990), computing the N and P intake from fish feeds and their retention in fish bodyweight. Impact factors were derived from Ecoinvent v3.7 (Wernet et al., 2016; Moreno et al., 2020), Agrifootprint v5 (Blonk Consultants, 2019) and Agribalyse (ADEME, 2018) databases implemented in Simapro software v9.2 (see supplementary Tables S3 and S4).

Data about the background phase related to the fish during the hatchery phase were obtained from the producer (the same for all the juveniles purchased) through an interview, which regarded the inputs and the management to obtain the fish at a body weight equal to the initial body weight of the fish in the experiment (see supplementary Table S4). In particular, data related to consumption of feeds and water, transport of feeds, rainbow eggs required for the number of juveniles purchased for the experimental trial were collected. Despite specific and accurate data related to the energy sources and the facilities were not available, the number of purchased juveniles (123) was negligible compared to the whole hatchery production. For this reason, the impact due to the facility embedded in the juveniles used in this experimental trial could be considered negligible. The production of the lettuce plants at the third true leaf stage was cut-off due to its very small contribution to the whole impact.

2.3. Life cycle impact assessment

The single substances and contributions were standardized to the common unit of the related impact category. Characterization factors from Myhre et al. (2013) were applied to GWP; CML-IA method (van Oers, 2016) to AP and EP; Cumulative Energy Demand method (implemented in Simapro v9.2 software) to CED; ILCD Midpoint (EC, 2012) to WD and ECO categories.

2.4. Interpretation of the results

The contribution of each production phase to each impact category was assessed by using the hotspot analysis (EC, 2010). Moreover, as aquaponic systems are multifunctional, producing more than one output, a scenario analysis was used to test different allocation methodologies on the variability of the impact results.

Due to the great contribution of electricity and feed to most of the impact categories, two scenarios were investigated to evaluate the effects of the change in the electricity source (from conventional grid mix to a photovoltaic source) and of the reduction of the feed conversion ratio (FCR). For this latter, a reduction from 1.6 (present study) to 1.2 was considered, being the latter value the average of FCR of previous studies (Aubin et al., 2009; Forchino et al., 2017; Roque d'Orbcastel et al., 2009).

3. Results

3.1. Gate-to-gate aquaponic and hydroponic system impact assessment

Results about the impact categories results obtained for the rainbow trout at low and high stocking densities in the aquaponic system are reported in Table 4. Considering mass allocation, to produce 1 kg increase of rainbow trout in the low-tech aquaponic system were emitted on average 8.8 kg CO2-eq (GWP), 56 g of SO2-eq (AP) and 64 g of PO4-eq (EP), while the CED was 161 MJ, the ECO was 186 CTUe and WD was 61 L. The farming of rainbow trout at a low stocking density generated a greater impact compared to a high stocking density in terms of all the impact categories, from +20% for WD to +35% for GWP. Considering the economic allocation, impact values were nearly 2.2 and 1.7 times greater than those found with the mass allocation method, at low and high stocking density respectively. Similarly to mass allocation, the low stocking density showed a higher impact compared to high stocking density in all the impact categories considered, from +56% in EP to +75% in GWP (Table 4).

The life cycle impact of the aquaponic production of rainbow trout was also calculated by expanding the system, including the production of lettuce leaves through an alternative system (hydroponic system) and then subtracting this impact from the whole impact associated with the aquaponic system (Table 3). With this approach, the rearing of rainbow trout generated a greater impact than that found with mass allocation method both for the low stocking density (2.2–2.5 times for CED, ECO, ED; 1.6–1.9 for GWP, AP) and the high stocking density (1.5–1.7 times for CED, ECO, WD; 1.2–1.3 for GWP, AP). The EP was similar between the expansion and mass allocation methods for both stocking densities. The low stocking density generated an impact from +51% (EP) to +94% (GWP) compared to the high stocking density.

