Journal of Cleaner Production 352 (2022) 131613

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Innovative options for the reuse and valorisation of aquaculture sludge and fish mortalities: Sustainability evaluation through Life-Cycle Assessment

Silvio Cristiano [a,*], Hallstein Baarset [b], Christian Bruckner [c], Johan Johansen [d], Roberto Pastres [a,e]

[a] Università Ca' Foscari Venezia, Campus Scientifico, via Torino 155, 30172, Mestre, Venice, Italy
[b] Waister AS, Åslyveien 15, 3170, Sem, Norway
[c] Norwegian Seaweed Institute AS, Inndyrveien 77, 8140, Inndyr, Norway
[d] Norwegian Institute for Bioeconomic Research, 1431, Ås, Norway
[e] Bluefarm s.r.l., Centro Vega ed. Pegaso, via delle Industrie 15, 30175, Marghera, Venice, Italy

A R T I C L E I N F O

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Farmed finfish
Circular economy
Recirculating aquaculture system (RAS)
Wastewater
Purification: filtration
Health
Safety
Environment

A B S T R A C T

Two Life-Cycle Assessments (LCAs) were conducted to evaluate the environmental performances of selected novel eco-intensification innovations for the treatment and valorisation of sludge and fish mortalities from finfish aquaculture. The first innovation is based on a new process for filtering and drying particles from the reject water from a Recirculating Aquaculture System (RAS), with end-of-life recovery of nutrients and biomass to be reused as organic fertiliser or as energy source. The second process is based on a new device for drying fish mortalities and reusing the end-product as ingredient in the pet food industry or as energy source. Innovations refer to a functional unit of 1 ton of farmed fish and of fish mortalities, respectively, and were tested with a RAS for smolt production within the physical system boundary of a Norwegian facility. A set of standard indicators was selected for the Life-Cycle Impact Assessment (LCIA). The results indicate that the new processes compare well with the established ones, showing a marked decrease in most impact categories: indicators decrease by −12% through to −67% when sludge treatment innovations are applied, and by more than −86% after novel changes about fish mortality, with water consumption instead increasing by +7% and up to +50%, respectively. Furthermore, the analysis provided insights which could lead to improve their environmental performances.

1. Introduction

Aquaculture is among the fastest expanding food sectors globally (European Commission, 2020), with an average growth rate of 5.3% in the period 2001–2018 (FAO, 2020). The most recent figures by the Food and Agriculture Organisation of the United Nations (*ibid.*) report an all-time peak of 114.5 million tonnes in fresh biomass from aquaculture production in 2018, with a global equivalent farmgate sale value of 263.6 billion USD, mostly consisting of aquatic animals (81.1 million tonnes, 250.1 billion USD), whose farming is dominated by finfish (54.3 million tonnes, 139.7 billion USD in that year). The uncontrolled intensification of aquaculture production has caused social and environmental issues in some regions (Troell et al., 2014). Strategies toward the improvement of the economic and environmental performances of aquaculture have been recently set in the European Union (European Commission, 2021). These strategies can be implemented in the framework of the ecological intensification of aquaculture, a new concept that promises to "address the double challenge of maintaining a level of production sufficient to support needs of human populations and respecting the environment in order to conserve the natural world and human quality of life" (Aubin et al., 2019).

Fish mortalities and discarded fish represent significant side streams in the aquaculture industry, in terms of currently disposed volumes, operational expenditures, by-product potential economic value, and – last but not least – health, safety, and environmental hazards (Baarset and Johansen, 2019): still based on an old technique such as fish silage (Raa et al., 1982), using formic acid, fish mortality disposal implies these types of hazards spanning from in-house contexts (Baarset and Johansen, 2019) to the vessels (Yang et al., 2020) and land vehicles to dispose of aquaculture special waste. In all types of land-based fish farming systems, sludge also plays a role in environmental and waste management for its containing often large amounts of nutrients (Lunda et al.,

* Corresponding author.
E-mail address: silvio.cristiano@unive.it (S. Cristiano).

https://doi.org/10.1016/j.jclepro.2022.131613
Received 12 October 2021; Received in revised form 25 March 2022; Accepted 30 March 2022
Available online 2 April 2022

2019) whose excess can cause water pollution concerns (Jasmin et al., 2020); as a matter of fact, there is a long standing record of scientific evidence connecting aquaculture to ecological impacts such as eutrophication (Gowen, 1994; Burkholder and Shumway, 2011; Song et al., 2019). On the contrary, the extraction of nutrients can purify wastewater while also capture nutrients, to be reused. This is why recovering nutrients from fish sludge has attracted relevant interest in recent years, as noted and reviewed by Zhang et al. (2020).

In the present paper, the hazards related to fish mortality disposal and the ecological impacts related to sludge disposal are both addressed from an overall environmental assessment perspective; such a focus fills a gap in scientific literature, and is expected to support sound design and decision making in an era of wished and declared ecological transition. Specifically, the environmental performances of two innovative processes, which could contribute to the eco-intensification of aquaculture, are compared to the established standard processes. The environmental costs and impacts related to current and innovative processes, including the reuse of by-products, for the management of RAS sludge and fish mortalities, were estimated through a selection of indicators. The evaluation followed the standard method of Life-Cycle Assessment (LCA) (ISO, 14040; Arvanitoyannis, 2008), as extensively used in aquaculture (Henriksson et al., 2012), and also recommended for the evaluation of eco-intensification innovations (Beltran et al., 2018; Little et al., 2018).

The selected case study is a modern smolt farm in Norway, where aquaculture is undergoing an intensification process, with production significantly increasing in each location (Baarset and Johansen, 2019), thus offering examples for the rest of Europe and beyond: recirculating systems are also frequent in Denmark and Spain and, across the Atlantic Ocean, in Canada and the United States of America (Ahmed and Turchini, 2021); fish mortalities are of course present in all types of aquaculture. The selected innovations for sludge and fish mortality treatment and valorisation were carried out within project Green Aquaculture INtensification in Europe (GAIN, 2018–2021),[1] funded within the European Commission's Horizon 2020 programme.

2. Materials and method

An environmental evaluation through Life-Cycle Assessment (§2.1) is conducted to assess the sustainability improvements of ecological intensification innovations for the reuse and valorisation of aquaculture sludge, fish mortalities, and discarded fish. As illustrated in §1 (Introduction), Norway and salmon production respectively represent a relevant context and a relevant production.

2.1. The Life-Cycle Assessment approach

The Life-Cycle Assessment (LCA) method is used here according to the ISO14040 standard (ISO, 2006). LCA is a tool for the environmental accounting of anthropogenic impacts, mostly connected to productive activities. LCA is "a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use" (Muralikrishna and Manickam, 2017). Life-Cycle Assessment is a widely recognised and implemented environmental assessment method in the aquaculture sector, as per the reviews and evaluations by Henriksson et al. (2012), Bohnes and Laurent (2019), and Bohnes et al. (2019). The LCA is here performed based on the four main steps recommended by the International Standard Organisation (ISO, 2006): Goal and scope definition (section 2.1.1); Life-Cycle inventory (sections 2.2.1 and 2.2.2, with modelling assumptions shown in sections 2.4.1 and 2.4.2); Life-Cycle Impact Assessment (section 3); and Results interpretation (section 4). Such a standardised rationale is also shown in Fig. 1.

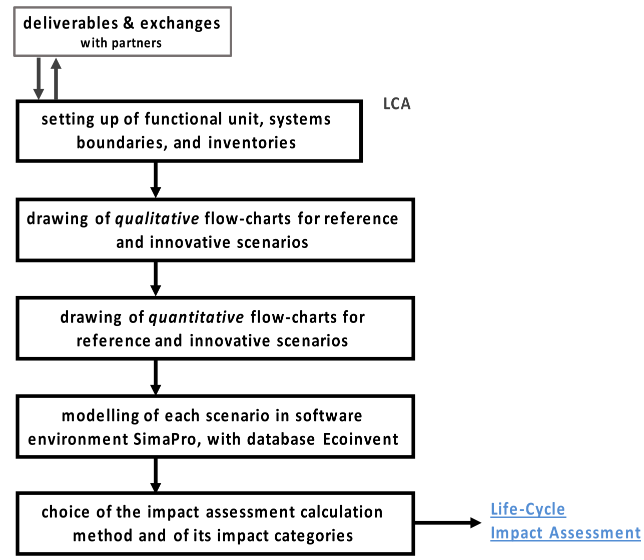

Fig. 1. LCA steps for calculating Life-Cycle Impact Assessment indicators.

