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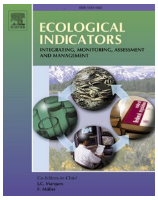

Original Articles

Emergy assessment to assess to ecological sustainability of smolt production and innovative options for the reuse and valorisation of aquaculture discards

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ABSTRACT

Two Emergy Assessments (EMA) were conducted to evaluate the ecological performances of novel eco-intensification innovations for the treatment and valorisation of sludge and fish mortalities from finfish aquaculture, including upstream directly and indirectly used resources such as energy, materials, and labour. One innovation consists in a novel process to filter and dry particles from the reject water out of a Recirculating Aquaculture System (RAS), with dried nutrients and biomass being reused as organic fertiliser or as an energy source. The other process concerns the disposal of fish mortalities, which are mixed with by-product from the brewery industry and dried. The resulting product can be used in the pet food industry or as an energy source. Both innovative solutions were tested on a RAS for smolt production in Norway. A set of standard Unit Emergy Values and emergy indicators was selected and calculated, including specific emergy (sej/kg), environmental loading ratio, and emergy sustainability index, among others. The results are compared with Life-Cycle Assessment values derived from the same innovations and with other emergy values obtained for other aquaculture processes. All in all, the novel solutions imply higher impacts related to water and technological inputs, yielding savings in the other indicators, thus confirming overall positive performances, yet requiring either some trade-off to be addressed and assessed more widely, or more efforts to possibly abate the factors that are responsible for increased impacts.

1. Introduction

Aquaculture is one of the fastest expanding food sectors worldwide (European Commission, 2020), growing at an average rate of over 5 % between 2001 and 2018 (FAO, 2020). The most recent data by United Nations' Food and Agriculture Organisation (*ibid.*) mark the highest peak ever of fresh biomass produced from aquaculture: almost 115 million ton in 2018; such numbers correspond to a global equivalent value of 263.6 billion USD at the farm gate, mostly related to aquatic animals, among which finfish stands out, with over 54 million ton and almost 140 billion USD in that same year. Such a growth in aquaculture production has often been uncontrolled in some regions, causing social and environmental issues (Troell et al., 2014). Some strategies aimed at improving aquaculture's environmental and economic performances have been recently set in Europe by the European Commission (2021). One of the ways to implement similar strategies is the framework of the ecological intensification, a new concept that would professedly "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 constitute relevant discards of the aquaculture industry from manifold points of view: volumes to be disposed of; operational monetary costs; potential economic value if recovered as by-products; health, safety, and environmental hazards (Baarset & Johansen, 2019). In all land-based aquaculture systems, sludge is also a crucial type of reject in terms of waste and environmental management: on the one hand it contains substances whose excess

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Table 1
"Annual raw data for sludge treatment evaluation at the selected demonstration plant" (adapted and expanded from Cristiano et al., 2022).

Required input	Unit	Amount in Sludge scenario A	Amount in Sludge scenario B
Fish feed	ton	1,300	1,300
Smolt eggs	item	9,500,000	9,500,000
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	15,000	15,000
Height above mean sea level	m	3	3
By-product 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

determines water pollution concerns (Jasmin et al., 2020); on the other hand, nutrients, i.e. nitrogen and phosphorus, can be recovered (Lunda et al., 2019) For such a reason, the nutrient recovery from fish farming reject water has been recently attracting an increasing interest (Zhang et al., 2020) (Table 1).

In this paper, the ecological requirements of two innovative processes for the recovery of nutrients and chemical energy from RAS sidestreams and for the disposal of mortalities are evaluated and compared with the processes currently employed. The resource demand is calculated, connected to both presently used and innovative processes. The tracked requirements include upstream directly and indirectly used resources such as energy, materials, and labour. The innovative options comprise the reuse of discards for the management of RAS sludge and fish mortalities as by-products. These innovations were preliminary estimated (Cristiano et al., 2022) by means of a selection of indicators, calculated following a standard method such as Life-Cycle Assessment (LCA) (ISO 14040: ISO, 2006; Arvanitoyannis, 2008), already tried and tested in aquaculture (Henriksson et al., 2012), and also suitable for the appraisal of eco-intensification innovations (Beltran et al., 2018; Little et al., 2018). Here, the LCA performances of the innovations at hand are compared with and integrated by an Emergy Assessment (EMA), identified as a promising emerging method to evaluate aquaculture operations (David et al., 2021a). EMA is also presented as one of the three most promising methods to assess the environmental sustainability of pond aquaculture (Henares et al., 2020) and, more in general, among the reference methods to assess the sustainability of aquaculture systems (Le Féon et al., 2021), together with LCA and life-cycle costing.

The adopted case study is a modern smolt farming plant in Norway, where aquaculture intensification processes have been ongoing in recent years, and where production has been significantly increasing (Baarset & Johansen, 2019). This represent a suitable condition for the adopted case study to serve as examples for other location as RAS: are also well established in Canada, in Denmark, in Spain, and in the United States (Ahmed & Turchini, 2021). The cost-effective disposal of fish mortalities and discarded fish is an issue for the whole fish farming sector. The innovation here presented were first developed and later independently assessed within project Green Aquaculture INtensification in Europe (GAIN, 2018–21),[1] funded by the European Commission within its Horizon 2020 programme.

2. Materials and method

A sustainability evaluation through Emergy Assessment (§2.1) is performed to understand the ecological implications of so-called ecological intensification innovative solutions to reuse and valorise aquaculture discards such as wastewater sludge, fish mortalities, and discarded fish. As reminded in §1 (Introduction), Norway is a relevant geoeconomic context and salmon production is a relevant economic sector.

2.1. *The emergy Assessment approach*

The Emergy Assessment (EMA) method is used here, as introduced by Odum (1996) and later systematised by Brown and Ulgiati (2016a,b). The concept of emergy allows one to quantify under one unit all the resources that have been directly and indirectly required upstream to realise a given product or service. Emergy is defined as "the available energy (exergy) of one kind previously used directly or indirectly to generate a service or a product". Through emergy, the performances of a system can be appraised through a common energy-based metrics: usually, the solar emjoule (sej), elaborated from the solar equivalent exergy by means of a unit conversion of 1 J (J) of solar radiation into 1 solar equivalent joule (seJ). The overall emergy requirements (energy, matter, information, labour, and services) per output unit is called a Unit Emergy Value (UEV) and measured as sej/unit (sej/J, sej/m^3, sej/kg, sej/bit, sej/h, sej/currency, etc.). In particular, the emergy per exergy unit is defined as transformity (sej/J), and emergy per mass unit as specific emergy (sej/kg). The calculation of the UEVs for materials – mostly expressed in terms of specific emergy – include the emergy requirements associated with the related inputs to produce them, ranging from raw materials (including their geobiophsyical generation and concentration, their extraction, and their processing) to human labour, passing through machineries, energy sources, and more; human labour is instead calculated based on the emergy per capita in a given geoeconomic context: emergy per capita in a year is associated to a full-time worker and, for instance, a 50 % part-time worker will imply half of the annual emergy per capita to be allocated, thus including livelihoods, leisure, and whatever is not directly related to working hours but still functional to them. "More than simply an environmental accounting method, the emergy accounting approach allows one to keep track of both the natural cycles required to generate and concentrate resources over time and of the anthropic processes to extract, manufacture, and delivery such resources and/or more elaborated products and services" (Cristiano, 2021). Emergy may be considered as a development of the idea of embodied energy (EE) (Costanza, 1980). Compared to an EE assessment, an EMA has a larger boundary over time; indeed, incorporating the processes to generate and/or concentrate a resource (e.g. a mineral ore or a liter of raw oil), millennial processes are also accounted for, hence the instrinsic scarcity of a given resource (Cristiano & Gonella, 2019). Compared to EE, EMA also expands over space, for it accounts for large-scale phenomena, indirectly contributing to local dynamics (*ibid.*). Finally, expansion also happens over resource category, since EMA also comprises natural flows such as solar radiation, wind, rain geopotential, geothermal heat, and gravitational energy) (*ibid.*). Morover, an EMA takes also into account labour and services which are required to provide relevant outputs. Labour and services virtually bring with them some fractions of the material and immaterial requirements associated with the larger economies in which the system at hand is framed (Ulgiati & Brown, 2014). As e.g. per Cristiano et al.

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[1] https://www.unive.it/pag/33897 (retrieved on 1st December 2021).

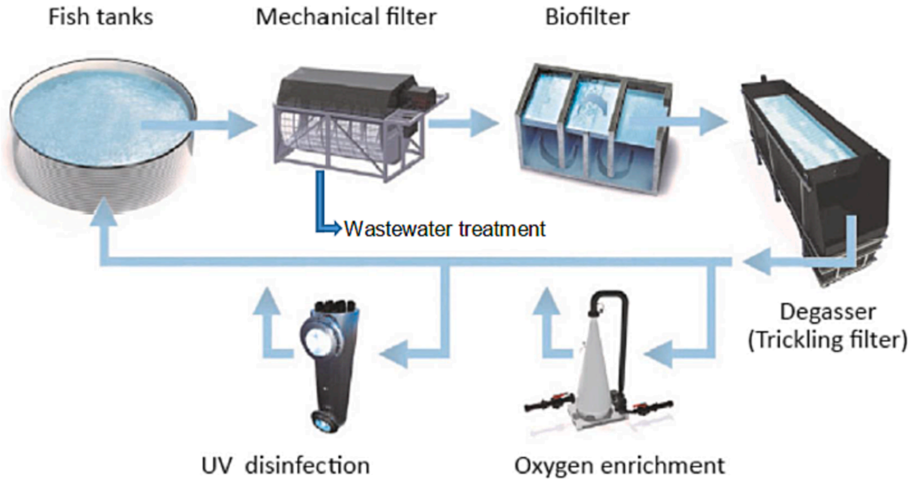

Fig. 1. Schematised operations in a RAS (Johansen et al., 2019; adopted from Bregnballe, 2015).

(2021), such an aspect “cannot be disregarded if a comprehensive sustainability evaluation is the goal”, forasmuch it provides instead “an added value to the assessment, much beyond and certainly complementing the usual monetary and energy evaluations”. An EMA first needs the boundaries of the studied process or system to be defined, and a systems diagram to be drawn by means of the symbols of the energy systems language (Odum, 1983; 1994; Brown, 2004). The driving flows of that process or system (energy, matter, and so on) are then identified and quantified, usually grouped in categories: (R) local renewable resources, provided by the geobiosphere for free; (N), local nonrenewables inside the boundary of the system; (F) other goods, imported from the outer economies (technosphere); and (L&S) imported labour and services. Inputs, originally expressed in their usual physical units (kg, m^3, J, kWh, etc.), are then converted into emergy units through suitable UEVs, all referred to the same global emergy baseline (GEB), which is the total emergy driving the geobiosphere during one year. The most recent GEB_{2016} of 1.2 □10^{25} seJ/yr is adopted, as developed by Brown et al. (2016). Besides the creation of new UEVs, an EMA allows to also calculate proper emergy indicators (Odum, 1996). Here, the following ones are selected and used: the emergy yield ratio (EYR), the emergy investment ratio (EIR), the environmental loading ratio (ELR), the emergy sustainability index (ESI), and the renewable emergy percentage (%Ren).