A gate-to-gate hotspot analysis for the LCA of the production of 1 kg increase of rainbow trout in our aquaponic system is described in Fig. 3. Electricity was the dominant contribution in all the impact categories, ranging from 64% of EP to 93% of ECO. Feed production accounted for 19% of WD, 10% of GWP, and 5–7% of the other impact categories (Fig. 3). Released nutrients had a notable contribution to EP (30%). Beyond fish feed, WD was mostly due to electricity use (60%) and water depleted during the trial (20%). On the other hand, impacts due to transport and facilities were lower than 1% for all the impact categories.

The replacement of the Italian electricity grid mix with a photovoltaic plant (Fig. 4) abated by 70–80% the GWP and AP emissions associated with 1 kg increase of rainbow trout (low and high stocking density, mass and economic allocation methods), whereas EP and WD values were nearly halved. The CED and ECO categories were the least affected, with a reduction of nearly 40% with respect to the reference scenario (i.e. electricity from the Italian electricity grid mix). With the system expansion, the use of electricity from photovoltaic plant abated

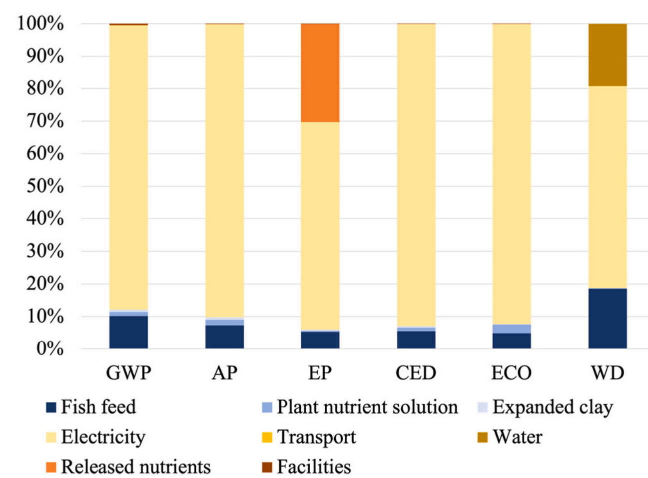

Fig. 3. Contribution (%) of the different production stages to each impact category value (GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion) for the gate-to-gate Life Cycle Assessment model of the low-tech aquaponic system (rainbow trout from 142 g to 330 g of mean body weight).

Table 4
Impact category values (gate-to-gate: low-tech aquaponic system, with rainbow trout from 142 g to 330 g) associated with the production 1 kg increase of rainbow trout, with two initial fish stocking densities (Low: 3.81 kg m^{-3} vs. High: 7.26 kg m^{-3}). The coproduction of rainbow trout and lettuce leaves was resolved by using mass allocation, economic allocation or system expansion methods.

Impact category[1]	Unit	Stocking density					
		Low			High		
		Mass allocation	Economic allocation	System expansion	Mass allocation	Economic allocation	System expansion
GWP	kg CO_2-eq	10.6	22.9	19.6	7.8	13.1	10.1
AP	g SO_2-eq	66	143	107	51	86	60
EP	g PO_4-eq	72	157	76	60	100	51
CED	MJ	189	409	404	146	244	220
ECO	CTUe	219	474	539	168	282	291
WD	m^3 eq	0.068	0.148	0.147	0.057	0.095	0.088

[1] GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion; CTUe: Comparative toxic units.