2.1.1. Goal and scope definition

The present assessment aims at estimating the environmental impact data related to selected eco-innovations in aquaculture, as shown in sections 2.2 and 2.3, compared with their business-as-usual scenarios. The LCA steps for calculating the Life-Cycle Impact Assessment (LCIA) indicators are standardised (ISO, 2006). As per LCA theory, in order to ease comparisons among processes, all data are referred to a functional unit (FU) (*ibid.*), i.e. a stated and fixed unit of output that is typical of the system to evaluate. In our study, a FU of 1 ton of farmed fish is considered for the wastewater treatment case studies, as illustrated in section 2.2.1, and a FU of 1 ton of fish mortalities for case studies illustrated in section 2.2.2. An advancement compared to conventional LCAs is represented by the fact that flow-charts resort here to the energy systems language (Odum, 1983; Brown, 2004); granted that a flow chart would be anyway required in a LCA, such a specific type of diagramming is expected to ease comparisons with other accounting approaches, including the above mentioned emergy one, which will be addressed in a later work (Cristiano et al., forthcoming).

An effort is made not to overestimate benefits from eco-innovations, in the spirit of a cautious assessment. A conceptual model (flow chart) is offered in §3 (Results) for each case study. The LCAs are here carried out by using software package SimaPro 9.0.0.49 (PRé, 2012).[2] Secondary data are obtained from database Ecoinvent 3.1[3] (Wernet et al., 2016). The allocation type is chosen as Cut-off, S, i.e. based on the cut-off principle (excluding inputs that are not relevant for the product system at issue) and at a system level.

The Life-Cycle Impact Assessment (LCIA) is performed by means of 16 impact indicators, borrowed from the LCA dealing with aquaculture (Bohnes and Laurent, 2019), as reviewed above, in order to build on previous assessments; human health impacts are also used on top of purey environmental ones, following Moretti et al. (2018) and based on a recent and regularly updated method like ReCiPe (Huijbregts et al., 2017). One adopted indicator has been considered with the method by United Nations' Intergovernmental Panel on Climate Change (IPCC), 100-year time span (Forster et al., 2007); 12 indicators with ReCiPe 2016 Midpoint (Huijbregts et al., 2017), egalitarian (E); another indicator with the method by Bösch et al. (2007); and 2 indicators with

[1] https://www.unive.it/pag/33897.

[2] https://simapro.com/.

[3] https://www.ecoinvent.org/database/older-versions/ecoinvent-31/ecoinvent-31.html.

Selected LCI results (Frischknecht et al., 2007) (see **Table A** as a supplementary material).

When applying the ReCiPe 2016 estimation method, the egalitarian (E) perspective is used, targeting long-term impacts and based on precautionary principles. In Cumulative Exergy Demand, both renewable and nonrenewable sources are included. The type and quality of energy sources will be assessed separately in a future work (Cristiano et al., forthcoming) through the above cited emergy accounting method.

Primary data about the eco-innovations were collected at the demonstration plant by company Helgeland Smolt AS,[4] located in Sundsfjord, municipality of Gildeskål, Norway. This is a modern smolt farm, whose RAS technologies are delivered by Veolia Krüger Kaldnes.[5]

2.1.2. Eco-innovation and life-cycle inventory for aquaculture sludge

Recirculating Aquaculture Systems (RAS) were proposed three decades ago (Helfrich and Libey, 1991), but were only recently established more widely after encountering some kinds of barriers (Badiola et al., 2012). RAS plants allow one to produce large quantities of fish with lower water consumption (Cristiano et al., 2021), compared with flow-through land-based systems. In the present work, they are addressed concerning selected innovations to decrease the environmental load of RASs, and to valorise their sludge. Recirculating systems are becoming more and more employed in salmon industry, in particular for smolt production. In a RAS (Fig. 2), the effluent is treated through mechanical filtration, so as to remove fish faeces, residual feed, and other particles; then, water enters a biofilter, converting ammonium into nitrate; oxygen is added in the gas control unit, while carbon dioxide in excess is removed in the degasser (trickling filter); eventually, a portion of water is sterilised by ultra-violet (UV) radiation before being mixed back into the main circulation in the fish tank (*ibid.*). About 1–2% of the water is replaced, to avoid nitrate accumulation (*ibid.*). In a RAS facility, the mechanical filter (40 and 80 μm mesh size), removes suspended matter, yielding a "reject water" rich in smaller particles, phosphorus and nitrogen. The process investigated in this paper aims at capturing these elements, thus reducing this environmental load due to the discharge of the reject water into the environment (namely, into surface water bodies), thus contributing to the ecological intensification of RAS farming.

A new filter-dryer system (S3) (Fig. 3) was introduced (Bruckner et al., 2021), aimed at reducing the amount of suspended matter in aquaculture wastewater streams and, at the same time, increasing the amount of removed particles. The sludge water is drawn up from the tank through the filter and into the vacuum drum; the absolute pressure is 0,5 atm inside the drum – a strong underpressure (the standard filter often have a small vacuum as well); this creates many small droplets who can be transported away to condense in the vacuum tank. The design capacity is 22 L/s, which is high enough to treat usual RAS-reject. The filtration process is as quick as conventional filtration. S3 uses vacuum to suck the wastewater from a sludge tank trough the filter cloth; this is happening on approximately 25% of he drum surface; the sludge (particles) remains on the filter surface where it is dried via the vacuum and a infrared unit (UV disinfection), while the drum moves one full cycle. The process includes two steps: a) filtration, using a mesh size of 6 μm, which removes 93% (±2.8%) of the suspended solids in the reject water and yields a filter cake with ≤10% water; b) driying of the filter cake by means of an energy-efficient infrared system. Conversely, classical filtration systems yield a sludge with ≥90% water, which needs to be dried further, or transported wet to potential customers, biogas plants, or waste incinerators (*ibid.*). As a result of the innovation at hand, the end product is instead already dried, and can be valorised as per the three options (B1, B2, and B3) described below.

Savings in transportation costs and resource requirements can therefore be achieved. The end product is a nutrient-rich dried sludge (dry matter 93–95%) which can be valorised in other economic sectors. Three different options for the reuse of such a dried sludge are assessed, as summarised in Table 1:

2.1.2.1. Sludge end-of-life valorisation option B1 – fertiliser. The dried by-product leaving the system is reused as such as an organic fertiliser. For the considered demonstration plant, this implies road transportation for 1,000 km.

2.1.2.2. Sludge end-of-life valorisation option B2 – bio-energy at cement factory. The dried sludge is used as biomass to produce energy at a cement factor; in our case study, this implies road transportation for 350 km.

2.1.2.3. Sludge end-of-life valorisation option B3 – biogas substrate. The dried output is used as a biomass for gasification and reuse as a secondary energy input, after road transportation for 535 km.

Some key features of the dried sludge can be reported: for valorisation as a fertiliser (B1), nitrogen 47 g/kg; phosphorus 24 g/kg; for valorisation as an energy source (B2–B3), average energy content 20 MJ/kg; fat 3.5%. Scenarios B1, B2, and B3 are compared with the A one, concerning a smolt RAS equipped with standard filter and waste water treatment facilities., where RAS reject is filtered, the new reject is released into the recipient, and the wet sludge (with water contents of 75% or more) are shipped by lorry for waste disposa of further treatment; at the studied facility, the normal disposal implies a sludge with a dry matter content of 10–20% being collected in a tank and transported by a road tanker to a biogas facility or a dump (535 km away).

Data reported in Table 1 are based on average annual values for years 2019 and 2020, directly measured and collected by the second author, and required, discussed, double checked, and organised by the first author.

2.1.3. Eco-innovation and life-cycle inventory for fish mortality disposal and valorisation

Mortalities represents a side stream in all fish farming (RAS, sea cages, and flow-through systems) as well as in transported live fish (Baarset and Johansen, 2019). In Norway, mortality in farmed salmon was 16.4% in 2018, corresponding to 6–9% of the biomass (*ibid.*). Similar figures are compatible with estimates by Bjørndal and Tusvik (2017). In Norway, fish mortalities are currently treated by the following process (*ibid.*): (1) Grinding; (2) Mixing with formic acid; (3) Storage in containers; (4) Transport (by truck or by ship) (5) Delivery to processing plant (e.g. biogas plant) (Raa et al., 1982).; As a consequence, Health, Safety, Environment (HSE) hazardous substances[6] are to be transported away from the plant, with risks from sea or road leaks. The innovation developed in the GAIN H2020 project aims at drying and sanitising the fish mortality biomass using a superheated steam (SHS) drying technology: by-product treatment is therefore mechanised, thus improving workers' safety and reducing operational costs (Baarset and Johansen, 2019; Baarset et al., 2021). The process is based on prototype "Waister 15" device (Fig. 4). Mortalities are ground upon entering the drying chamber in the innovative SHS dryer and a structure material, i.e. dry spent grain, is added, to facilitate the grinding. The resulting dried product consists of a microbiologically stable powder that can be stored and transported by ordinary trucks. Two alternative cooling media were tested, i.e. water and a water (70%)/glycol (30%) solution. When using water only, heat can be reused in the rest of the RAS. Recovery of cooling

[4] https://www.veoliawatertechnologies.com/en/case-studies/helgeland-smolt.