2.2. Previous emergy evaluations of aquaculture systems

A systematic literature review of EMAs concerning the aquaculture sector is given in David et al. (2021a). Prior to, Maiolo et al. (2021) performed an EMA to understand possible sustainability gains deriving from the use of novel or underexploited ingredients for aquafeed. David et al. (2018) evaluated the sustainability of tilapia (*Oreochromis niloticus*) case farming by Tietê River, state of São Paulo, Brazil. The same species was later studied also in biofloc-based systems (David et al., 2021b). Again in Brazil, Lima et al. (2012) compared organic and conventional marine shrimp (*Penaeus vannamei*) farms in Guaraíra Lagoon, in the state of Rio Grande do Norte, while Cavallett *et al.* (2007) focused on fish aquaculture chains in the state of Santa Catarina, including tilapia (*Oreochomis* sp.), pacú (*Piractus mesopotamicus*), mirror carp (*Cyprinus carpio*), bighead carp (*Aristichtys nobilis*), silver carp (*Hypophthalmichthys molitrix*), and African catfish (*Clarias* sp.). Williamson et al. (2015) evaluated the sustainability of two oyster aquaculture systems in Maryland’s Chesapeake Bay, United States of America. Wilfart et al. (2013) used both LCA and EMA to study a RAS for salmon production, a semi-extensive polyculture pond, and an extensive polyculture pond in France. Li et al. (2011) applied EMA to three aquaculture systems in the Chinese wetlands at the estuary of Pearl River. At the Pearl River Delta, instead, Zhang et al. (2017) evaluated largemouth bass (*Micropterus salmoides*) production. Shi et al. (2013) assessed monoculture and integrated multi-trophic aquaculture systems in Sanggou Bay, China. Also in China, in Nansi Lake area, Zhang et al. (2011) performed an EMA of three wetland fish farming systems dealing with silver carp (*Hypophthalmichthys molitrix*) and spotted silver carp (*Aristichthys mobilis*). Vassallo et al. (2009) assessed an inshore Mediterranean marine fish farm in the Ligurian Gulf, Italy, breading Gilthead seabream (*Sparus aurata*). A doctoral thesis by Bergquist (2008) had addressed some monocultures of black tiger prawn (*Penaeus monodon*) and milkfish (*Chanos chanos*), and a polyculture of the two former species together with mudcrab (*Scylla serrata*). Actually, though, the very Odum (2000, 2002) evaluated salmon and shrimp production in the United States, and aquatic trophic chains are present in many of his works on emergy accounting. Compared to all of the reviewed works above, our work exhibits the following novelties and differences: (1) it expands the boundary and complexity by addressing full production chains based on industrial-like aquaculture, i.e. supported by machinery and targeting large-scale production; (2) it provides multiple alternatives and their discussion, so as not to let data refer to just isolated cases; and (3) it addresses highly topical issues of the present decade, by including and critically assessing manifold options to save and to recirculate materials and energy, also explicitly addressing eco-intensification actions and fish mortality disposal – all features that, to the best of our knowledge, have not been studied so far in scientific works, instead limiting to some aspects of production or rather to primary-like production, e.g. not really involving machineries and recent technology or production innovations.

2.3. Case study: Eco-innovation for RAS sludge

Recirculating Aquaculture Systems (RAS) were introduced about thirty years ago (Helfrich & Libey, 1991) but they became more widely adopted in the last two decades (Badiola et al., 2012). More recently, RAS are becoming increasingly used in the salmon industry, particularly in smolt production. In a RAS (Fig. 1), wastewater is usually filtered mechanically, for the removal of residual feed, fish faeces, and other particles; reject water is then channelled into a biofilter, which converts ammonium into nitrate; later, excess carbon dioxide is removed by means of a degasser (trickling filter), and water is enriched with oxygen; water is then disinfected thanks to ultra-violet (UV) rays before being eventually poured back into the main fish tank (*ibid.*). Circularity is of course not perfect (cf. Cristiano et al., 2020), as (1–2 % of new water is required to avoid accumulating nitrates. In a RAS, the mechanical filter

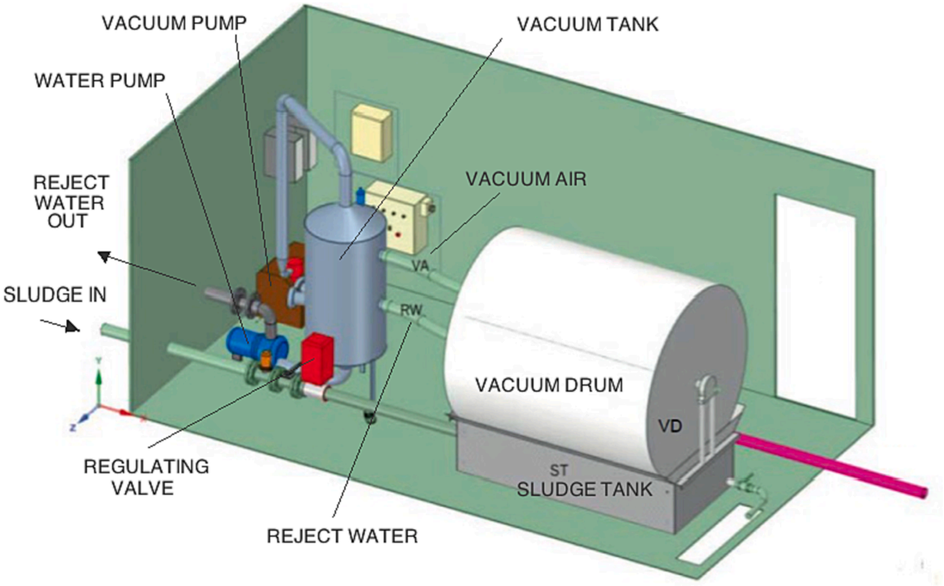

Fig. 2. Main components of the S3 filter-dryer system (Cristiano et al., 2022; after Bruckner et al., 2021).

(mesh size: 40 and 80 μm) removes suspended matter, thus yielding a reject water that is rich in phosphorus and nitrogen. The innovative process that aims at capturing these nutrients, thus reducing the environmental load of the aquaculture facility due to the discharge of the reject in water bodies.

An innovative filter-dryer system (S3) (Fig. 2) was designed (Bruckner et al., 2021) to decrease to increase the concentration of particles in the fish sludge, thus reducing the concentration of nitrogen and phophorus in the reject water. The process comprises two steps: a) filtration, with a mesh size of 6 μm, removing 93 % (±2.8 %) of the suspended solids in the wastewater and yielding a filter cake with a water content of less than 10 %; b) drying of the filter cake through an energy-efficient infrared system (*ibid.*). In the first step, I sludge is extracted from the tank via the filter and through the vacuum drum, with an absolute pressure of 0,5 atm inside the drum (i.e. a strong underpressure); this generate numerous droplets that can be carried away so as to condense in the vacuum tank (*ibid.*). The innovation is designed with a capacity of 22 L/s – large enough to treat the usual side streams of a RAS (*ibid.*), here based on an annual production of 1,300 ton of smolts. Filtration is as fast as conventional filtration (*ibid.*). The innovative S3 system uses vacuum to extract the reject water from a sludge tank trough the filter cloth; this happens on nearly 25 % of the surface of the drum. In the second step, the particles on the filter surface are dried by means of the vacuum and of a infrared unit, while the drum completes a full cycle (*ibid.*). Filtration systems currently being used produce a sludge with a water content of at least 90 %, which of course needs to be either further dried locally or transported while still wet to potential second raw material customers, waste incinerators, or biogas plants (*ibid.*). The new process here presented gives a dried product, (dry matter 93–95 %) which is rich in nutrients such as phosphorus and nitrogen, and which can be reused and valorised in other economic processes as per the three end-of-life options (B1, B2, and B3) that are detailed below.

Like assessed by means of Life-Cycle Assessment in Cristiano et al. (2022), three reuse and valorisation options are considered:

“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.

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.

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”.

Based on the enf-of-life valorisation option, some information about the dried sludge is here provided (*ibid.*): if valorised as a fertiliser (B1), phosphorus 24 g/kg, nitrogen 47 g/kg; if valorised as an energy source (B2–B3), average energy content 20 MJ/kg, fat 3.5 %. These scenarios (B1, B2, and B3) are compared with the reference scenario (A), i.e. a smolt RAS system with standard filter and sludge 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 disposal 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)” (*ibid.*).

2.4. Case study: Eco-innovation for fish mortality disposal and valorisation

Fish mortalities are a side stream from all types of fish farming and from transported live fish (Baarset & Johansen, 2019). In 2018, mortality represented over 16 % of farmed salmon in Norway, i.e. 6–9 % of the bred biomass (Oliveira et al., 2021). These values meet previous estimates by Bjørndal & Tusvik (2017). In Norway, fish mortalities are presently ground; mixed with formic acid; stored in containers; and transported either by truck or by ship and delivered to further processing plants (e.g. biogas plant) (Raa et al., 1982). This way, Health, Safety, Environment (HSE) hazardous substances[2] are to be carried away from the breeding plant, and this implies a series of risks, including sea or road leaks. The innovations developed in GAIN aims to dry and sanitise the fish mortality biomass by means of a drying technology based upon superheated steam (SHS).. The new process relies upon prototype “Waister 15” device. Fish “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

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[2] “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” (Cristiano et al., 2022, based upon Baarset & Johansen, 2019).

Table 2
Inputs and outputs for the treatment of 1 ton of fish mortality at the selected demonstration plant (adapted and expanded from Cristiano et al., 2022).

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	0.8	0.3	0.3
Height above mean sea level	m	5	5	5
Formic acid transport	*t*-km	10	–	–
New machinery transport	*t*-km	–	19	19
By-product transportation	*t*-km	2,000	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].

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 water at 45–60 °C corresponding to up to 60 % of electric power consumption is available. The volume and the mass of the dried fish mortalities are nearly 86 % smaller than those obtained through business-as-usual ensilage (Baarset et al., 2021).

Three scenarios for mortality disposal are here appraised, as shown 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.

The innovative scenarios (D and E) are divided into three sub-scenarios each, based upon their respective end-of-life reuse and valorisation option, designed based on the same source (Baarset, 2021) and similarly to the end-of-life scenarios used for sludge valorisation sub-scenarios B1, B2, B3. End-of-life options consists in the following (Cristiano et al., 2022):

"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)". Such trip costs approximately 35 €/ton, and the dried product has a market value of nearly 1,350 €/ton.

"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" (*ibid.*). Such trip costs approximately 12 €/ton, and the dried product has a market value of nearly 27 €/ton.

"Fish mortality end-of-life valorisation option 3 – Biogas substrate

Fig. 3. The Norwegian municipality of Gildeskål, where the demonstration plant is located (public domain).

The dried mortalities are used as biomass for gasification. For the demonstration plant to evaluate, this implies road transportation to Denmark (1,735 km)" (*ibid.*). Such trip costs approximately 50 €/ton, and the dried product is received free of charge and is not paid as a secondary resource (so its market value is zero).