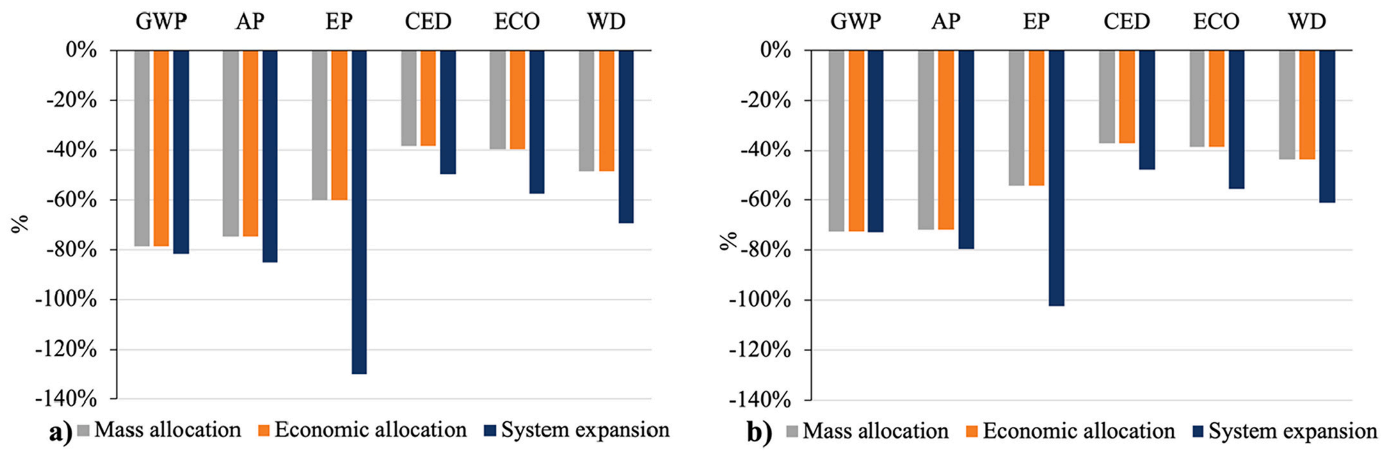

Fig. 4. Percentage reduction in the environmental impact of the tested low-density (a) and high-density (b) aquaponic systems when changing the electricity source from the Italian grid mix (current system) to a photovoltaic plant. GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion. Data were analysed considering mass allocation (whole impact allocated on the basis of the mass – kilograms - of fish and lettuce produced during the experiment), economic allocation (whole impact allocated on the basis of the relative economic value of the fish and lettuce leaves produced), and system expansion (expanded the system to include the production of lettuce through a traditional system and subtracting this impact to the whole impact associated to the aquaponic system).

the impact values by nearly 50% to 130%, depending on the impact categories (Fig. 4). In fact, with the system expansion, the impact associated with the lettuce leaves co-product (produced in an alternative system) was subtracted from the total impact of the aquaponics system. Thus, since the amount of PO_4-eq associated with the whole aquaponics was lower than that associated with the hydroponic one (0.603 kg and 0.761 kg in the Low and the High stocking density, respectively, vs. 0.780 kg), the EP decrease was more than 100% when the photovoltaic source replaced the conventional electricity mix grid.

The reduction of FCR from 1.6 to 1.2 decreased the eutrophication potential by nearly 10% in the mass and economic allocation and by 20% in the system expansion for both stocking density systems (Fig. 5).

3.2. Cradle-to-gate life cycle impact assessment

The cradle-to-gate life cycle impact associated with the production of 1 kg of rainbow trout is reported in Table 5. Considering mass allocation, the farming of rainbow trout at a low stocking density generated a greater impact compared to a high stocking density in terms of GWP (+34%), AP (+28%), CED (+30%), ECO (+31%), whereas little or no differences were found for EP and WD, respectively (Table 5). With the economic allocation, the trout production at the low stocking density generated a higher impact (from +40% to +74%) compared to the high stocking density in all the categories, except for WD (0%). A similar trend was observed also with the system expansion method (from +18% of EP to +91% of GWP) in the low compared to the high density system, without differences for WD.

The results of the cradle-to-gate hotspot analysis (Fig. 6) showed that the aquaponic stage accounted for 96–99% of the GWP, AP, EP, CED, and ECO values in the whole production cycle considered, whereas the contribution to WD was almost totally provided by the off-system stage (i.e. from the flow-through commercial hatchery from which trout juveniles were purchased). For the other impact categories, the main contribution from the hatchery was provided by fish feed, which accounted for 2–3% of total GWP, AP, EP, and CED; contributions due to rainbow trout eggs and transport were lower than 1%.