[5] https://www.krugerkaldnes.no/en.

[6] Potentially causing acid etching to lungs, skin, eyes, etc.; when stored inside tanks, it may produce explosive gases that are also harmful to breath; worker's injuries and some fatal accidents were registered (Baarset and Johansen, 2019).

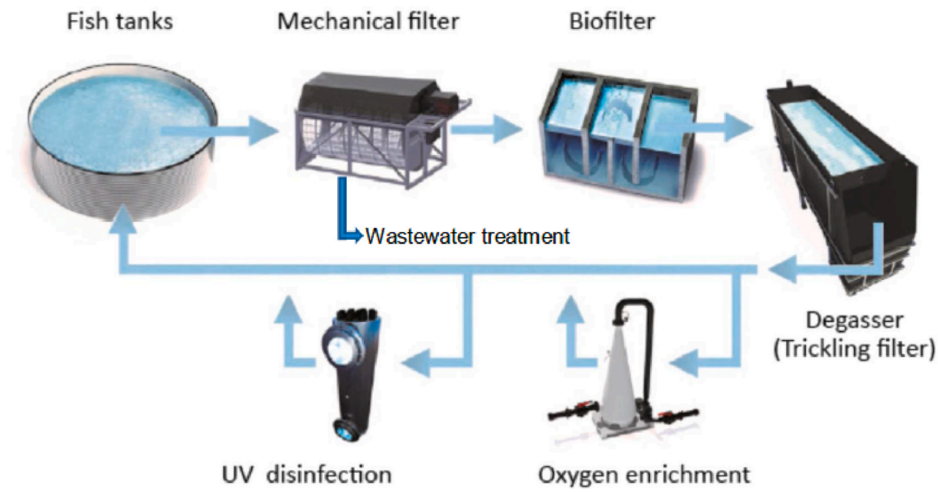

Fig. 2. Principle drawing of a RAS (Johansen et al., 2019; adopted from Bregnballe, 2015).

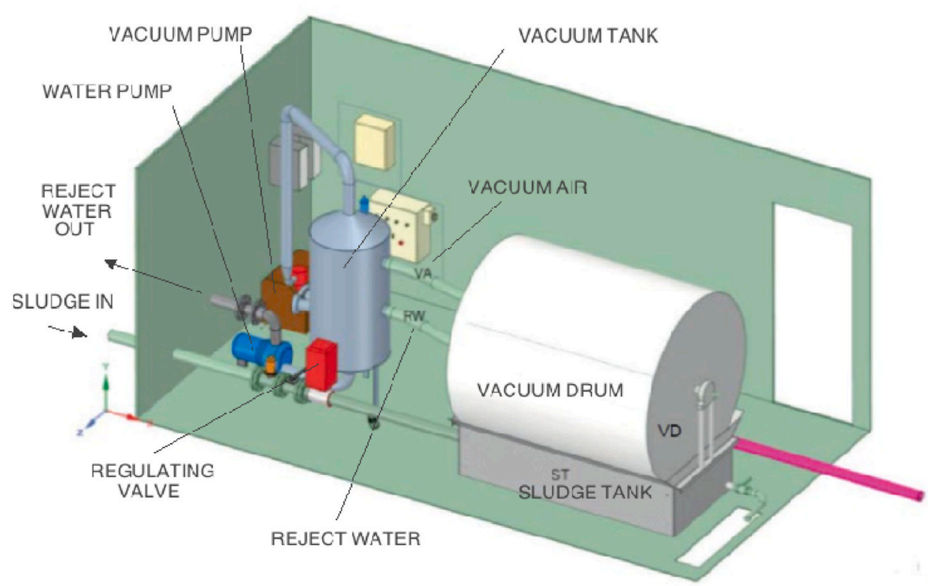

Fig. 3. The main components of the S3 filter-dryer system (after Bruckner et al., 2021).

water at 45–60 °C corresponding to up to 60% of electric power consumption is available. In a RAS facility with 95% water recycling, this corresponds to raising the temperature of the inlet water with 1 °C. Therefore, the mass and volume of the dried mortalities are one order of ≈86% smaller than the ones obtained after business-as-usual ensilage (*ibid.*).

The following scenarios for mortality disposal are investigated, as summarised in Table 2:

- **Fish mortality reference scenario (C)**: ensilage;
- **Fish mortality innovative scenario (D)**: super-heated steam (SHS) dryer and cooling water;
- **Fish mortality innovative scenario (E)**: SHS dryer and water/glycol cooling medium.

Scenarios D and E are divided into three sub-scenarios each, according to their end-of-life valorisation options, built based on the same source (Baarset, 2021) and similarly to the ones used for sludge scenarios B1, B2, B3:

2.1.3.1. Fish mortality end-of-life valorisation option 1 – animal feed ingredient for pet food. The dried output is used as an ingredient for pet food. For the demonstration plant at hand, this implies road transportation for 1,190 km. Regulations exist by country and mortality type, so restrictions may apply (e.g. for discarded fish only).

2.1.3.2. Fish mortality end-of-life valorisation option 2 – bio-energy at cement factory. The dried output is used as biomass to produce energy at a cement factory. In our case study, this implies road transportation for 350 km.

2.1.3.3. Fish mortality end-of-life valorisation option 3 – biogas substrate. The dried mortalities are used as biomass for gasification. For the demonstration plant to evaluate, this implies road transportation to Denmark (1,735 km).

2.1.4. Life-cycle modelling choices for sludge treatment scenarios and end-of-life valorisation options

Structures and steel machinery are modelled with a lifetime of 20 years, according to their producers and users. The water comes from

Table 1
Annual raw data for sludge treatment evaluation at the selected demonstration plant.

Required input	Unit	Amount in Sludge scenario A	Amount in Sludge scenario B
Fish feed*	ton	(1,300)	(1,300)
Structures	m^3	776	778
Machinery	ton	0.3	0.4
Electricity	MWh	11.05	11.23
Net water after recirculation	m^3	5,000	6,000
Lubricant oil	L	–	10
Filter membrane	kg	–	20
Land occupation	m^2 * yr	500	500
Output transportation	t-km	350,000	6,000 (B1); 1,900 (B2); 2,900 (B3)
Outputs		**Amount in Sludge scenario A**	**Amount in Sludge scenario B**
Smolts	ton	1,300	1,300
Wet sludge	m^3	500	–
Dry sludge for valorisation	ton	–	5.4
Evaporated/ discharged water	m^3	4,500	600

*Not included in the LCA, as this major input is the same for all scenarios.

Fig. 4. "Waister 15 drying technology for mortalities" (Baarset et al., 2021).

industrial pipes and is assumed as water for turbine use in Norway. Directly occupied land is inserted as sparsely vegetated area, calculated based on an expected lifetime of 30 years (out of 1.5 ha). Electricity is elaborated as medium voltage from the Norwegian country mix. Steel machinery is referred to European steel product manufacturing, and assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016), yielding downgraded low-alloyed steel. RAS structures are approximated as

Table 2
Inputs for the treatment of 1 ton of fish mortality at the selected demonstration plant.

Required input	Unit	Scenario C	Scenario D	Scenario E
Water	m^3	0.905	10.8	0.005
Glycol	kg	–	–	2.2
Formic acid	L	94.8	–	–
Filter	kg	–	0.023	0.023
Steel machinery	kg	3.2	5.8	5.8
Lubricant oil	L	–	1	1
Structure material	kg	–	80	80
Electricity	kWh	29.2	1,228	1,228
(Heat recovery potential)	kWh	–	−736	–
Land occupation	m^2 * yr	0.8	0.3	0.3
Formic acid transport	t-km	10	–	–
New machinery transport	t-km	–	19	19
Output transportation	t-km		330 (D1); 98 (D2); 482 (D3)	330 (E1); 98 (E2); 482 (E3)
Outputs		**Scenario C**	**Scenario D**	**Scenario E**
Fish silage	ton	2	–	–
Dried by-product	ton	–	0.278	0.278
Condensate	ton	–	0.722	0.722
Hot water	m^3	–	10.8	10.8

[Data adjusted from an annual treatment of 18.885 ton (18,885 kg) of fish mortalities].