2.5. The appraised demonstration plant

Primary data about the eco-innovations to be here assessed were collected at the demonstration plant run by the company Helgeland Smolt AS[3]: a questionnaire was developed and supervised by the first author of this article (S.C.), progressively filled in with information deriving from on-site visits and interviews to the staff conducted by the business-oriented authors (C.B.; H.B.). The plant is located in Sundsfjord, municipality of Gildeskål, Norway (Fig. 3). This facility is praised as a modern smolt farm. Its RAS technologies are by Veolia Krüger Kaldnes.[4] Of course, this is the same plant also assessed through LCA (Cristiano et al., 2022).

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

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

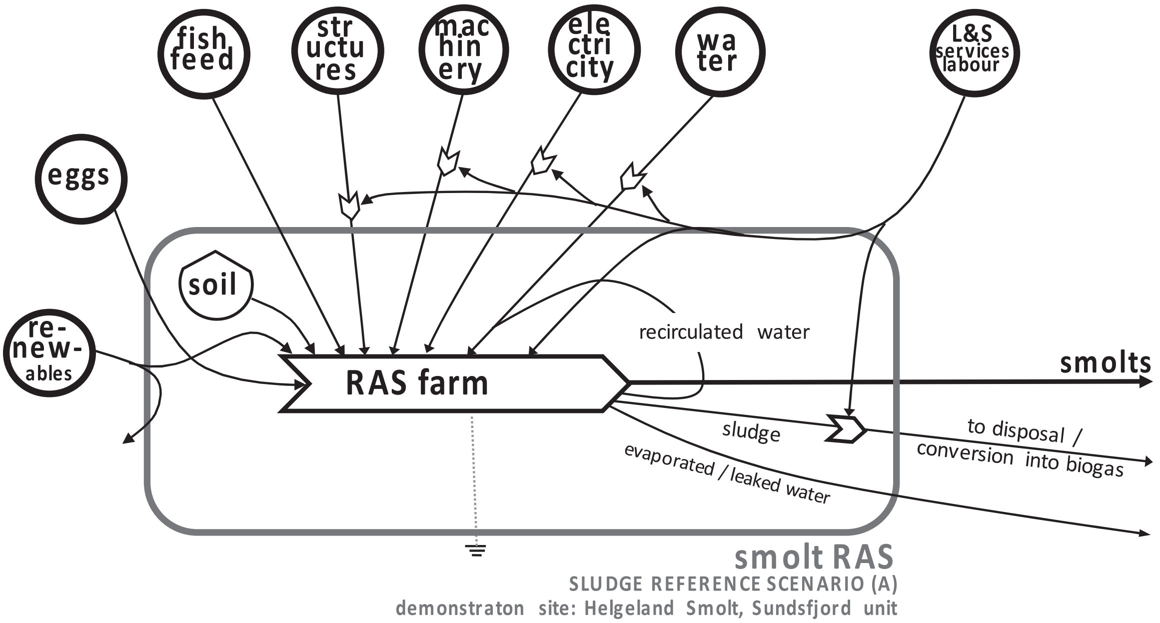

Fig. 4. Systems diagram for smolt production, including sludge treatment reference scenario (A).

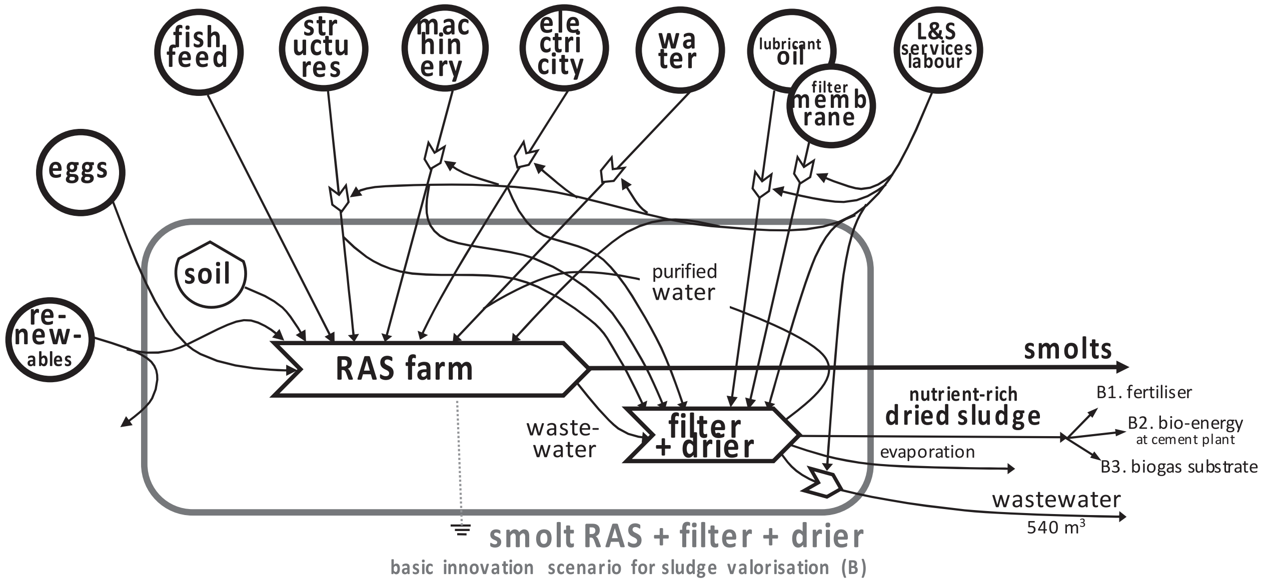

Fig. 5. Systems diagram for smolt production, including sludge treatment innovative scenario (B).

2.6. Modelling choices for sludge treatment scenarios, mortality treatment scenarios, and valorisation options

To allow for result comparisons across different environmental accounting methods, the modelling choices for the present Emergy Assessment (EMA) comply with the ones that were previously made for the Life-Cycle Assessment (LCA) of the same innovations for aquaculture (Cristiano et al., 2022). According to EMA praxis, primary data (“raw amounts”), lifetimes, data references and – if need be – assumptions are all reported in the emergy tables and in their footnotes, as available in §3 (Results and discussion). UEV references are all referred to the current global emergy baseline GEB_{2016} of 1.2E + 25 sej (Brown et al., 2016), and reported in a dedicated column of each table (“UEV ref.”). As also reminded of later, all tables report both inputs and outputs, so the obtained emergy values can be adapted to functional units, and new UEVs derived and calculated.

3. Results

3.1. Systems diagrams

According to the EMA procedure (§2.1), the scenarios to be addressed (§2.3–2.4) at the selected demonstration plant ((§2.5) have been organised in systems diagrams drawns through the energy language symbols (§2.1). The diagrams describe the current process for smolt production in a RAS, including sludge treatment (Fig. 4), smolt production in a RAS, including the innovation for sludge treatment (Fig. 5), the current process (ensilage) to treat fish mortality and discarded fish (Fig. 6), and the two innovations to treat and valorise fish mortalities either using just water (Fig. 7) or a water–glycol mix (Fig. 8) as the cooling medium of the process. The innovative scenarios comprise three different output alternatives corresponding to the three end-of-life options, as illustrated above (§2.3–2.4). Lighter stocks and flows

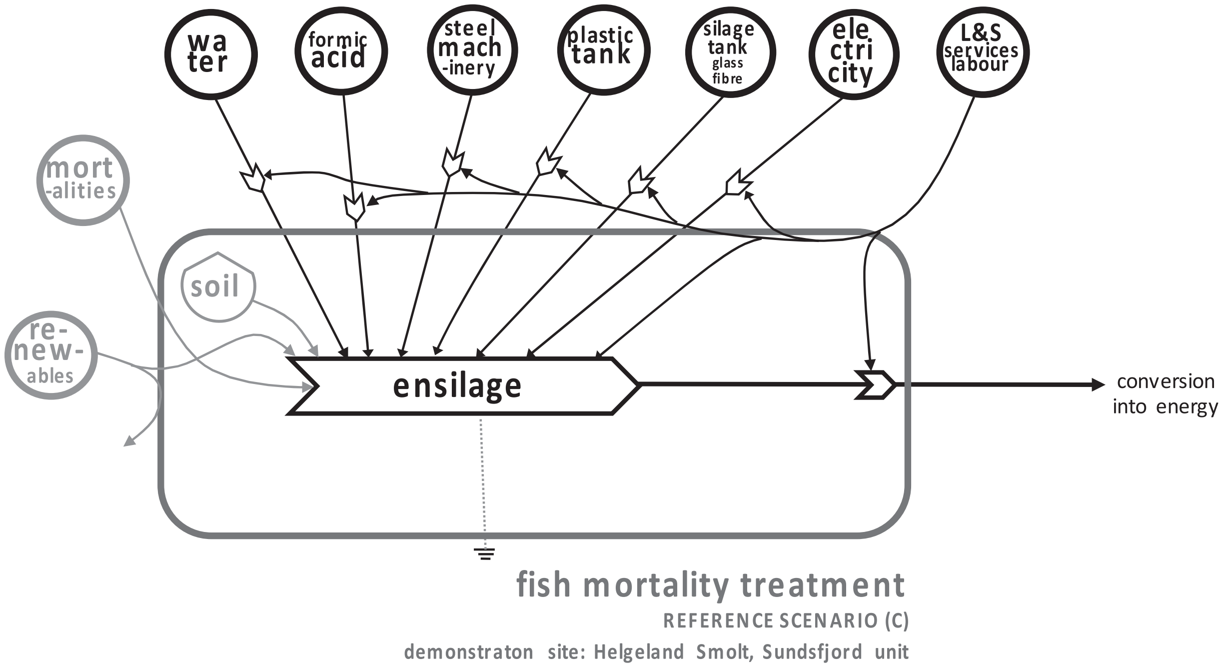

Fig. 6. Systems diagram for fish mortality treatment reference scenario (C).