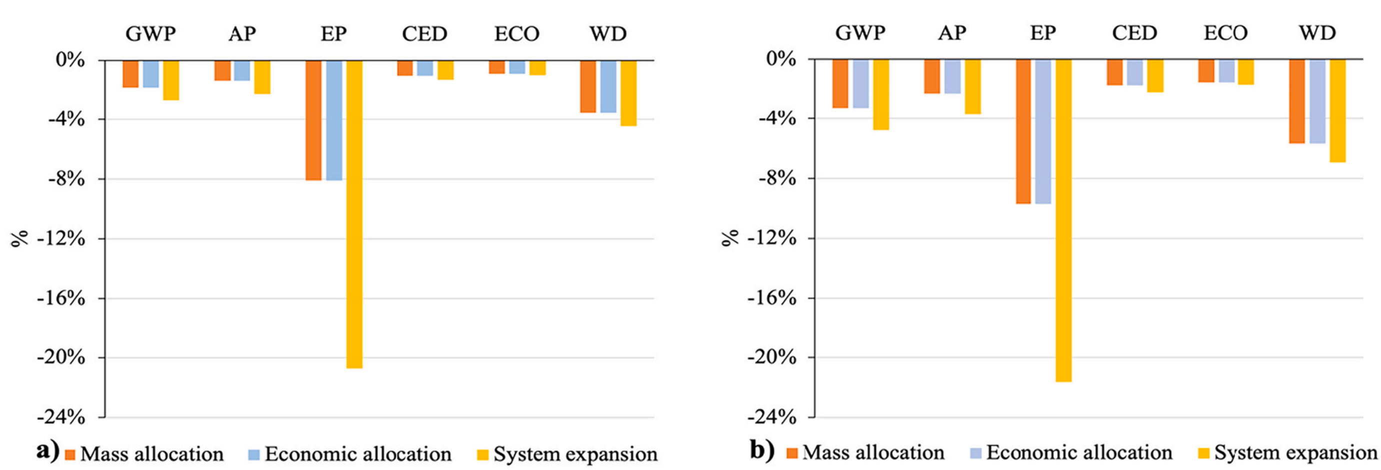

Fig. 5. Percentage reduction in the environmental impact of the tested low-density (a) and high-density (b) aquaponic system resulted from the reduction of feed conversion ratio from 1.6 to 1.2. GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion. Data were analysed considering mass allocation (whole impact allocated on the basis of the mass – kilograms - of fish and lettuce produced during the experiment), economic allocation (whole impact allocated on the basis of the relative economic value of the fish and lettuce leaves produced), and system expansion (expanded the system to include the production of lettuce through a traditional system and subtracting this impact to the whole impact associated to the aquaponic system).

Table 5
Impact category values (cradle-to-gate, low-tech aquaponic system plus background hatchery system) associated with the production of 1 kg of live rainbow trout from a low-tech aquaponic system characterized by two initial fish stocking densities (Low: 3.81 kg m^{-3} vs. High: 7.26 kg m^{-3}). The coproduction of rainbow trout and lettuce leaves was resolved by using mass allocation, economic allocation or system expansion methods.

Impact category[1]	Unit	Stocking density					
		Low			High		
		Mass allocation	Economic allocation	System expansion	Mass allocation	Economic allocation	System expansion
GWP	kg CO_2-eq	6.5	13.7	11.8	4.8	7.9	6.2
AP	g SO_2-eq	40	85	65	32	52	37
EP	g PO_4-eq	46	96	50	43	70	42
CED	MJ	114	242	240	88	145	131
ECO	CTUe	128	277	315	97	163	168
WD	m^3 eq	19	19	19	19	19	19

[1] GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion; CTUe: Comparative toxic units.