Liquid manure storage and processing facility, including construction, repair, and partial replacement, as a global average plant excluding Switzerland.[7] Freight transport is computed based on European lorries with carrying capacities of 3.5–7.5 metric ton and emission category EURO4. For lubricant (lubricating) oil, a European production is chosen. Filter membrane, to be replaced annually, is modelled as high-density polyethylene, recycled, from Europe except for Switzerland, to be disposed of in a sanitary landfill at the end of its life cycle. Fish feed, as explained above, is not accounted for: as a matter of fact, including fish feed would have masked the environmental advantaged that the large scale adoption of this new process would bring about; although this choice can be seen as useful for comparisons, the LCIA results ought not to be considered as benchmarks for 1 ton of fish production.

In scenario A, end-of-life conversion of undried sludge into biogas is modelled as Biogas, treatment of sewage sludge by anaerobic digestion. In sub-scenario B1, fertiliser is modelled as an item that is present in the category of chemicals, namely, Compost, treatment of bio-waste, industrial composting, average global value excluding Switzerland; indeed, such an item represents nutrients coming from agricultural and food processing by-products. In sub-scenario B2, the closest item to account for its reuse for energy production in a cement plant is identified as Peat – in the category of Fuels – inasmuch as it is a source of energy composted of organic matter and also containing animal waste. Moreover, in the adopted database it is especially available as developed from the inventories by the Nordic Countries Power Association, thus even more relevant for the case study at hand. In sub-scenario B3, the dry matter converted into biogas is computed as a global average value for Biogas, with particular reference to the one coming from the treatment of sewage sludge; nevertheless, since the item in the database exhibits an average dry matter of 5%, while the innovation at hand is already dried, the equivalent amount of saved biogas is multiplied by 20 in order to account for the correct mass of dry matter, considering an average

[7] The item Fish curing plant, including both construction and maintenance, is also present, but only as a whole plant, with not enough information about volumes and materials.

density equal to that of water (inasmuch as it is the main component of the process in the database and since the nutrients have similar densities too).

2.1.5. Life-cycle modelling choices for fish mortality treatment scenarios and end-of-life valorisation options

For the modelling of annual flows, the fact is considered that 18.885 ton of fish mortalities are processed every year in the plant at hand. Steel machinery is computed with a lifetime of 10 years, according to its producers, the plastic tank for the formic acid is replaced every year, and the textile filter is changed three times a year. As to the database for modelling, the water (from an adjacent power plant) is computed as water for turbine use in Norway; although this is something site-specific, reused water from industrial plants can potentially represent a common situation for aquaculture by-product processing plants. Directly occupied land is inserted as sparsely vegetated area. Electricity is elaborated as medium voltage from the Norwegian country mix. Steel machinery is referred to European steel product manufacturing, and assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016) yielding downgraded low-alloyed steel. Freight road transport is modelled based on European lorries with carrying capacities of 3.5–7.5 metric ton and emission category EURO4. Silage tank is computed as a glass fibre object, European production, later disposed of in a landfill as inert waste at the end of its life cycle. The formic acid is modelled based on its production in Europe by the methyl formate route; a density of 1.22 kg/L is used for calculations. The plastic tank in which it is delivered is assumed to be made of recycled high-density polyethylene (HDPE) from Europe; at the end of its life cycle, this tank is expected to be recycled in Europe with a mass-to-mass efficiency of 75% (based on Rigamonti et al., 2009) yielding downgraded granulate amorphous polyethylene terephthalate. The mass of each textile filter is calculated based on a surface mass of 400 g/m^2 (communicated by its producer) and on a squared surface of 60 cm per side (inferred from the technical sheets of the Waister 15 machine); according to its producer's technical sheet, the filter is made of aramidic fibre[8] but, since this textile fibre is not present in the Ecoinvent 3.1 database, a viscose textile fibre is chosen (global production); by law, this is incinerated at the end of its life cycle. The structure material, represented by dry spent grains – by-product of beer production – in the eco-innovation at hand, is computed as bagasse, i.e. the by-product of ethanol production from sweet sorghum (same type of product: end by-product for alcohol production; same vegetable origin: a cereal; general global location); the end of its life cycle depends on the use of the final product from the eco-innovated fish mortality plant, as this is the structure material of the now reusable by-product to valorise. For lubricant (lubricating) oil, a European production is chosen. After double checking its function and nature, the glycol present in the cooling mix of scenario E is chosen as European liquid propylene glycol; a density of 1.036 kg/L is adopted for calculations. As to the three sub-scenarios related to the end-of-life alternatives for the valorisation of the dried fish mortalities, two elements are considered: transportation inputs and avoided products due to the reuse in other human economies. Concering the former, mass-distance on-road choices are made with the same choices described above; regarding the latter, yielded savings are accounted for as negative (avoided) inputs. In sub-scenarios 1, the closest animal feed ingredients for pets to be possibly considered as an avoided product are found in fish-based products, present in the category of Animal feed, namely Small pelagic fish, fresh, adjusted for the rest of the world other than Ecuador, and Fishmeal, for the rest of the world other than Peru; however, only 5% in mass of the avoided product is assumed to be represented by the first-quality small pelagic fish, while the other 95% is modelled as a by-product from anchovy processing. In sub-scenarios 2, the closest item to account for its reuse for energy production in a cement plant is identified as Peat – in the category of Fuels – inasmuch as it is a source of energy composted of organic matter and also containing animal remains; moreover, in the adopted database it is especially available as developed from the inventories by the Nordic Countries Power Association, thus even more relevant for the case study at hand. In sub-scenarios 3, the resource savings due to the final product's reuse as biogas substrate are modelled as avoided Biogas, from grass – in the category of Fuels, subcategory of Biogas – since this is the closest source of biogas coming from similarly dried organic matter; the volume of gas produced out of one ton of dried matter was taken from Martin and Parsapour (2012), dedicating a studio to the same component of the structure material of our case study (brewer's spent grain): 60,000 ton of fresh brewer's spent grain yield 5,880,000 Nm^3 of biogas (*ibid.*); since our case study has dried (not fresh) brewer's spent grain, some adjustments are made based on a 77% water content (after Jackowski et al., 2020), thus adopting a value of 127.3 Nm^3 produced out of each ton of dried product. The modelling of the current conversion of silage (scenario C) into energy (as saved Norwegian electricity mix, as above) bases on a silage density of 1.75 kg/L (Perez, 1995), i.e. 1.75 ton/m^3, and on a conversion factor of 1,623 kWh/m^3 (Fjørtoft et al., 2014).

3. Life-Cycle Impact Assessment results

3.1. Functional unit and flow-charts for aquaculture sludge treatment and by-product valorisation

A reference functional unit (FU) of 1 ton of farmed smolts is chosen[9]; inputs from Table 1, referred to one year of operations with an average production of 1,300 ton of smolts. For sludge scenarios A and B (i.e., regular RAS and its innovation), data are organised and allocated according to the chosen FU and, where pertinent, to the input lifetime (e.g. machinery). Quantitative flow-charts are offered for sludge scenarios A (Fig. 5) and B (Fig. 6).

3.2. Functional unit and flow-charts for fish mortality treatment and by-product valorisation

A reference functional unit (FU) of 1 ton of fish mortalities to be treated is chosen; inputs from Table 2 are already set on this FU. For fish mortality scenarios C, D, and E (i.e., current treatment by ensilage, innovative treatment with water as cooling medium, and innovative treatment with water and glycol as colling media), data are organised and allocated according to the chosen FU and – where pertinent – to the input lifetime (e.g. machinery). Quantitative flow-charts are offered for fish mortality scenarios C (Fig. 7), D (Fig. 8), and E (Fig. 9). LCA modelling choices are detailed in section 2.4.2.

3.3. Life-Cycle Impact Assessment indicators of aquaculture sludge treatment and by-product valorisation

The Life-Cycle Impact Assessment indicators for the RAS sludge treatment, as defined above, are presented in Table 3 for the selected impact categories: there, percentage changes in the innovative scenario (B) and its by-product valorisation options (B1, B2, B3) are also reported in comparison with the reference scenario (A). Process contributions to a relevant indicator such as Global Warming Potential and to the only indicator showing an opposing trend after innovations, i.e. Water consumption, are shown in Fig. 10 and Fig. 11, respectively: the former is mostly contributed to by Fish feed and Structures, with a significant role also played by Transport in Scenario A; the main inputs to the latter are

[8] Written communication issued by the producer on the 10th of February 2020.

[9] The alternative option of setting the FU on the sludge to treat would be misleading, since water volumes change.