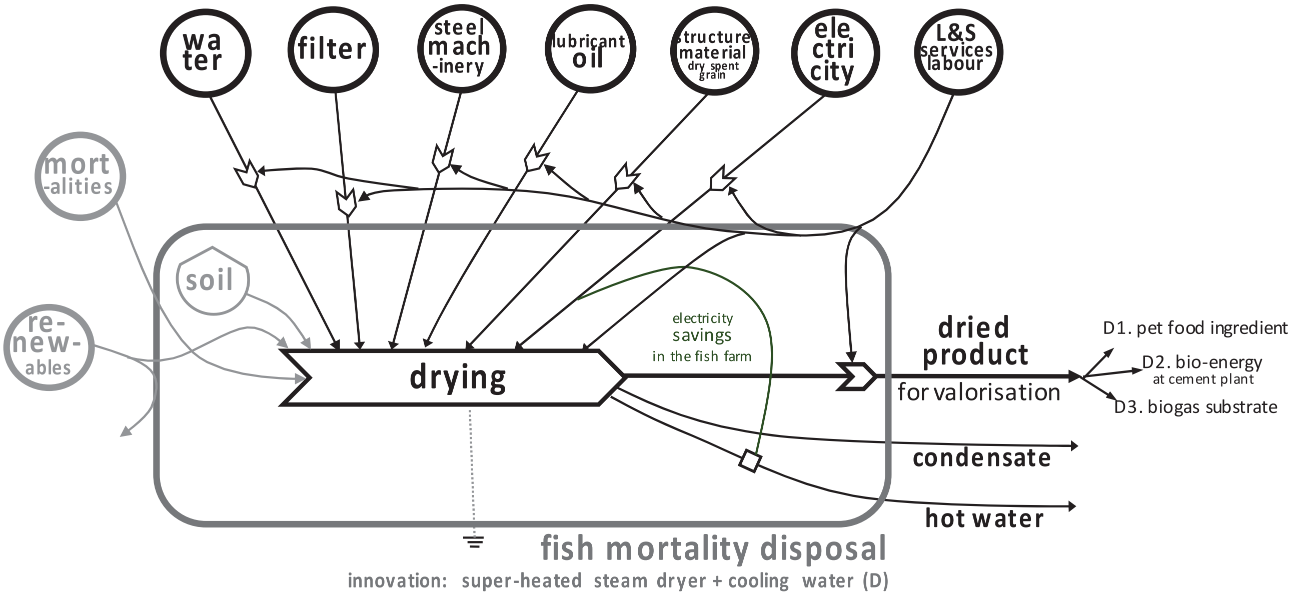

Fig. 7. Systems diagram for fish mortality treatment innovative scenario with water as cooling medium (D).

represent the neglected inputs, as motivated in the corresponding emergy tables (§3.2).

3.2. Emergy Assessment

The results of the EMA are provided for each assessed scenario: the current process for RAS sludge treatment (Table 3), the innovation for RAS sludge treatment (Table 4), the current process (ensilage) to treat fish mortality and discarded fish (Table 5), and the two innovations to treat and valorise fish mortalities either using just water (Table 6) or a water–glycol mix (Table 7) as the cooling medium of the process. Again, the innovative scenarios comprise three different output alternatives corresponding to the three end-of-life options. All tables report both inputs and outputs, so the obtained emergy values can be adapted to functional units, and new UEVs derived and calculated. Such novel UEVs can be considered as indicators to provide benchmarks and allow for comparisons among aquaculture products, including innovative circular practices; they consist in: specific emergy (sej/kg), built based on the mass of produced salmon, emergy per currency (sej/€), based on salmon's market value; specific emergy of silage (sej/kg), specific emergy of dried by-product (sej/kg), and emergy per currency unit (sej/€) of the by-product, differentiated by end-of-life valorisation.

4. Discussion

Detailed interpretation and discussion of the EMA results for the selected case studies are offered in sections 4.1 and 4.2, respectively about the eco-innovations for aquaculture sludge valorisation and for

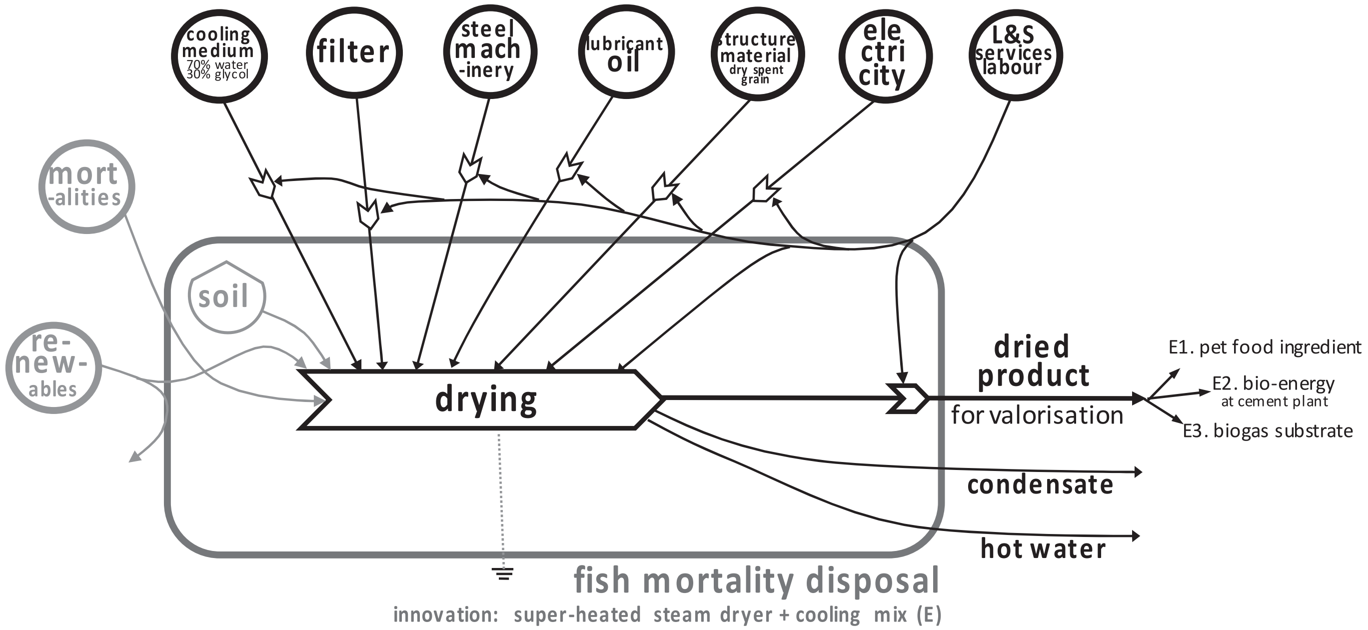

Fig. 8. Systems diagram for fish mortality treatment innovative scenario with glycol-based cooling mix (E).

fish mortality disposal and valorisation. It may be useful to keep in mind that the environmental performances refer to fixed functional units before and after the evaluated innovations; cumulative results at the reference aquaculture plant may therefore be different with increasing production volumes. Speaking of functional units, these are the same as in the LCA applied to the same innovations (Cristiano et al., 2022); compared to LCA, instead, additional information is to be surveyed and calculated (primary data), including above all local renewable sources, labour, and services, on top of intrinsically including – through UEVs (secondary data) – energy quality (Ulgiati & Brown, 1992). Aquaculture systems have already been jointly assessed through LCA and EMA by Wilfart et al. (2013) and Henares et al. (2020). The potential added value of performing an EMA to complement a LCA are explained by Raugei et al. (2014): “the Emergy perspective is […] irreducibly different from the LCA one” and would provide “a complementary donor-side perspective, a unified measure of the provision of environmental support, and an indication of the work of the environment that would be needed to replace what is consumed”; as a starting point, excluding local renewable sources, labour, and services, common inventories can be built, although the way each input is elaborated is, as recalled, quite different.

4.1. *Case study: Eco-innovation for aquaculture sludge*

The order of magnitude of the values obtained out of the EMA for salmon production, are consistent with the emergy values of previous studies, as cited in section 2.2. When discussing the two scenarios that were assessed in the present work, the order of magnitude stays the same before and after the innovation for wastewater filtration, drying, and by-product reuse in a smolt farm with a RAS: a negligible decrease (almost –1%) is only found in the total emergy for smolt production, while the remainders do not exceed –0.1 %. This can be ascribed to the significant impact of fish feed – as also found in the previous LCA and anyway a recurring issue in aquaculture environmental assessments (Cristiano et al., 2022) – and here amplified by the concurrent presence of another significant input such as salmon eggs. In particular, fish feed accounts for almost 17 % of the total emergy requirements without labour and services (U), and salmon eggs for almost 83 % (indeed, through the emergy concept even an egg brings the “memory” of the geobiophysical efforts that were required upstream, and without which that egg would not be obtained – a frontier approach in sustainability and resilience studies). For the very nature of an EMA, it would make no much sense to perform an assessment without such inputs; nevertheless, full emergy tables (Tables 3 and 4) can be discussed after virtually removing the inputs related to fish feed, salmon eggs, and their related labour and services: namely, lines 6, 14, 17, and 18; this way, i.e. leaving apart these inputs, innovations would deliver –88 % and –3% decreases if labour and services are respectively excluded or included. As a matter of fact, when the inputs for fish feed and salmon eggs are virtually excluded, the assessed innovation for sludge valorisation allows for significant relative savings: –98 % in terms of fuel for by-product transportation, and –88 % for the connected services. These relative savings are partially counterbalanced by increased inputs for machinery (+33 %), net water use (+20 %), with the same percentage variations in their related services. The largest inputs for labour and services, i.e. workers and contractors, undergo negligible increases (smaller than + 2 %). When comparing EMA results with LCA results from Cristiano *et al.* (*ibid*), some similarities and some differences can be found. On the one hand, the dwarfing role of fish feed and the additional water requirements are both confirmed, as detailed above, just like the savings deriving from transporting the by-product once alternative end-of-life valorisation options are introduced. On the other hand, significant impacts are found from a previously neglected input such as salmon eggs and for the new machinery that allows for the innovation at hand. Trade-offs exist between saved requirements and invested requirements to allow for those savings, including new invested technology and net water use. Ethical and more comprehensive socio-economic considerations fall beyond the purposes of the current study. The size of these savings and additional requirements to invest are anyway dwarfed if the leading inputs in smolt production are accounted for; therefore, eco-innovation solutions ought to mostly tackle those inputs in future developments in aquaculture. Some considerations may be dedicated to absolute values: even in the presence of –1% total emergy savings, generously assuming that all the annual farmed salmons in the entire world (2.5 million tonnes; International Salmon Farmers Association, 2018) are produced through industrial processes and that all of them adopt the innovations at hand, savings may be of the order of magnitude of 10^{18} sej, i.e. the per capita requirements of almost ten persons in Norway (National Environmental Accounting Database, 2014) – even less if we acknowledge that it is highly unlikely that all farmed salmon in

Table 3
Emergy Assessment of smolt production based on sludge reference scenario (A).