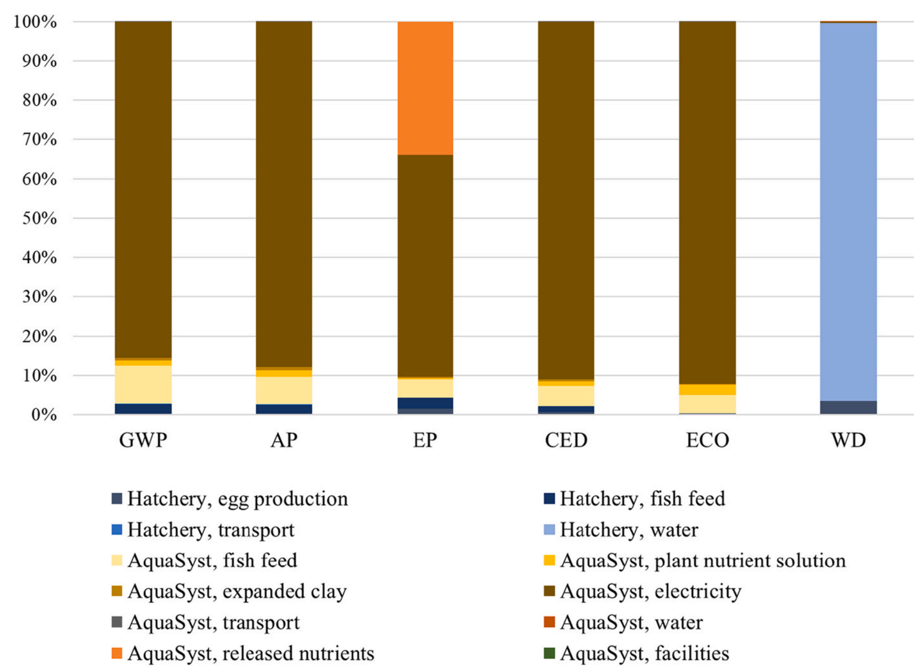

Fig. 6. Contribution (%) of the different production stages to each impact category value (GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; CED: Cumulative energy demand; ECO: Freshwater ecotoxicity; WD: Water depletion) for the cradle-to-gate Life Cycle Assessment model (low-tech aquaponic system (AquaSyst) plus background hatchery system (Hatchery), with rainbow trout from 0 g to 330 g of mean body weight).

4. Discussion

To our knowledge, this is the first LCA study on rainbow trout reared in a real aquaponic setup and using data obtained from an experimental growth trial, whereas LCA could afford to gain quantitative insights on the impact differences between management strategies (i.e., stocking density) and production stages (hatchery in the cradle-to-gate model and grow-out in the gate-to-gate model).

We analysed seven impact categories and we hereafter discuss the major hotspots found in the experimental system studied. Then, we provide scenario analyses to test solutions that can potentially reduce the impact of the hotspots detected.

The gate-to-gate LCA model showed that the production of rainbow trout at a low stocking density had a greater environmental impact per 1 kg increase than the production at a high density in terms of all the impact categories assessed. Since no difference was observed in fish growth between the two stocking densities, this result was due to the use of a lower quantity of inputs (e.g. electricity) per 1 kg increase of rainbow trout in the high compared to the low stocking density system. In fact, as LCA is a quantitative method (Finnveden et al., 2009), the reduction of inputs per 1 kg increase of rainbow trout is reflected in the impact results. Other methods and indicators related to environmental burdens have been developed in the last decades, considering different steps of Drivers-Pressures-State-Impact-Responses framework (DPSIR; EEA, 1999; Halberg et al., 2005). The greater the production system output is, the greater the absolute environmental burden is expected. However, food systems are set to answer to a food demand. Thus, quantitative, product-related methods, such as LCA, have a greater capacity than others to give insights to achieve the food demand with the minimum environmental burden and with positive effects on the subsequent DPSIR steps. In other words, LCA can suggest production practices (R step) that decrease the environmental burdens associated with the food production systems.

Although this is the first study evaluating the environmental effects of different fish stocking densities in aquaponics, similar results were also observed in previous LCA studies on Indonesian (Mungkung et al., 2013) and Egyptian (Yacout et al., 2016) tilapia traditional farms with different production practices (intensive vs. semi-intensive) and stocking densities. Overall, the increase of system productivity has led to a decrease in the environmental impact of trout aquaponic farming, as already observed in other aquaculture (Mungkung et al., 2013; Yacout et al., 2016) and animal production systems (Gerber et al., 2011; de Vries and de Boer, 2010).