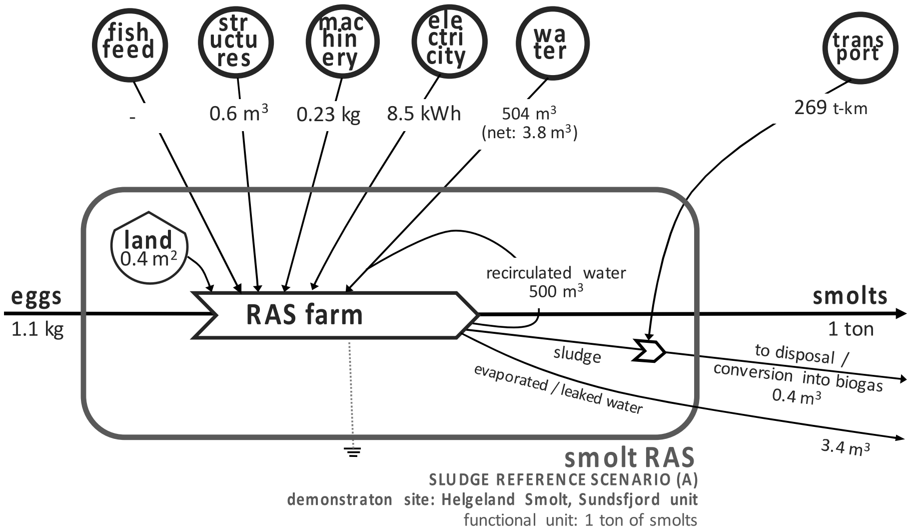

Fig. 5. Quantitative flow-chart for sludge treatment reference scenario (A).

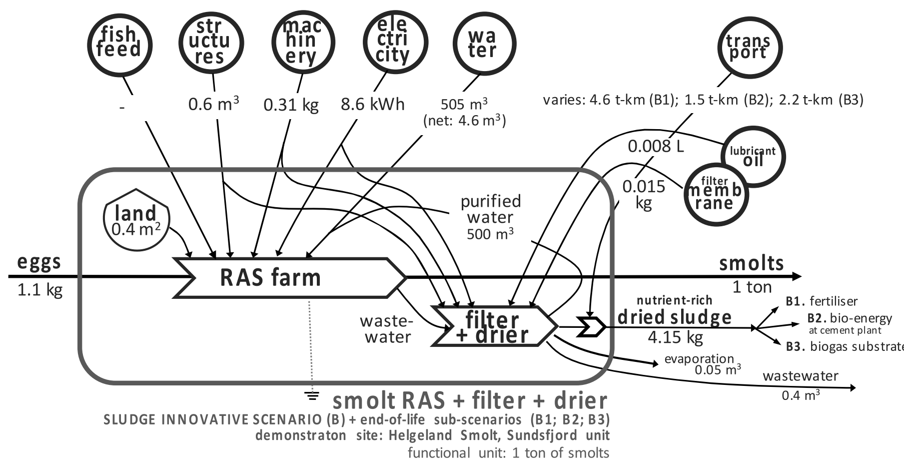

Fig. 6. Quantitative flow-chart for sludge treatment innovative scenario (B).

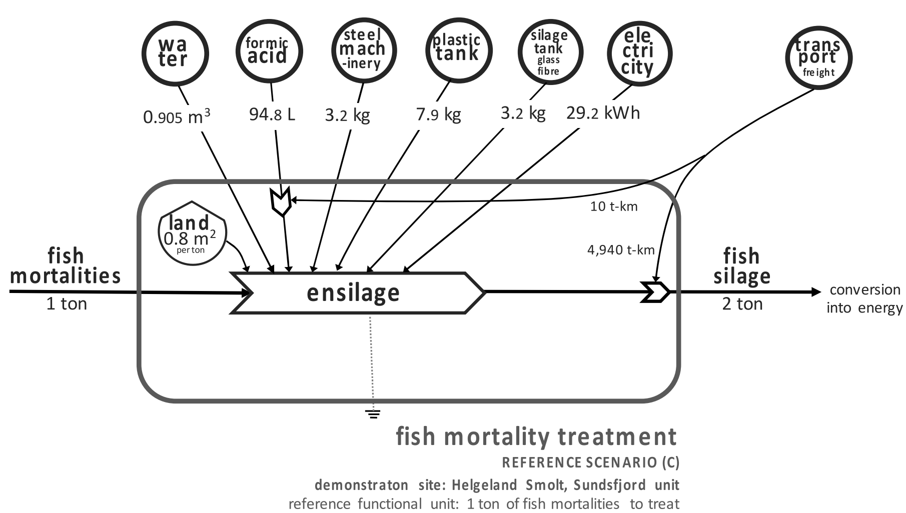

Fig. 7. Quantitative flow-chart for fish mortality treatment reference scenario (C).

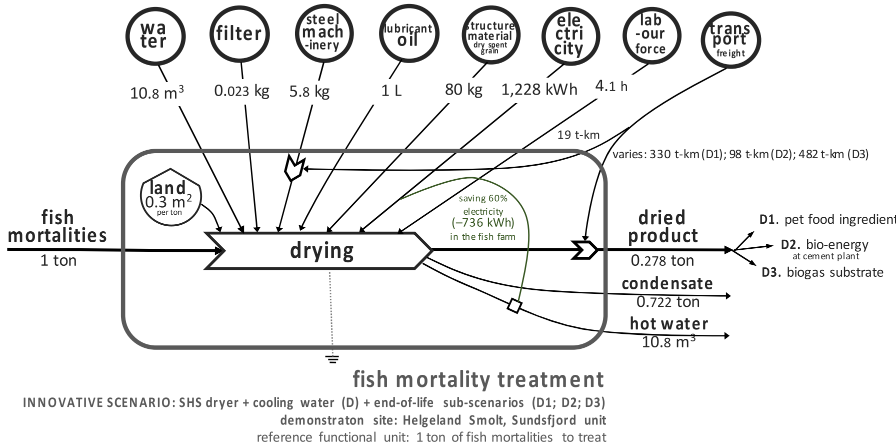

Fig. 8. Quantitative flow-chart for fish mortality treatment innovative scenario with water as cooling medium (D).

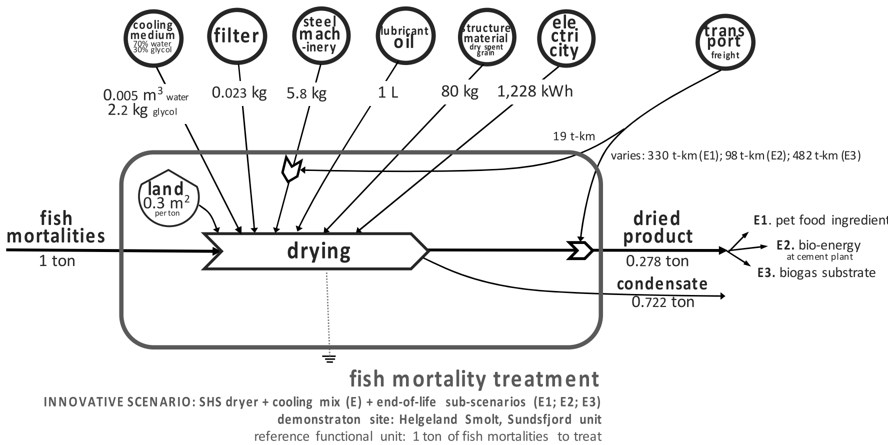

Fig. 9. Quantitative flow-chart for fish mortality treatment innovative scenario with glycol-based cooling mix (E).

Table 3
LCIA indicators for sludge treatment evaluation at the selected demonstration plant.

Impact category	Unit	Scenarios				Comparison with A			Method
		A	B1	B2	B3	B1	B2	B3	
Global Warming Potential	kg CO_2 eq	233	99	98	98	**−57%**	**−58%**	**−58%**	[a]
Stratospheric ozone depletion	kg CFC11 eq	1.E−04	4.E−05	4.E−05	4.E−05	**−67%**	**−67%**	**−67%**	[b]
Terrestrial acidification	kg SO_2 eq	0.7	0.3	0.3	0.3	**−56%**	**−57%**	**−57%**	[b]
Eutrophication, freshwater	kg P eq	0.04	0.03	0.03	0.03	**−33%**	**−33%**	**−33%**	[b]
Eutrophication, marine	kg N eq	0.003	0.002	0.002	0.002	**−41%**	**−42%**	**−42%**	[b]
Mineral resource scarcity	kg Cu eq	2.5	2.1	2.1	2.1	**−16%**	**−16%**	**−16%**	[b]
Fossil resource scarcity	kg oil eq	67	21	20	21	**−68%**	**−69%**	**−69%**	[b]
Water consumption	m^3	5.7	6.1	6.1	6.1	**+7%**	**+7%**	**+7%**	[b]
Terrestrial ecotoxicity	kg 1,4-DCB	3,240	1,780	2.E+3	1,770	**−45%**	**−45%**	**−45%**	[b]
Freshwater ecotoxicity	kg 1,4-DCB	1.E+4	9,600	9,560	9,570	**−24%**	**−25%**	**−25%**	[b]
Marine ecotoxicity	kg 1,4-DCB	2.E+4	2.E+4	2.E+4	2.E+4	**−25%**	**−25%**	**−25%**	[b]
Human carcinogenic toxicity	kg 1,4-DCB	9.E+5	8.E+5	8.E+5	8.E+5	**−12%**	**−12%**	**−12%**	[b]
Human non-carcinogenic toxicity	kg 1,4-DCB	2.E+4	1.E+4	1.E+4	1.E+4	**−26%**	**−27%**	**−27%**	[b]
Cumulative Exergy Demand	MJ	3,663	1,522	1,453	1,506	**−58%**	**−60%**	**−59%**	[c]
Land occupation	m2 * a	24.6	18.9	18.8	18.7	−23%	−24%	−24%	[d]
Biochemical Oxygen Demand	kg	0.6	0.2	0.2	0.2	**−64%**	**−64%**	**−64%**	[d]

Functional unit: 1 ton of produced smolts out of a RAS plant. **Method key**: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4.