#	Item	Unit	Raw amount per year	UEV (sej/unit)*	UEV ref.	Solar emergy (E + 12 sej/yr)
	Local renewable inputs (R)					
1	Solar radiation	J	1.16E + 12	1	[a]	1
2	Geothermal heat flow	J	2.60E + 10	4,900	[b]	127
3	Wind, kinetic energy	J	3.62E + 11	790	[b]	286
4	Rain, geopotential	J	3.61E + 08	12,800	[b]	5
	Driving renewable input**					286
	Local nonrenewable sources (N)					
5	Topsoil	J	15,000	9.37E + 04	[c]	1,096
	Imported material inputs (F)					
6	Fish feed	kg	1,300,000	1.59E + 13	[d]	20,649,200
7	Structures (as Reinforced concrete)	kg	2,330	1.58E + 12	[e]	3,678
8	Machinery (as Large electric appliance)	kg	300	7.22E + 12	[e]	2,165
9	Electricity, Norwegian mix	MWh	11.05	7.96E + 14	[f]	8,791
10	Net water after recirculation	m^3	5,000	1.00E + 11	[b]	500
11	Lubricant oil (as Oil)	L	–	5.76E + 12	[g]	–
12	Filter membrane (as Plastics)	kg	–	6.48E + 12	[h]	–
13	Fuel for by-product transportation (Diesel)	kg	23,864	6.40E + 12	[g]	152,727
14	Salmon eggs	item	9,500,000	1.06E + 13	[d]	100,700,000
	Labour and services (L&S)					
15	Labour, equivalent full time workers	item	18	2.54E + 17	[f]	4,572,000
16	Contractors, external services	€	750,000	3.19E + 11	[f]	239,250
17	Services, eggs purchase	€	1,900,000	3.19E + 11	[f]	606,100
18	Services, fish feed purchase	€	1,820,000	3.19E + 11	[f]	580,580
19	Services, structure investment amortisation	€	1,553,000	3.19E + 11	[f]	495,407
20	Services, machinery investment amortisation	€	46,000	3.19E + 11	[f]	14,674
21	Services, electricity	€	1,105,000	3.19E + 11	[f]	352,495
22	Services, water	€	656,000	3.19E + 11	[f]	9,570
23	Services, by-product transportation	€	234,000	3.19E + 11	[f]	74,646
	Total emergy input (U)			sej	no L&S	**1.22E + 20**
	Total emergy input (ULS)			sej	with L&S	**1.28E + 20**
	Percentage of labour and services in total emergy input (ULS)			kg		**4.7 %** 1,300,000
	Produced smolts			m^3		500
	Wet sludge			kg		–
	Dry sludge for valorization			m^3		4,500
	Evaporated/discharged water			€/kg		10
	Average bulk value of smolts			sej/kg		**9.35E + 13**
	Specific emergy of produced smolts			sej/kg	no	**9.88E + 13**
				sej/€	L&S	**9.88E + 12**
	Emergy per currency				with L&S with L&S	

*Calculated or converted from other works according to the **GEB$_{2016}$ of 1.2E + 25 sej** (Brown et al., 2016).
**As per Brown & Ulgiati (2016b), we use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources (here, wind and rain).
Footnotes: Area of the RAS: 15,000 m^2. **1.** Annual solar insolation in Gildeskål area, Norway: 24 kWh/m^2 (after Hagos et al., 2014), i.e. 8.6 E + 07 J/m^2; albedo of built environments: 0.1 (Wolf & Lundholm, 2008). **2.** Local heat flow: 55 mW/m^2 (Pascal, 2015). **3.** Average annual local surface wind speed in Inndyr, Gildeskål area: 4.96 m/s (after Weatherspark, 2021); surface wind / geostrophic wind ratio: 0.6 (our assumption based on previous literature); drag coefficient: 1.00E-03 (Miller, 1964); average density of air in the area: 1.225 kg/m^3 (our calculation based on local elevation). **4.** Elevation: 3 m (direct survey at the plant); average annual rainfall in Inndyr, Gildeskål area: 1,024 mm (after Weatherspark, 2021); runoff: 0.8 (our estimation based on previous literature for built environments; Ali et al., 2021). **5.** Erosion rate estimated at 0.69 kg/m^2/yr (La Rosa et al., 2008); average carbon concentration in topsoil: 5 % (after De Vilbiss and Brown, 2015); energy content in soil 5,400 kcal/kg (Ulgiati et al., 1992). **6.** Direct survey at the plant. **7.** 776 m^3 of structures, with assumed structural density of 5 %, so with an expected volume of reinforced concrete equal to 38.8 m^3; assuming a reinforced concrete density of 2,400 kg/m^3, and a lifetime of 40 years, the annual raw amount was calculated as 2.33E + 03 kg. **8.** Direct survey; total mass; based on an assumed expected lifetime of 15 years. **13.** Considering 3 MJ per ton-km (European Environmental Agency, 2000), and an average heat value of 44 MJ/kg for diesel. **15–23.** Based on direct surveys. **19.** Adjusted to the assumed lifetime of 40 years. **20.** Adjusted to the assumed lifetime of 15 years.
UEV references: **a.** By definition. **b.** After De Vilbiss & Brown (2015). **c.** Odum (1996). **d.** Odum (2001). **e.** After Cristiano et al. (2021), based on a large electric/electronic appliance of 125 kg. **f.** National Environmental Accounting Database (2014) (after Sweeney et al., 2007). **g.** Brown et al. (2011); for lubricant oil only, based on an assumed density of 0.9 kg/L. **h.** Brown & Buranakarn (2003).

the world is industrialised and that all salmon industries would adopt the innovations at issue; this confirms the considerations we have made above about the negligible effects.

4.2. Case study: Eco-innovation for fish mortality disposal and valorisation

The novel application of EMA to fish discard treatment does not allow for comparisons with previous findings. When appraising the environmental performances of the selected reference and innovative treatment scenarios for fish mortality drying and reuse options, some remarks may be made instead. Both eco-innovations perform very well, abating emergy requirements by two orders of magnitude: values are abated by –99 % in total emergy both with and without labour and services. Similar decreases can be also observed in the specific emergy, again without distinction whether labour and services are included or not: –94 % for the innovation with heat reuse in the fish farm and water used as the cooling medium for fish mortality treatment, and –93 % for the innovation with no heat reuse but rather resorting to a cooling mix containing 70 % glycol and 30 % water: scenario D (Table 6) performs tbetter than scenario E (Table 7), and both perform better than reference

Table 4
Emergy Assessment of smolt production based on sludge innovative scenario (B).

#	Item	Unit	Raw amount per year	UEV (sej/unit)*	UEV ref.	Solar emergy (E + 12 sej/yr)
Local renewable inputs (R)						
1	Solar radiation	J	1.16E + 12	1	[a]	1
2	Geothermal heat flow	J	2.60E + 10	4,900	[b]	127
3	Wind, kinetic energy	J	3.62E + 11	790	[b]	286
4	Rain, geopotential	J	3.61E + 08	12,800	[b]	5
	Driving renewable input**					286
Local nonrenewable sources (N)						
5	Topsoil	J	15,000	9.37E + 04	[c]	1,096
Imported material inputs (F)						
6	Fish feedStructures	kg	1,300,000	1.59E + 13	[d]	20,649,200
7	(as Reinforced concrete)Machinery	kg	2,330	1.58E + 12	[e]	3,688
8	(as Large electric appliance)	kg	400	7.22E + 12	[e]	2,886
9	Electricity, Norwegian mix	MWh	11.23	7.96E + 14	[f]	8,939
10	Net water after recirculationLubricant oil	m^3	5,000	1.00E + 11	[b]	600
11	(as Oil)Filter membrane	L	10	5.76E + 12	[g]	58
12	(as Plastics)Fuel for by-product transportation	kg	20	6.48E + 12	[h]	130
13	(Diesel)	kg	6,000 $^{(B1)}$	6.40E + 12	[g]	2,618 $^{(B1)}$
		kg	1,900 $^{(B2)}$	6.40E + 12	[g]	829 $^{(B2)}$
		kg	2,900 $^{(B3)}$	6.40E + 12	[g]	1,266 $^{(B3)}$
14	Salmon eggs	item	9,500,000	1.06E + 13	[d]	100,700,000
Labour and services (L&S)						
15	Labour, full time equivalent workers	item	18.01	2.54E + 17	[f]	4,574,000
16	Contractors, external services	€	760,000	3.19E + 11	[f]	242,440
17	Services, eggs purchase	€	1,900,000	3.19E + 11	[f]	606,100
18	Services, fish feed purchase	€	1,820,000	3.19E + 11	[f]	580,580
19	Services, structure investment amortisation	€	1,554,000	3.19E + 11	[f]	495,726
20	Services, machinery investment amortisation	€	61,000	3.19E + 11	[f]	19,459
21	Services, electricity	€	1,123,000	3.19E + 11	[f]	358,237
22	Services, water	€	36,000	3.19E + 11	[f]	358,237
23	Services, by-product transportation	€	58,800 $^{(B1)}$	3.19E + 11	[f]	18,768 $^{(B1)}$
		€	18,600 $^{(B2)}$	3.19E + 11	[f]	5,943 $^{(B2)}$
		€	28,400 $^{(B3)}$	3.19E + 11	[f]	9,071 $^{(B3)}$
24	Services, lubricant oil and filter membrane	€	9,000	3.19E + 11	[f]	2,871
Total emergy input (U)				sej	no L&S	**1.21E + 20**
Total emergy input (ULS)				sej	with L&S	**1.28E + 20**
Percentage of labour and services in total emergy input (ULS)						**5.5 %**
Produced smolts				kg		1,300,000
Wet sludge				m^3		–
Dry sludge for valorization				kg		5,400
Evaporated/discharged water				m^3		600
Average bulk value of smolts				€/kg		10
Specific emergy of produced smolts				sej/kg	no L&S	**9.34E + 13**
				sej/kg	with L&S	**9.87E + 13**
Emergy per currency				sej/€	with L&S	**9.87E + 12**

*Calculated or converted from other works according to the **GEB_{2016} of 1.2E + 25 sej** (Brown et al., 2016).

**As per Brown & Ulgiati (2016b), we use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources (here, wind and rain).

Footnotes: Area of the RAS: 15,000 m^2. **1.** Annual solar insolation in Gildeskål area, Norway: 24 kWh/m^2 (after Hagos et al., 2014), i.e. 8.6 E + 07 J/m^2; albedo of built environments: 0.1 (Wolf & Lundholm, 2008). **2.** Local heat flow: 55 mW/m^2 (Pascal, 2015). **3.** Average annual local surface wind speed in Inndyr, Gildeskål area: 4.96 m/s (after Weatherspark, 2021); surface wind / geostrophic wind ratio: 0.6 (our assumption based on previous literature); drag coefficient: 1.00E-03 (Miller, 1964); average density of air in the area: 1.225 kg/m^3 (our calculation based on local elevation). **4.** Elevation: 3 m (direct survey at the plant); average annual rainfall in Inndyr, Gildeskål area: 1,024 mm (after Weatherspark, 2021); runoff: 0.8 (our estimation based on previous literature for built environments; Ali et al., 2021). **5.** Erosion rate estimated at 0.69 kg/m^2/yr (La Rosa et al., 2008); average carbon concentration in topsoil: 5 % (after De Vilbiss and Brown, 2015); energy content in soil 5,400 kcal/kg (Ulgiati et al., 1992). **6.** Direct survey at the plant. **7.** 778 m^3 of structures, with assumed structural density of 5 %, so with an expected volume of reinforced concrete equal to 38.9 m^3; assuming a reinforced concrete density of 2,400 kg/m^3, and a lifetime of 40 years, the annual raw amount was calculated as 2.33E + 03 kg. **8.** Direct survey; total mass; based on an assumed expected lifetime of 15 years. **13.** Considering 3 MJ per ton-km (European Environmental Agency, 2000), and an average heat value of 44 MJ/kg for diesel. **15–24.** Based on direct surveys. **19.** Adjusted to the assumed lifetime of 40 years. **20.** Adjusted to the assumed lifetime of 15 years.