The hotspot analysis of the present study confirmed that the main contributors to the environmental impact in an aquaponic system are the electricity used for system functioning, even in a low-tech system, and the production of fish feed (Fig. 2), as already observed by almost all the authors that have published about LCA in aquaponics (Chen et al., 2020; Ghamkhar et al., 2020; Forchino et al., 2017; Maucieri et al., 2018) as recently reviewed (Wu et al., 2019; Greenfeld et al., 2022). Indeed, results about energy use are often difficult to compare among studies due to differences among geographical regions, farm settings, and practices (Wu et al., 2019). Under the conditions of our low-tech aquaponic system (no water temperature control), the production of 1 kg increase of rainbow trout required 57.8 kWh and 30.3 kWh electricity in the low and high stocking density aquaponic systems, respectively (calculated from data in Table 2). These values were largely lower compared to the energy (159 kWh; including both electricity and propane) used to produce 1 kg increase of tilapia by Love et al. (2015) in a small-scale raft aquaponic system using tank water heaters, greenhouse heating, and fluorescent light fixtures. According to the same authors, energy was addressed directly and indirectly for heating water and the largest use of electricity was in tank water heaters. Generally, in recirculating aquaculture systems, including aquaponics, electricity can contribute to 50% of GWP and CED and up to 30% of AP (Chen et al., 2020). Therefore, the reduction of energy consumption and of the impact related to energy production is a first major challenge for aquaponic production. As found in the scenario based on the use of a photovoltaic source to generate electricity, the switch from the Italian electricity mix to renewable sources could be a viable solution to abate the impact of the electricity still needed.

Fish feed has been found to be the major material contributor to the environmental impact in aquaculture (Aubin et al., 2009; Avadí and Fréon, 2015; Roque d'Orbcastel et al., 2009; Mungkung et al., 2013; Samuel-Fitwi et al., 2013; Yacout et al., 2016) and aquaponics (Chen et al., 2020; Ghamkhar et al., 2020), being the main source to provide protein and essential nutrients in the case of carnivorous fish. Nevertheless, the reduction of the environmental impact generated by fish feed seems more difficult to be achieved (Forchino et al., 2017) and largely depends on the improvement of FCR (i.e. the reduction of its value). The average FCR obtained in our system was 1.6, higher than those previously reported in trout RAS and aquaponics (Forchino et al., 2017). The low environmental control and low farming intensity of our low-tech system, where fish were kept sometimes under sub-optimal temperature and oxygen conditions, may have reduced the overall feed efficiency. In fact, previous studies showed that as farming intensity increases (i.e. high technology, environmental control and fish stocking density) FCR improves (Ghamkhar et al., 2021). However, the results found in this study in the second scenario (FCR improved from 1.6 to 1.2, see Fig. 5) evidenced that the improvements in the environmental footprint was interesting only for EP, likely because of electricity contribution on the overall impact results. On the other hand, an increase of the environmental control of the aquaponic system, through a higher level of technological equipment (e.g. water oxygenation and temperature control) will surely increase electricity demand and overall impacts of farmed trout.

Nutrient release is one of the major concerns related to agricultural productions (Joyce et al., 2019). However, in aquaponics systems, the nutrients produced by fish are recycled and used as fertilizer for plant growth. In our system, the release of nitrogen and phosphorous contributed to 30% of the eutrophication potential, while the remaining part was derived from electricity and feed production. Previous studies have observed divergent results about the effect of the stocking density on EP category, exacerbating (Maucieri et al., 2020) or mitigating (Ghamkhar et al., 2021) the whole impact. This might imply the need for upgrading the system set-up, enhancing the removal of solids derived from fish faeces and uneaten feed.

In aquaponics, the addition of a micronutrient-rich solution is necessary to obtain plant yields comparable to those observed in hydroponic cultivations. In fact, despite nutrients such as zinc (Zn), manganese (Mn), and iron (Fe) can derive from fish feed, while copper (Cu) and boron (B) from tap water (Delaide et al., 2017), key micronutrients in aquaponic systems are often present at very low concentrations to sustain optimal plant performance (Bittsanszky et al., 2016; Delaide et al., 2017; Nozzi et al., 2018; Roosta, 2014). However, we found that plant nutrients solution used in the aquaponic system did not determine a great contribution to the impact category values. On the other hand, the nutrient solution showed a notable contribution in the hydroponic system, consistently with Jaeger et al. (2019).