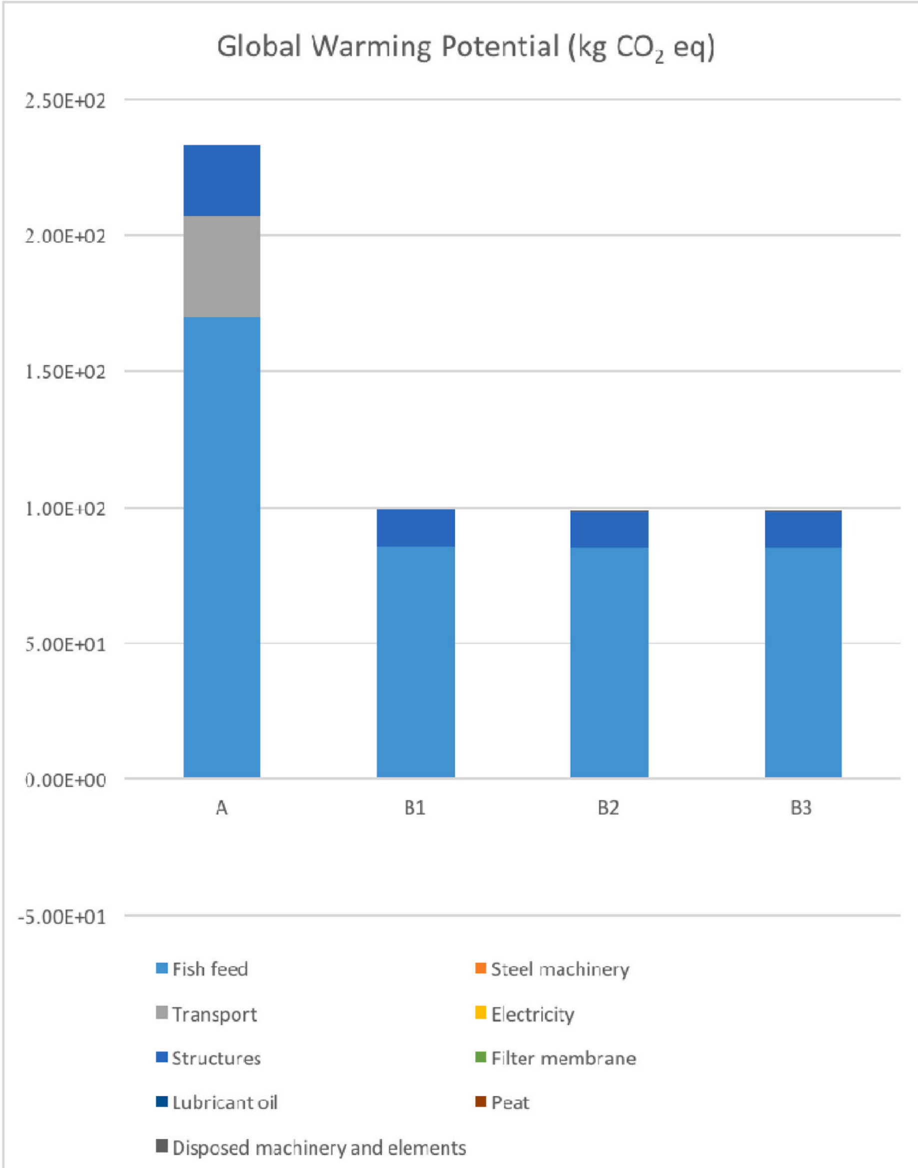

Fig. 10. Process contributions to Global Warming Potential in scenarios of sludge treatment evaluation.

represented by Fish feed, Structures, and of course Water.

3.4. Life-Cycle Impact Assessment indicators of fish mortality treatment and by-product valorisation

The Life-Cycle Impact Assessment indicators for the fish mortality treatment scenarios, as defined above, are presented in Tables 4a and 4b for the selected impact categories: there, percentage changes in the innovative scenarios (D and E, respectively) and their by-product valorisation options (D1, D2, D3, E1, E2, E3) are also reported in comparison with reference scenario (C).

3.5. Sensitivity analysis

After calculating the LCIA indicators, a check is performed to test their sensitivity to input variations due to uncertainty or actual flow changes. This sensitivity analysis is carried out by increasing and reducing the inputs that are associated with the largest impact(s), so as to understand their effect on the indicators. For scenarios A and B (RAS sludge valorisation), two indicators are selected; namely, the one with the largest and the smallest percentage reduction when the innovations are introduced, i.e. respectively Mineral resource scarcity (−68% or more) and Human carcinogenic toxicity (−12%). A ±20% variation in their driving input (the RAS structures) generates a ±2% change in the Mineral resource scarcity indicator in all scenarios, and slightly different variations in the Human carcinogenic toxicity when passing from scenario A (±10%) to the three scenarios B1, B2, and B3 (±8%). For scenarios C, D, and E (fish mortality treatment), a focus is dedicated to the indicator exhibiting the largest reduction after the introduction of the innovations, i.e. Terrestrial acification. A ±20% variation in its driving input (Transportation) respectively generates ±14%, ±11%, ±8% variations in scenarios and subscenarios C, D, and E. The controversial indicator Water consumption is also addressed in all scenarios: its ±20% variation of its driving input for RAS sludge valorisation (Transportation) yields ±7% and ±9% variations respectively in scenario A and subscenarios B1, B2, and B3; for the fish mortality treatment, the same variation in its driving input in scenario C (Formic acid) yield a ±12% variation in the indicator, while a ±20% variation of the driving input in the innovative scenario groups D and E (Electricity) averagely determines a ±10% variation in the Water consumption indicator. All