UEV references: **a.** By definition. **b.** After De Vilbiss & Brown (2015). **c.** Odum (1996). **d.** Odum (2000). **e.** After Cristiano et al. (2021), based on a large electric/electronic appliance of 125 kg. **f.** National Environmental Accounting Database (2014) (after Sweeney et al., 2007). **g.** Brown et al. (2011); for lubricant oil only, based on an assumed density of 0.9 kg/L. **h.** Brown & Buranakarn (2003).

scenario C (Table 5). The improved performances of the innovated process cannot neglect the predominant impact of formic acid, dwarfing any other input in reference scenario C. Therefore, the tiny preference for scenario D assumes a greater value for all of the remaining inputs. Improvements close to two orders of magnitude were also found in the different environmental impact indicators obtained through the LCA (Cristiano et al., 2022), again with a predominant role of formic acid in scenario C and with an overall preference for scenario D over scenario E. As outlinzzaed in that work, some restrictions exist, since by-product 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” (*ibid.*). In other words, circular valorisation should be thoroughly addressed not as a way to cut off impacts through environmental accounting tricks, but rather as a function of real opportunities for an overall decrease in human environmental impacts.

Table 5
Emergy Assessment of current fish mortality treatment through ensilage (scenario C).

#	Item	Unit	Raw amount per year	UEV (sej/unit)*	UEV ref.	Solar emergy (E + 10 sej/yr)
Local renewable inputs (R)						
1	Local renewables	–	–	–	–	–
Local nonrenewable sources (N)						
2	Topsoil	–	–	–	–	–
Imported material inputs (F)						
3	Water	m^3	0.905	1.00E	[b]	9
4	Glycol	kg	–	+ 11	[i]	–
5	Formic acidFilter	L	94.8	6.27E	[l]	71,681,774
6	(as Synthetic	kg	–	+ 12	[m]	–
7	fibre)Machinery	kg	3.2	7.55E	[e]	254,720
	(as Large electric			+ 15		
	appliance)			4.02E		
				+ 12		
				7.96E		
				+ 14		
8	Structure material	kg	–	1.10E	[n]	–
9	(as Grain	kWh	29	+ 13	[f]	2,324
10	digestate)	kg	–	7.96E	[g]	–
11	Electricity,	kg	136	+ 11	[g]	87,273
12	Norwegian	kg	1,000	6.40E	–	–
	mixFuel for new			+ 12		
	machinery			6.40E		
	transport			+ 12		
	(Diesel)Fuel for			–		
	by-product					
	transportation					
	(Diesel)					
	Fish mortalities					
Labour and services (L&S)						
13	Labour, equivalent	item	0.001	2.54E	[f]	25,400
14	full time	€	0	+ 17	[f]	0
	workersServices,			3.19E		
	water			+ 11		
	(free from					
	adjacent power					
	plant)					
15	Services, glycol	€	–	3.19E	[f]	–
16	purchase	€	98	+ 11	[f]	3,126
17	Services, formic	€	–	3.19E	[f]	–
18	acid purchase	€	–	+ 11	[f]	–
19	Services,	€	1	3.19E	[f]	32
20	machinery	€	–	+ 11	[f]	–
21	investment	€	375	3.19E	[f]	11,963
22	amortisation	€	–	+ 11	[f]	–
	Services,			3.19E		
	machinery			+ 11		
	transportation,			3.19E		
	amortised			+ 11		
	Services,			3.19E		
	electricity			+ 11		
	Services, structure			3.19E		
	material			+ 11		
	Services, by-					
	product					
	transportation					
	Services, lubricant					
	oil and filter					
Total emergy input (U)				sej	no	**7.19E + 17**
Total emergy input (ULS)				sej	L&S	**7.20E + 17**
Percentage of labour and services in total					with	**0.1 %**
emergy input (ULS)				kg	L&S	2,000
Fish silage				kg		–
Dried by-product				kg		–
Condensate				m^3		–
Hot water				kWh		–
Heat recovery potential				€/kg		0
Average bulk value of silage				€/kg		–
Average bulk value of dried by-product				€/kg		–
				€/kg		–
				sej/kg		**3.60E + 14**
Specific emergy of silage				sej/kg	no	**3.60E + 14**
				sej/kg	L&S	–
Specific emergy of dried by-product				sej/kg	with	–
				sej/€	L&S	**Not**
Emergy per currency					no	**Applicable**
					L&S	
					with	
					L&S	
					with	
					L&S	

*Calculated or converted from other works according to the **GEB$_{2016}$ of 1.2E + 25 sej** (Brown et al., 2016).

Footnotes: Area: 0,8 m^2, adjusted to the functional unit (1 ton of fish mortalities out of annual 18.9 ton); **1–2.** Neglected inputs due to the extremely small area. **3–21.** Direct survey at the plant. **12.** Fish mortalities are here neglected since they represent the transformed object, similarly to patients is the hospital assessed by Cristiano et al. (2021). **13.** Considering 3 MJ per ton-km (European Environmental Agency, 2000), and an average heat value of 44 MJ/kg for diesel. **7.** Adjusted to the assumed lifetime of 15 years.

UEV references: **b.** After De Vilbiss & Brown (2015). **e.** After Cristiano et al. (2021), based on a large electric/electronic appliance of 125 kg. **f.** National Environmental Accounting Database (2014) (after Sweeney et al., 2007). **g.** Brown et al. (2011); for lubricant oil only, based on an assumed density of 0.9 kg/L. **i.** Paoli et al. (2008). **l.** Our calculation based on an original transformity by Fahd et al. (2011) and on an energy density of 1.77 kWh/L (Mardini & Bicer, 2021). **m.** Pulselli et al. (2014).

5. Conclusion

An Emergy Assessment (EMA) is presented here for the environmental appraisal of eco-intensification innovations for the treatment of aquaculture sludge and fish discards from a RAS smolt farm, as per a real production plant in Norway. This support to performance and alternative option meauserement is meant as to produce environmental information – under the form of indicators – to support more sustainable management. EMA results can be associated with those of a Life-Cycle Assessment of the same innovations at the same plant (Cristiano et al., 2022).

From the application of EMA to the sludge innovations it emerges that:

- The predominance of inputs related to fish feed and salmon eggs distorts the other results, suggests no significant improvement as a result of the assessed innovations; however, when this kind of inputs is virtually removed, savings may be noted up to – 88 % after the innovation is applied, requiring resource investments, mostly in terms of new machinery (+33 %) and increased net water use (+20 %), more than overcome by savings in fuel for by-product transportation (–98 %).
- Both the increased impacts related to water consumption and the dwarfing distortion due to fish feed were already detected in the LCA, while salmon eggs were not considered and new machinery played a minor role there.
- Trade-offs exist between saved requirements and invested requirements to allow for those savings, including new invested technology and net water use. Ethical and more comprehensive socio-economic considerations fall beyond the purposes of the current study. The size of these savings and additional requirements to invest are anyway dwarfed if the leading inputs in smolt production are accounted for; therefore, eco-innovation solutions ought to mostly tackle those inputs in future developments in aquaculture.

Table 6
Emergy Assessment of innovative fish mortality treatment and valorisation, with water as the cooling medium (scenario D).

#	Item	Unit	Raw amount per year	UEV (sej/unit)*	UEV ref.	Solar emergy (E + 10 sej/yr)
Local renewable inputs (R)						
1	Local renewables	–	–	–	–	–
Local nonrenewable sources (N)						
2	Topsoil	–	–	–	–	–
Imported material inputs (F)						
3	Water	m^3	10.8	1.00E + 11	[b]	108
4	GlycolLubricant oil	kg	–	6.27E + 12	[i]	–
5	(as Oil)Filter	L	1	5.76E + 12	[g]	576
6	(as Synthetic fibre)Machinery	kg	0.023	4.02E + 12	[m]	9
7	(as Large electric appliance)	kg	5.8	7.96E + 14	[e]	461,680
8	Structure material (as Grain digestate)Electricity, Norwegian mix	kg	80	1.10E + 13	[n]	88,000
9	(net after recovery)Fuel for new machinery transport	kWh	492	7.96E + 11	[f]	39,163
10	(Diesel)Fuel for by-product transportation	kg	1	6.40E + 12	[g]	640
11	(Diesel)	kg	23 $^{(D1)}$	6.40E + 12	[g]	14,400 $^{(D1)}$
		kg	7 $^{(D2)}$	6.40E + 12	[g]	4,276 $^{(D2)}$
		kg	33 $^{(D3)}$	6.40E + 12	[g]	21,033 $^{(D3)}$
12	Fish mortalities	kg	1,000	–	–	–
Labour and services (L&S)						
13	Labour, equivalent full time workersServices, water	item	0.0002	2.54E + 17	[f]	5,985
14	(free from adjacent power plant)	€	0	3.19E + 11	[f]	0
15	Services, glycol purchaseServices, lubricant oil purchase	€	–	3.19E + 11	[f]	–
16	(billed with #17)	€	0	3.19E + 11	[f]	0
17	Services, machinery investment amortisationServices, machinery	€	253	3.19E + 11	[f]	8,071
18	transport	€	0	3.19E + 11	[f]	0
19	(billed with #17)	€	28	3.19E + 11	[f]	893
20	Services, electricity	€	28	3.19E + 11	[f]	893
21	Services, structure material	€	35 $^{(D1)}$	3.19E + 11	[f]	1,117 $^{(D1)}$
	Services, by-product transportation	€	12 $^{(D2)}$	3.19E + 11	[f]	383 $^{(D2)}$
		€	50 $^{(D3)}$	3.19E + 11	[f]	1,595 $^{(D3)}$
22		€	8	3.19E + 11	[f]	239
	Services, filter purchase					
Total emergy input (U)				sej	no L&S	**6.11E + 15**
Total emergy input (ULS)				sej	with L&S	**6.29E + 15**
Percentage of labour and services in total emergy input (ULS)						**2.8 %**
Fish silage				kg		–
Dried by-product				kg		278
Condensate				kg		722
Hot water				m^3		10.8
Heat recovery potential (already computed in #9)				kWh		–736
Average bulk value of silage				€/kg		–
Average bulk value of dried by-product				€/kg		1.35
				€/kg		0.03
				€/kg	no L&S	0
Specific emergy of silage				sej/kg	with L&S	–
				sej/kg	no L&S	–
Specific emergy of dried by-product				sej/kg	with L&S	**2.20E + 13**
				sej/kg	with L&S	**2.26E + 13**
Emergy per currency of by-product, valorised as pet food ingredient				sej/€	with L&S	**1.67E + 13**
valorised as biomass at cement factory				sej/€	with L&S	**8.37E + 14**
valorised as biomass for gasification				sej/€		**N/A**

*Calculated or converted from other works according to the **GEB_{2016} of 1.2E + 25 sej** (Brown et al., 2016).

Footnotes: Area: 0,8 m^2, adjusted to the functional unit (1 ton of fish mortalities out of annual 18.9 ton); **1–2.** Neglected inputs due to the extremely small area. **3–21.** Direct survey at the plant. **12.** Fish mortalities are here neglected since they represent the transformed object, similarly to patients is the hospital assessed by Cristiano et al. (2021). **13.** Considering 3 MJ per ton-km (European Environmental Agency, 2000), and an average heat value of 44 MJ/kg for diesel. **7.** Adjusted to the assumed lifetime of 15 years. **9.** The net value is obtained after 736 of heat recovery potential in the RAS are subtracted to the input of 1,228 kWh.