In the Mediterranean context, rainbow trout are typically farmed in flow-through systems, known to use a greater amount of water (+90–99%) if compared with closed RAS, such as aquaponics (Samuel-Fitwi et al., 2013; Ghamkhar et al., 2021). In fact, in our study, nearly all water was consumed in the hatchery phase, whereas the aquaponic system consumed less than 0.04% of the total water consumption. In addition, studies showed a reduction in water consumption per unit of product with the increase of farming intensity (Aubin et al., 2009), with low-stocking density systems having greater (+28%) water use compared with high-density systems (Mungkung et al., 2013). These results were observed also in our aquaponics system when applied a gate-to-gate approach (i.e. when considering only the impact related to the rearing of trout in our aquaponic system), where a greater water depletion was found to produce 1 kg increase of trout at low compared to high stocking density when considering both mass allocation (+20%) and economic allocation (+56%).

The LCA analysis of multifunctional processes has to face the problem of partitioning the whole impact to the different co-products obtained. As different resolution methods can be used, this choice can affect the impact values per unit of each co-product and thus the main results. In aquaponics LCA studies, different methods have been used: mass allocation (Forchino et al., 2017; Ghamkhar et al., 2020), economic allocation (Hindelang et al., 2014; Hollmann, 2017), nutrient-based allocation (Jaeger et al., 2019), and system expansion (Boxman et al., 2017), besides no impact allocation with the use of a combined fish-vegetable functional unit (Cohen et al., 2018; Greenfeld et al., 2021; Valappil, 2021).

Each method has some advantages and disadvantages and how to choose a multifunctionality resolution method has been widely debated, particularly in animal production (Pelletier et al., 2015; Wilfart et al., 2021; Ijassi et al., 2021). Mass allocation can be stable over time and easy to use, but it cannot distinguish possible qualitative differences. Economic allocation reflects the socio-economic demand related to the co-products, so including qualitative traits, but prices can change over time following the evolution of that demand, with no relationships with the characteristics of the production system. System expansion theoretically modifies the system boundaries by the inclusion of an alternative system to produce one co-product. Thus, results can be very sensitive to the alternative system chosen.

In this study, mass allocation, economic allocation, and system expansion were used. These three methods were applied to study the sensitivity of the results to the fish-vegetable multifunctionality resolution problem. As for the gate-to-gate model, the high-stocking density system had a lower environmental impact than the low stocking density with all the resolution methods, which reveal robust results of the present study. On the other hand, the absolute values of the impact categories largely changed with the different methods, being results in economic allocation and system expansion more similar compared to results of mass allocation.

Both economic allocation and system expansion gave more focus to the fish rather than the lettuce leaves, as the fish price was the greatest (economic). Moreover, results from the equivalent-hydroponic system were used to evaluate the impact due to the sole fish in the aquaponic system (system expansion), whereas the study was addressed to compare the environmental footprint of two different fish stocking density. On the other hand, mass allocation was the only method independent from external traits/systems. Accordingly, results from the three methods give a comprehensive view on the environmental footprint of the aquaponic system assessed in this study.

5. Conclusions

From the environmental point of view, a high fish stocking density determined a lower impact per kg increase of fish produced, especially in terms of global warming, cumulative energy demand and freshwater ecotoxicity. The electricity used for the system functioning was the major hotspot observed in the tested system. The replacement of the energy source from the common grid mix to renewable sources such as photovoltaic systems can substantially reduce the environmental impact derived from electricity, especially in terms of global warming. The farming of rainbow trout in recirculating coupled aquaponics is a promising alternative to common flow-through systems, particularly in view of minimizing the depletion of water resources. Nevertheless, the impact derived from water depletion should be carefully evaluated in cradle-to-gate perspective, i.e. from raw material extraction to the farm gate (before product being transported to the consumer), as off-system stages (i.e. hatchery phase) could strongly increase the overall water consumption required for fish production.

CRediT authorship contribution statement

Francesco Bordignon: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Enrico Sturaro:** Conceptualization, Writing – review & editing. **Angela Trocino:** Conceptualization, Writing – review & editing. **Marco Birolo:** Writing – review & editing. **Gerolamo Xiccato:** Conceptualization, Writing – review & editing, Funding acquisition. **Marco Berton:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing.

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.

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