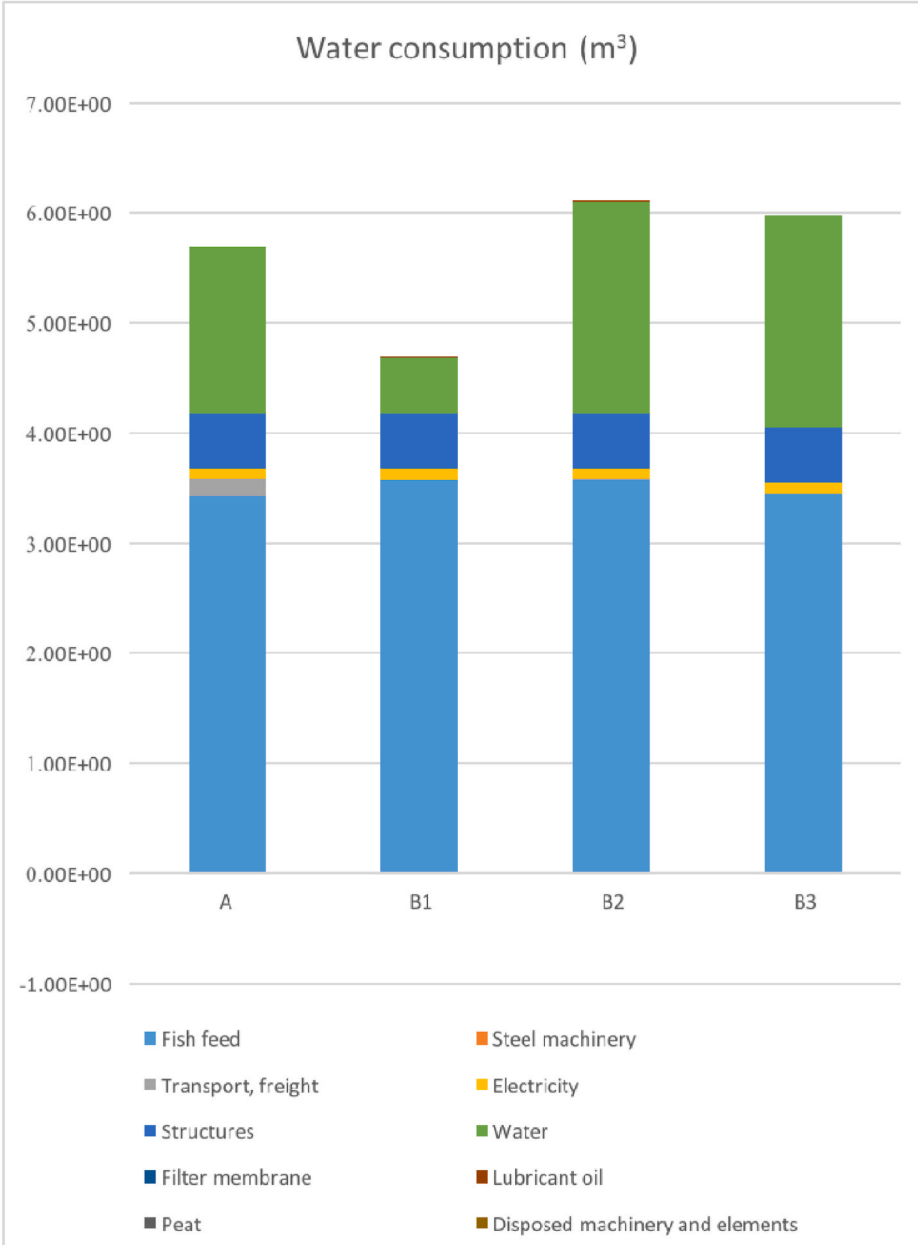

Fig. 11. Process contributions to Water consumption in scenarios of sludge treatment evaluation.

the selected inputs yield reduced changes in the addressed indicators, averagely halving them.

4. Results interpretation and discussion

The punctual interpretation and discussion of the LCIA results for the selected case study is offered in sections 4.1 and 4.2, respectively for the eco-innovations concerning RAS sludge valorisation and for fish mortality treatment and valorisation. While reading such results, it might be useful to keep in mind that environmental gains are referred to fixed functional units before and after the assessed innovations, so results might differ when production volumes increase after intensification.

4.1. RAS sludge valorisation

The LCIA indicators for sludge valorisation options regarding the innovations at hand for wastewater filtration, drying, and by-product reuse (Table 3) suggest that the new process leads to a decrease in all impact indicators (encompassing both purely environmental and human health impact categories), except for the water use, which instead increases after the assessed innovations are introduced. On the other hand, the three end-of-life options for the valorisation of the new by-product, i.e. nutrients reuse as ingredient in fertiliser, energy in cement plant, and conversion into biogas, did not show significant differences. Reductions vary significantly based on the impact category. Among the largest variations compared to reference scenario A, Cumulative Exergy Demand decreases by nearly −60%, with minor oscillations in the three sub-scenarios; this may be explained by the fact that used-up energy is a common focus in sustainability-oriented proposals, also resulting in monetary savings. Reductions greater than −50% are also found in Global Warming Potential, Terrestrial acidification, Fossil resource scarcity, and Biochemical Oxygen Demand. Smaller reductions may be noted in Mineral resource scarcity, water-related and human-related toxicity indicators, especially human carcinogenic toxicity, decreasing by −12%. On the one hand, these are mostly indirect indicators that may be escape priorities in sustainable innovation design; on the other hand, this suggests that the tools to achieve environmental gains in other impact categories are still framed in a scarcely sustainable technological dimension. In any case, this stresses the importance to match a life-cycle environmental assessment in addition to intuitive sustainability design and money saving choices only. It may be worth observing changes in Water consumption, slightly increasing (+7%) in all of the innovative scenarios. Mineral resource scarcity and Land occupation might be directly and indirectly influenced by the need for new machinery when passing from reference scenario A to the innovative scenarios (B1, B2, B3), with minerals and processing plants required for the production of metal components. In order to avoid underestimations when exporting to other contexts, water has been entirely allocated to the eco-innovation at issue while modelling all scenarios: this led to estimate a water consumption increase of +7%. On the one side, it might be worth noting that net input water increases by +21% from scenario A (3.8 m^3) to scenario B (4.6 m^3), while the overall demand that is tracked by the above mentioned indicator is smaller (+7%). This suggests that some improvements are present in the indirect water uses in the innovative sub-scenarios, which could be relevant for the application of the innovations in areas where water scarcity could be an issue, while still standing out as a warning to be addressed in refining innovations, especially if the afore-mentioned water scarcity is taken into consideration. One final remark for the LCIA of sludge valorisation ought to be made: as explained in Table 3 and in section 2.4.2, fish feed was not accounted for in this assessment, which is focused on the comparison of two processes for treating wastewater: including fish feed would have masked the environmental advantaged that the large scale adoption of this new process would bring about.

4.2. Fish mortality and discarded fish treatment, and by-product valorisation

As to the LCIA indicators for fish mortality treatment scenarios and their related by-product reuse options (see Table 4a and **4b)**, more definite aspects arise. Mmrked differences appears among the reference scenario C and each of the innovative scenarios D and E, and in their six end-of-life valorisation options. Fourteen out of fifteen LCIA indicators show significant decreases in the overall environmental and human health impacts as a result of the implementation of the eco-innovations at issue, targeting fish mortality treatment and end-of-life by-product reuse. These indicators decrease by at least −80%, suggesting overall positive performances. The Cumulative Exergy Demand shows a net decrease for all sub-scenarios (varying between −70% and −95%), also presenting a reduction in the use of non-renewable sources and an increase in the use of renewable sources. Reductions larger than −100% are due to the saved resources following the valorisation options that allow for the end-of-life reuse of the obtained by-products.

The reuse of a local by-product from another agri-food sector, namely spent grains used in beer production, contributes to the general abatement of the selected indicators when passing from reference scenario C to both innovative scenarios D and E; this suggests that good performances may be reached while recirculating materials that would be otherwise thrown out, while this appears not to always happen in so-called circular economy design. The innovation with water as a cooling medium (scenario D) stands out as the best performing one, and its electricity demand is balanced by the energy savings it allows in the fish farm for the reuse of the heat from the cooling water. Conversely, the innovation using a glycol-water cooling medium (E) demands much less water, yet not allowing for energy savings; moreover, its requiring glycol also partially affects several indicators. As to the end-of-life options modelled and assessed for both innovations D and E, clearly different performances emerge from their environmental indicators. Option 1 (reuse as ingredient in pet food) averagely performs better than option 2 (valorisation as energy in a cement plant), and option 2 slightly better than option 3 (gasification). The reuse of dried fish by-products as an ingredient for pet food production allows for savings in by-products from other aquaculture (and, more in general, animal production) and partly from fishing activities (and related transportation, as tracked from instance in a reduced Global Warming Potential). Nevertheless, two restrictions exist: reuse may be only authorised for discarded fish (not fish mortalities), and gains might be resized whenever the reuse of other by-products from food processing for human consumption are currently present as alternatives in pet food production, e.g. as the result of more attempts to recirculate currently wasted resources from other industrial productions. As to the other end-of-life options, reuse as direct energy production in a nearby cement plant seems to perform better than gasification in overall less numerous plants, thus usually requiring longer distances to be travelled from the fish farm. Environmental issues related to construction materials (Cristiano et al., 2021) and biogas production (Spagnolo et al., 2020) have been associated with further issues, which obviously fall well beyond the purposes of the present paper. On the Scenarios D and E, however, directly and indirectly require more water, regardless of their sub-scenarios. Similarly to what happened to sludge treatment innovative scenarios, opposite trends can be found in Water consumption; as a matter of fact, changes in such an indicator, when the eco-intensification innovations are introduced, vary

Table 4a
LCIA indicators for fish mortality treatment evaluation at the selected demonstration plant.