UEV references: b. After De Vilbiss & Brown (2015). **e.** After Cristiano et al. (2021), based on a large electric/electronic appliance of 125 kg. **f.** National Environmental Accounting Database, Italy (2014) (after Sweeney et al., 2007). **g.** Brown et al. (2011); for lubricant oil only, based on an assumed density of 0.9 kg/L. **i.** Paoli et al. (2008). **l.** Our calculation based on an original transformity by Fahd et al. (2011) and on an energy density of 1.77 kWh/L (Mardini & Bicer, 2021). **m.** Pulselli et al. (2014).

From the application of EMA to the fish mortality and fish discard treatment innovations it emerges that:

- Resouce requirements, measured in emergy terms, decrease by two orders of magnitude after the selected innovations are applied, with abatements ranging between –93 % and –99 % in the selected emergy values.
- Results are conditioned by a dwarfing role of formic acid, only present in the reference scenario; on the one hand, this suggest that its removal has clear environmental consequences; on the other hand, the slight differences between the two alternative innovations assume a larger importance, with the reuse of cooling heat in the fish farm and the use of pure water as a cooling medium perform better than using a cooling mix, containing 70 % glycol, and without reusing that heat.
- The overall success of the innovations at hand, and in particular of the former, were previously found in the other environmental indicators that could be found after the LCA was applied, sometimes reaching a two order of magnitude, just as found in the present EMA.

Table 7
Emergy Assessment of innovative fish mortality treatment and valorisation, with cooling mix (scenario E).

#	Item	Unit	Raw amount per year	UEV (sej/unit)*	UEV ref.	Solar emergy (E + 10 sej/yr)
Local renewable inputs (R)						
1	Local renewables	–	–	–	–	–
Local nonrenewable sources (N)						
2	Topsoil	–	–	–	–	–
Imported material inputs (F)						
3	Water	m^3	0.005	1.00E + 11	[b]	less than1
4	GlycolLubricant oil	kg	2.2	6.27E + 12	[i]	1,379
5	(as Oil)Filter	L	1	5.76E + 12	[g]	576
6	(as Synthetic fibre)Machinery	kg	0.023	4.02E + 12	[m]	9
7	(as Large electric appliance)	kg	5.8	7.96E + 14	[e]	461,680
8	Structure material (as Grain digestate)Electricity, Norwegian mix	kg	80	1.10E + 13	[n]	88,000
9	(net after recovery)Fuel for new machinery transport	kWh	1,228	7.96E + 11	[f]	97,749
10	(Diesel)Fuel for by-product transportation	kg	1	6.40E + 12	[g]	640
11	(Diesel)	kg	23 $^{(D1)}$	6.40E + 12	[g]	14,400 $^{(D1)}$
		kg	7 $^{(D2)}$	6.40E + 12	[g]	4,276 $^{(D2)}$
		kg	33 $^{(D3)}$	6.40E + 12	[g]	21,033 $^{(D3)}$
12	Fish mortalities	kg	1,000	–	–	–
Labour and services (L&S)						
13	Labour, equivalent full time workersServices, water	item	0.0002	2.54E + 17	[f]	5,985
14	(free from adjacent power plant)	€	0	3.19E + 11	[f]	0
15	Services, glycol purchaseServices, lubricant oil purchase	€	4	3.19E + 11	[f]	137
16	(billed with #17)	€	0	3.19E + 11	[f]	0
17	Services, machinery investment amortisationServices, machinery	€	253	3.19E + 11	[f]	8,071
18	transport	€	0	3.19E + 11	[f]	0
19	(billed with #17)	€	36	3.19E + 11	[f]	1,148
20	Services, electricity	€	28	3.19E + 11	[f]	893
21	Services, structure material	€	35 $^{(D1)}$	3.19E + 11	[f]	1,117 $^{(E1)}$
	Services, by-product transportation	€	12 $^{(D2)}$	3.19E + 11	[f]	383 $^{(E2)}$
		€	50 $^{(D3)}$	3.19E + 11	[f]	1,595 $^{(E3)}$
22		€	8	3.19E + 11	[f]	239
	Services, filter purchase					
Total emergy input (U)				sej	no L&S	**6.71E + 15**
	Total emergy input (ULS)			sej	with L&S	**6.83E + 15**
	Percentage of labour and services in total emergy input (ULS)					**1.2 %**
	Fish silage			kg		–
	Dried by-product			kg		278
	Condensate			kg		722
	Hot water			m^3		10.8
	Heat recovery potential (already computed in #9)			kWh		–736
	Average bulk value of silage			€/kg		–
	Average bulk value of dried by-product			€/kg		1.35
				€/kg		0.03
				€/kg	no L&S	0
	Specific emergy of silage			sej/kg	with L&S	–
				sej/kg	no L&S	–
	Specific emergy of dried by-product			sej/kg	with L&S	**2.41E + 13**
				sej/kg	with L&S	**2.46E + 13**
	Emergy per currency of by-product, valorised as pet food ingredient			sej/€	with L&S	**1.82E + 13**
	valorised as biomass at cement factory			sej/€	with L&S	**9.10E + 14**
	valorised as biomass for gasification			sej/€		**N/A**

*Calculated or converted from other works according to the **GEB_{2016} of 1.2E + 25 sej** (Brown et al., 2016).

Footnotes: Area: 0,8 m^2, adjusted to the functional unit (1 ton of fish mortalities out of annual 18.9 ton); **1–2.** Neglected inputs due to the extremely small area. **3–21.** Direct survey at the plant. **12.** Fish mortalities are here neglected since they represent the transformed object, similarly to patients is the hospital assessed by Cristiano et al. (2021). **13.** Considering 3 MJ per ton-km (European Environmental Agency, 2000), and an average heat value of 44 MJ/kg for diesel. **7.** Adjusted to the assumed lifetime of 15 years. **9.** The net value is obtained after 736 of heat recovery potential in the RAS are subtracted to the input of 1,228 kWh.

UEV references: **b.** After De Vilbiss & Brown (2015). **e.** After Cristiano et al. (2021), based on a large electric/electronic appliance of 125 kg. **f.** National Environmental Accounting Database (2014) (after Sweeney et al., 2007). **g.** Brown et al. (2011); for lubricant oil only, based on an assumed density of 0.9 kg/L. **i.** Paoli et al. (2008). **l.** Our calculation based on an original transformity by Fahd et al. (2011) and on an energy density of 1.77 kWh/L (Mardini & Bicer, 2021). **m.** Pulselli et al. (2014).

Some common lessons may be learnt for other applications and researches in aquaculture and in other sectors. Besides the performances of the innovations at hand, it may be useful to keep in mind the primary role in terms of environmental impacts deriving from fish feed, fish eggs, and formic acid.

Ethical Statement

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

CRediT authorship contribution statement

Silvio Cristiano: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hallstein Baarset:** Data curation. **Christian Bruckner:** Data curation. **Johan Johansen:** Data curation. **Roberto Pastres:** Funding acquisition, Supervision, Conceptualization.

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.

Data availability

Data will be made available on request.

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References

Ahmed, N., Turchini, G.M., 2021. Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. J. Clean. Prod. 126604.

Ali, M., Cristiano, S., Geng, Y., Gonella, F., Ulgiati, S., 2021. Environmental assessment of healthcare facilities in the Global South–a case study from Pakistan. J. Environ. Account. Manage. 9 (03), 285–297.

Arvanitoyannis, I.S., 2008. ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste management for the food industries 97–132.

Aubin, J., Callier, M., Rey-Valette, H., Mathe, S., Wilfart, A., Legendre, M., Fontaine, P., 2019. Implementing ecological intensification in fish farming: definition and principles from contrasting experiences. Rev. Aquac. 11 (1), 149–167.

Baarset, H., & Johansen, J. (2019). Innovative processes for mortality disposal in aquaculture. *Deliverable 2.2. GAIN - Green Aquaculture INtensification in Europe*. EU Horizon 2020 project grant n°. 773330. 15 pp.

Baarset, H., Bruckner, C., Cristiano, S., Kreiss, K. (2021). Eco-efficient disposal of aquaculture mortalities. Deliverable 2.6. *GAIN – Green Aquaculture INtensification in Europe*. EU Horizon 2020 project grant n°. 773330.

Baarset, H. (2021). End-of-life scenarios for the dried products derived from aquaculture side-streams. Waister. Memo for partners' internal use dated 03 March 2021.

Badiola, M., Mendiola, D., Bostock, J., 2012. Recirculating Aquaculture Systems (RAS) analysis: main issues on management and future challenges. Aquac. Eng. 51, 26–35.

Beltran, A.M., Chiantore, M., Pecorino, D., Corner, R.A., Ferreira, J.G., Cò, R., Guinée, J. B., 2018. Accounting for inventory data and methodological choice uncertainty in a comparative life cycle assessment: the case of integrated multi-trophic aquaculture in an offshore Mediterranean enterprise. Int. J. Life Cycle Assess. 23 (5), 1063–1077.

Bergquist, D. A. (2008). *Colonised Coasts: Aquaculture and Emergy Flows in the World System: Cases from Sri Lanka and the Philippines* (Doctoral dissertation, Kulturgeografiska institutionen).

Bjørndal T., & Tusvik A. (2017). Land based farming of salmon: economic analysis. NTNU Working paper series No. 1/2017. ISSN 2464-3025. https://www.ntnu.no/documents/1265701259/1281473463/WPS+1+2017.pdf/6ee4cd65- e3b0-44a6-aa42-d017cb42d020 [retrieved May 28, 2021].

Bregnballe, J., 2015. Recirculation Aquaculture. An introduction to the new environmentally friendly and highly productive closed fish farming systems. www.fao.org/3/a-i4626e.pdf.

Brown, M.T., 2004. A picture is worth a thousand words: energy systems language and simulation. Ecol. Model. 178 (1–2), 83–100.

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38 (1), 1–22.

Brown, M.T., Protano, G., Ulgiati, S., 2011. Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. Ecol. Model. 222 (3), 879–887.

Brown, M.T., Campbell, D.E., De Vilbiss, C., Ulgiati, S., 2016. The geobiosphere emergy baseline: a synthesis. Ecol. Model. 339, 92–95.

Brown, M.T., Ulgiati, S., 2016a. Assessing the global environmental sources driving the geobiosphere: a revised emergy baseline. Ecol. Model. 339, 126–132.

Brown, M.T., Ulgiati, S., 2016b. Emergy assessment of global renewable sources. Ecol. Model. 339, 148–156.

Bruckner, C., Johansen, J., Ferreira Novio, M., Svenningson, L., Baarset, H., Conceição, L., & Soula, M. (2021). Eco-efficient solutions for reusing aquaculture side stream. Deliverable 2.5. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant n°. 77330.

Costanza, R., 1980. Embodied energy and economic valuation. Science 210 (4475), 1219–1224.

Cristiano, S., 2021. Organic vegetables from community-supported agriculture in Italy: emergy assessment and potential for sustainable, just, and resilient urban-rural local food production. J. Clean. Prod. 292, 126015.