Impact category	Unit	Scenarios				Comparison with C			Method
		C	D1	D2	D3	D1	D2	D3	
Global Warming Potential	kg CO_2 eq	2750	43	91	278	**−98%**	**−97%**	**−90%**	[a]
Stratospheric ozone depletion	kg CFC11 eq	1.E−03	1.E−04	1.E−04	2.E−04	**−90%**	**−91%**	**−88%**	[b]
Terrestrial acidification	kg SO_2 eq	8.5	−1.3	0.3	0.8	**−116%**	**−97%**	**−91%**	[b]
Eutrophication, freshwater	kg P eq	0.413	0.019	0.018	0.038	**−95%**	**−96%**	**−91%**	[b]
Eutrophication, marine	kg N eq	0.030	0.005	0.005	−0.001	**−83%**	**−83%**	**−104%**	[b]
Mineral resource scarcity	kg Cu eq	8.0	0.7	0.4	1.0	**−92%**	**−95%**	**−87%**	[b]
Fossil resource scarcity	kg oil eq	984	12	−30	96	**−99%**	**−103%**	**−90%**	[b]
Water consumption	m^3	24	24	25	26	**0%**	**+4%**	**+7%**	[b]
Terrestrial ecotoxicity	kg 1,4-DCB	2.E+4	1,670	715	2,510	**−93%**	**−97%**	**−89%**	[b]
Freshwater ecotoxicity	kg 1,4-DCB	73	5	3	8	**−93%**	**−96%**	**−89%**	[b]
Marine ecotoxicity	kg 1,4-DCB	9.E+5	5.E+4	3.E+4	9.E+4	**−94%**	**−96%**	**−89%**	[b]
Human carcinogenic toxicity	kg 1,4-DCB	6,400	503	363	788	**−92%**	**−94%**	**−88%**	[b]
Human non-carcinogenic toxicity	kg 1,4-DCB	7.E+5	5.E+4	3.E+4	8.E+4	**−94%**	**−96%**	**−89%**	[b]
Cumulative Exergy Demand	MJ	38,119	4,088	1,923	7,750	**−89%**	**−95%**	**−80%**	[c]
Land occupation	m^2 * a	138	13	8	5	**−91%**	**−94%**	**−97%**	[d]
Biochemical Oxygen Demand	kg	8.5	−6.7	0.3	0.7	**−179%**	**−97%**	**−92%**	[d]

Functional unit: 1 ton of fish mortalities. **Method key**: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4.

Table 4b
LCIA indicators for fish mortality treatment evaluation at the selected demonstration plant.

Impact category	Unit	Scenarios				Comparison with C			Method
		C	E1	E2	E3	E1	E2	E3	
Global Warming Potential	kg CO_2 eq	2750	71	118	305	**−97%**	**−96%**	**−89%**	[a]
Stratospheric ozone depletion	kg CFC11eq	1.E−03	2.E−04	2.E−04	3.E−04	**−84%**	**−85%**	**−81%**	[b]
Terrestrial acidification	kg SO_2 eq	8.5	−1.3	0.3	0.8	**−115%**	**−96%**	**−90%**	[b]
Eutrophication, freshwater	kg P eq	0.413	0.029	0.027	0.047	**−93%**	**−93%**	**−89%**	[b]
Eutrophication, marine	kg N eq	0.030	0.006	0.006	−0.001	**−80%**	**−80%**	**−102%**	[b]
Mineral resource scarcity	kg Cu eq	8.0	0.8	0.5	1.1	**−90%**	**−93%**	**−86%**	[b]
Fossil resource scarcity	kg oil eq	984	21	−22	104	**−98%**	**−102%**	**−89%**	[b]
Water consumption	m^3	24	35	36	37	**+42%**	**+47%**	**+50%**	[b]
Terrestrial ecotoxicity	kg 1,4-DCB	2.E+4	1,730	771	2,560	**−93%**	**−97%**	**−89%**	[b]
Freshwater ecotoxicity	kg 1,4-DCB	73	6	4	9	**−92%**	**−95%**	**−88%**	[b]
Marine ecotoxicity	kg 1,4-DCB	9.E+5	6.E+4	4.E+4	1.E+5	**−93%**	**−95%**	**−89%**	[b]
Human carcinogenic toxicity	kg 1,4-DCB	6,400	592	452	877	**−91%**	**−93%**	**−86%**	[b]
Human non-carcinogenic toxicity	kg 1,4-DCB	7.E+5	5.E+4	3.E+4	8.E+4	**−93%**	**−96%**	**−89%**	[b]
Cumulative Exergy Demand	MJ	38,119	7,957	5,806	11,623	**−79%**	**−85%**	**−70%**	[c]
Land occupation	m^2 * a	138	19	14	11	**−86%**	**−90%**	**−92%**	[d]
Biochemical Oxygen Demand	kg	8.5	−6.3	0.6	1.1	**−175%**	**−92%**	**−87%**	[d]

Functional unit: 1 ton of fish mortalities. **Method key**: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4.

between none (D1) to +50% (E3), with increases being anyway much smaller in sub-scenarios D than in E. Impacts on water demand are also indirectly linked to the higher electricity consumptions that is required to run the innovative machines, which is partially mitigated by the improvement performances connected to the end-of-life valorisation scenarios as well as to such innovations. In particular, although coming and being reused from an adjacent power plant, water has been entirely allocated while modelling the LCA so as to avoid the underestimation of its impacts if exported elsewhere; if valorisation processes are systematically designed close to other plants where water can be reused, the overall environmental impacts would be further abated. Besides the opportunity not to necessarily require virgin water, these increases appear as a warning to be addressed, as suggested above related to the sludge treatment innovations.

Out of purely LCA-based considerations, it may be useful to recall that health, safety, and environmental hazards are decreased, and so are management monetary expenditures, as previously found by Baarset and Johansen (2019), Baarset et al. (2021), and Cristiano et al. (2021). Moreover, while well performing from environmental and economic perspectives, the three end-of-life scenarios for recirculated organic material are of course subject to variables such as normative frameworks and social acceptability issues, e.g. when reusing aquaculture discards as pet food, or when still using (yet bio-) gas as an energy source while tackling climate change.

5. Conclusion

A Life-Cycle Assessment is presented here for the environmental evaluation of novel eco-intensification options for the treatment of aquaculture sludge and fish mortalities and for the reuse of their by-products, as tested in a smolt plant in Norway:

- 15 out of 16 impact indicators showed a decrease in both wastewater and fish mortality treatment case studies, ranging from poorer −12% (Human carcinogenic toxicity) and −16% (Mineral resource scarcity) up to −69% (Fossil fuel scarcity) in the former, and from −70% (Cumulative Exergy Demand in sub-scenario E3) up to −179% (Biochemical Oxygen Demand in sub-scenario D1) in the latter; as to the former, eco- and human-related toxicity indicators suggest margins for further improvement (currently not exceeding −25%);
- an exception is represented by Water consumption, with such an indicator increasing in both case studies after innovations are considered (respectively, +7% and from none to +50%) presumably due to a larger material input in the innovative scenario (+21%) in the former and to water use as a cooling medium or in a cooling mix, together with glycol;
- the three end-of-life valorisation options for wastewater treatment (reuse as ingredient in organic fertiliser, energy use in cement plant, and gasification) all seem to perform in a similar way, so no alternative stands out in any of the selected environmental impact categories.
- in terms of proximity and design, a processing plant for fish mortality treatment that is close and interconnected with a fish farm allows to save resources in the transport before the treatment, and to return the heat contained in the cooling water; this way, net electric power consumption can be reduced with up to 60% heat recovery from the drying process (replacing electric power used for heating the RAS facility inlet water), with overall environmental gains in several LCIA indicators, varying based on the energy mix of the reference country.

Core lessons may be learned:

- end-of-life valorisation options as energy sources after combustion or alike do not show any impressive environmental performances, inasmuch as still causing environmental and human health impacts; on the contrary, the best performing innovations are those allowing for energy savings;
  - in locally recirculated by-products from another agri-food sector (here, spent grains used as a structure material) show good performances: the best performing end-of-life option is the one that allows for the valorisation of the by-product as biomass in another food supply chain (here, pet food, even though for discarded fish only), using less non-renewable inputs; the intuitive benefits following the design of a more circular and renewable-based supply chain look confirmed, at least per production yield unit, with a preference for material reuse/saving rather than for conversion into yet "bio-based" energy; in other words, the so-called circular economy has some potential when it shifts from narrative to real and really required reuses and connected material savings.

Contraints and potentials of another approach that can be integrated with LCA (Raugei et al., 2014), i.e. emergy accounting (Odum, 1996), have been recently explored by David et al. (2021); the same case studies are being evaluated also through such approach, as comparatively done in two steps by Cristiano (2021) and Maiolo et al. (2021); this will represent the basis of a future work.

Ethical statement

The author declares that he adheres to the Journal's Publishing Ethics.

CRediT authorship contribution statement

Silvio Cristiano: Interviews, data collection, assessment, interpretation, and writing. **Hallstein Baarset:** input data provision for fish mortalities. **Christian Bruckner:** Input data provision for sludge valorisation. **Johan Johansen:** Input data provision for sludge valorisation. **Roberto Pastres:** Conceptualization, Funding acquisition, Supervision.

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

This research was funded by European Commissions' Horizon 2020 Framework Programme under Grant Agreement no. 77330 ("Green Aquaculture INtensification in Europe").

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131613.

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