Cristiano, S., Gonella, F., 2019. To build or not to build? Megaprojects, resources, and environment: an emergy synthesis for a systemic evaluation of a major highway expansion. J. Clean. Prod. 223, 772–789.

Cristiano, S., Zucaro, A., Liu, G., Ulgiati, S., Gonella, F., 2020. On the systemic features of urban systems. A look at material flows and cultural dimensions to address post-growth resilience and sustainability. Front. Sustain. Cities 2, 12.

Cristiano, S., Ulgiati, S., Gonella, F., 2021. Systemic sustainability and resilience assessment of health systems, addressing global societal priorities: learnings from a top nonprofit hospital in a bioclimatic building in Africa. Renew. Sustain. Energy Rev. 141, 110765.

Cristiano, S., Baarset, H., Bruckner, C., Johansen, J., Pastres, R., 2022. Innovative options for the reuse and valorisation of aquaculture sludge and fish mortalities: sustainability evaluation through Life-Cycle Assessment. J. Clean. Prod. 352, 131613.

David, L.H.C., Pinho, S.M., Garcia, F., 2018. Improving the sustainability of tilapia cage farming in Brazil: An emergy approach. J. Clean. Prod. 201, 1012–1018.

David, L.H., Pinho, S.M., Agostinho, F., Kimpara, J.M., Keesman, K.J., Garcia, F., 2021a. Emergy synthesis for aquaculture: a review on its constraints and potentials. Rev. Aquac. 13 (2), 1119–1138.

David, L.H., Pinho, S.M., Keesman, K.J., Garcia, F., 2021b. Assessing the sustainability of tilapia farming in biofloc-based culture using emergy synthesis. Ecol. Ind. 131, 108186.

De Vilbiss, C., Brown, M.T., 2015. New method to compute the emergy of crustal minerals. Ecol. Model. 315, 108–115.

European Commission, 2020. Oceans and Fisheries. retrieved June 1, 2021. https://ec.europa.eu/oceans-and-fisheries/ocean/blue-economy/aquaculture_it.

European Commission (2021). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Commitee of the Regions. Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN [retrieved June 1, 2021].

European Environment Agency. (2000). *Are we moving in the right direction?: indicators on transport and environment integration in the EU; TERM 2000*. European Environment Agency.

Fahd, S., Fiorentino, G., Mellino, S., Ripa, M., Ulgiati, S., 2011. Biorefinery implementation in marginal land – a focus on the multifuncional use of regional agriculture. Trends Future Sustain. Dev. 43.

FAO – Food and Agriculture Organization of the United Nations (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en.

Hagos, D.A., Gebremedhin, A., Zethraeus, B., 2014. Solar water heating as a potential source for inland Norway energy mix. J. Renew. Energy 2014. https://doi.org/10.1155/2014/968320.

Helfrich, L.A., Libey, G.S., 1991. Fish farming in recirculating aquaculture systems (RAS). Virginia Cooperative Extension.

Henares, M.N., Medeiros, M.V., Camargo, A.F., 2020. Overview of strategies that contribute to the environmental sustainability of pond aquaculture: rearing systems, residue treatment, and environmental assessment tools. Rev. Aquac. 12 (1), 453–470.

Henriksson, P.J., Guinée, J.B., Kleijn, R., de Snoo, G.R., 2012. Life cycle assessment of aquaculture systems—a review of methodologies. Int. J. Life Cycle Assess. 17 (3), 304–313.

International Salmon Farmers Association (2018*). Salmon farming – Sustaining communities and feeding the world.* https://sjomatnorge.no/wp-content/uploads/2018/06/ISFA-Report-2018-FINAL-FOR-WEB.pdf.

ISO – International Organisation for Standardisation (2006). ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework. https://www.iso.org/standard/37456.html.

Jasmin, M.Y., Syukri, F., Kamarudin, M.S., Karim, M., 2020. Potential of bioremediation in treating aquaculture sludge. Aquaculture 519, 734905.

Johansen, J., Bruckner C., Baarset, H., Soula M., & Conceição L. (2019). Innovative methodologies for reusing aquaculture side streams. Deliverable 2.1. *GAIN – Green Aquaculture Intensification in Europe*. EU Horizon 2020 project grant n°. 77330. 18 pp.

La Rosa, A.D., Siracusa, G., Cavallaro, R., 2008. Emergy evaluation of Sicilian red orange production. A comparison between organic and conventional farming. J. Clean. Prod. 16 (17), 1907–1914.

Le Féon, S., Dubois, T., Jaeger, C., Wilfart, A., Akkal-Corfini, N., Bacenetti, J., Aubin, J., 2021. DEXiAqua, a Model to Assess the Sustainability of Aquaculture Systems: Methodological Development and Application to a French Salmon Farm. Sustainability 13 (14), 7779.

Li, L., Lu, H., Ren, H., Kang, W., Chen, F., 2011. Emergy evaluations of three aquaculture systems on wetlands surrounding the Pearl River Estuary. China. *Ecological Indicators* 11 (2), 526–534.

Lima, J.S.G., Rivera, E.C., Focken, U., 2012. Emergy evaluation of organic and conventional marine shrimp farms in Guaraira Lagoon, Brazil. J. Clean. Prod. 35, 194–202.

Little, D.C., Young, J.A., Zhang, W., Newton, R.W., Al Mamun, A., Murray, F.J., 2018. Sustainable intensification of aquaculture value chains between Asia and Europe: a framework for understanding impacts and challenges. Aquaculture 493, 338–354.

Lunda, R., Roy, K., Másílko, J., Mráz, J., 2019. Understanding nutrient throughput of operational RAS farm effluents to support semi-commercial aquaponics: easy upgrade possible beyond controversies. J. Environ. Manage. 245, 255–263.

Maiolo, S., Cristiano, S., Gonella, F., Pastres, R., 2021. Ecological sustainability of aquafeed: An emergy assessment of novel or underexploited ingredients. J. Clean. Prod. 294, 126266.

Mardini, N., Bicer, Y., 2021. Direct synthesis of formic acid as hydrogen carrier from CO2 for cleaner power generation through direct formic acid fuel cell. Int. J. Hydrogen Energy 46 (24), 13050–13060.

Miller, B.I., 1964. A study of the filling of Hurricane Donna (1960) over land. Mon. Weather Rev. 92 (9), 389–406.

National Environmental Accounting Database (2014). *National Environmental Accounting Database, version 2.0.* http://www.emergy-nead.com/home (retrieved December 2022).

Odum, H.T., 1994. Ecological and General Systems: An Introduction to Systems Ecology. University Press of Colorado, Niwot CO.

Odum, H.T., 1996. Environmental accounting: emergy and environmental decision making. Wiley.

Odum, H.T., 2002. Emergy accounting. In *Unveiling Wealth*. Springer, Dordrecht, pp. 135–146.

Odum, H. T. (1983). Systems Ecology; an introduction.

Odum, H. T. (2001). Emergy Evaluation of Salmon Pen Culture. In: Microbehavior and Macroresults: Proceedings of the Tenth Biennial Conference of the International Institute of Fisheries Economics and Trade, July 10-14, 2000, Corvallis, Oregon, USA. Compiled by Richard S. Johnston and Ann L. Shriver. International Institute of Fisheries Economics and Trade (IIFET), Corvallis.

Oliveira, V.H., Dean, K.R., Qviller, L., Kirkeby, C., Bang Jensen, B., 2021. Factors associated with baseline mortality in Norwegian Atlantic salmon farming. Sci. Rep. 11 (1), 1–14.

Paoli, C., Vassallo, P., Fabiano, M., 2008. Solar power: an approach to transformity evaluation. Ecol. Eng. 34 (3), 191–206.

Pascal, C., 2015. Heat flow of Norway and its continental shelf. Mar. Pet. Geol. 66, 956–969.

Pulselli, R.M., Pulselli, F.M., Mazzali, U., Peron, F., Bastianoni, S., 2014. Emergy based evaluation of environmental performances of Living Wall and Grass Wall systems. Energ. Buildings 73, 200–211.

Raa, J., Gildberg, A., Olley, J.N., 1982. Fish silage: a review. Crit. Rev. Food Sci. Nutr. 16 (4), 383–419.

Raugei, M., Rugani, B., Benetto, E., Ingwersen, W.W., 2014. Integrating emergy into LCA: potential added value and lingering obstacles. Ecol. Model. 271, 4–9.

Shi, H., Zheng, W., Zhang, X., Zhu, M., Ding, D., 2013. Ecological–economic assessment of monoculture and integrated multi-trophic aquaculture in Sanggou Bay of China. Aquaculture 410, 172–178.

Sweeney, S., Cohen, M.J., King, D., Brown, M.T., 2007. Creation of a global emergy database for standardized national emergy synthesis. Emergy Synthesis 4, 483–497.

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., De Zeeuw, A., 2014. Does aquaculture add resilience to the global food system? Proc. Natl. Acad. Sci. 111 (37), 13257–13263.

Ulgiati, S., Brown, M.T., 2014. Labor and services as information carriers in emergy-LCA accounting. J. Environ. Account. Manage. 2 (2), 163–170.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1992. Emergy analysis of Italian agricultural system. The role of energy quality and environmental inputs. In: Bonati, L. (Ed.), Trends in Ecological Physical Chemistry. Elsevier, Amsterdam, pp. 187–215.

Vassallo, P., Beiso, I., Bastianoni, S., Fabiano, M., 2009. Dynamic emergy evaluation of a fish farm rearing process. J. Environ. Manage. 90 (8), 2699–2708.

Weatherspark (2021). Average weather in Inndyr, Norway. https://weatherspark.com/y/78277/Average-Weather-in-Inndyr-Norway-Year-Round [retrieved December 2021.

Wilfart, A., Prudhomme, J., Blancheton, J.P., Aubin, J., 2013. LCA and emergy accounting of aquaculture systems: Towards ecological intensification. J. Environ. Manage. 121, 96–109.

Williamson, T.R., Tilley, D.R., Campbell, E., 2015. Emergy analysis to evaluate the sustainability of two oyster aquaculture systems in the Chesapeake Bay. Ecol. Eng. 85, 103–120.

Wolf, D., Lundholm, J.T., 2008. Water uptake in green roof microcosms: Effects of plant species and water availability. Ecol. Eng. 33 (2), 179–186.

Zhang, H., Gao, Y., Shi, H., Lee, C.T., Hashim, H., Zhang, Z., Li, C., 2020. Recovery of nutrients from fish sludge in an aquaponic system using biological aerated filters with ceramsite plus lignocellulosic material media. J. Clean. Prod. 258, 120886.

Zhang, L.X., Ulgiati, S., Yang, Z.F., Chen, B., 2011. Emergy evaluation and economic analysis of three wetland fish farming systems in Nansi Lake area, China. *J. Environ. Manage.* 92 (3), 683–694.

Zhang, K., Yu, D., Xie, J., Wang, G., Yu, E., Gong, W., Liu, B., 2017. Emergy evaluation of largemouth bass (Micropterus salmoides) aquaculture system in the Pearl River Delta, China. *J. Fish. China* 41 (9), 1424–1433.