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THE ASSESSMENT OF AQUACULTURE SUSTAINABILITY BY MEANS OF LIFE CYCLE ASSESSMENT AND OTHER RESOURCE ACCOUNTING METHODOLOGIES

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Coordinatore del Dottorato
ch. prof. Enrico Bertuzzo

Supervisore
ch. prof. Roberto Pastres

Dottorando
Silvia Maiolo, matricola 956 302

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ABSTRACT

Life Cycle Analysis (LCA) allows to quantify the environmental sustainability of a product throughout its complete life cycle, from raw material extraction to the disposal process. In the framework of this doctoral thesis, the analysis has been applied to aquaculture (the farming of fish, molluscs or algae), a sector with a prominent role in the agri-food industry and characterised by a global growing trend.

Previous studies proved aquaculture to be more environmentally sustainable than other branches of animal husbandry, including for example the beef industry. However, aquaculture is a vast and heterogeneous sector and LCAs carried out so far show several gaps, both from a methodological point of view and as regards the number of production processes analysed. In this thesis, after a thorough analysis of the existing literature, LCA methodology has been applied to different production processes, focusing on fish species relevant in a national and European context. In one case, the environmental impacts were re-analysed adopting a complementary resource accounting tool, the emergy analysis.

LIST OF ACRONYMS

AP	Acidification Potential
AWARE	Available WAter REmaining per area
BRU	Biotic Resource Use
CED	Cumulative Energy Demand
CO_2	Carbon dioxide
DMB	Dry Microalgae Biomass
EP	Eutrophication Potential
FETP	Freshwater Ecotoxicity
FM	Fishmeal
FU	Functional Unit
GWP	Global Warming Potential
IC	Impact Category
ILCD	International Reference Life Cycle Data System (European Commission)
IM	Insect Meal
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoules
NPP	Net Primary Production
PBM	Poultry By-product Meal
PO_4^{3-}	Phosphate

SDGs Sustainable Development Goals

SETAC Society for Environmental Toxicology and Chemistry

SO_2 Sulphur dioxide

TETP Terrestrial Ecotoxicity

UNEP United Nations Environment Program

1,4-DCB 1,4-dichlorobenzene

ACKNOWLEDGEMENTS

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Chapter 1. INTRODUCTION

1. Aquaculture and LCA

From 1995 to 2016 aquaculture grew at an average annual rate of 6.6% (FAO, 2017) and in 2016 the world production reached 80.0 million tonnes (FAO, 2018), a quantity equal to the amount produced by fishery. Fishing activities are often far from being sustainable: while, since the late 1990s, fishery management in the developed countries significantly improved, the situation in the least developed countries is worsening and the fraction of world marine fish stocks that are within biologically sustainable levels declined from 90% in 1974 to 67% in 2015 (FAO, 2018). Aquaculture, besides reducing fishing pressure (and thus allowing the recovery of overfished stocks), makes fish available at low prices, affordable by the poorer segments of the community (NACA/FAO, 2001). Moreover, fish have a high capacity to satisfy the metabolic needs for proteins (FAO, 2018). As such, aquaculture products represent a viable solution to cope with protein deficiency which is, together with micronutrients deficiency, the most common form of malnutrition in low-income food-deficit countries (*e.g.* most of the countries in sub-Saharan African regions and in Central and South Asia, like Kazakhstan, Afghanistan and India) (FAO, 2001). The ongoing improvements in aquaculture techniques can further increase the production and thus help reaching the world's Sustainable Development Goals (SDGs), especially SDG 2 (End Hunger), SDG 3 (Good Health and Well-Being) and SDG 14 (Life Below Water). Still, this growing production trend has raised several concerns about aquaculture sustainability, in terms of both the availability of natural resources consumed and the amount of pollutants released into the environment. Consequently, the scientific community is focusing more and more on the quantification of aquaculture environmental impacts.

In this regard, Life Cycle Assessment (LCA) certainly represents a structured, comprehensive and internationally standardised method which allows both to identify critical aspects along a supply chain and to quantitatively compare the environmental performances of a product/process with alternative solutions (Wolf et al., 2012). LCA methodology was born in the 1960s as a tool to investigate packaging and waste management issues. For about 30 years its use has remained limited to these two sectors and LCA was finally brought to international attention during the late 80s (Baumman and Tillman, 2004). The growing debate about the applicability to other production sectors led to the organisation of international workshops and to the subsequent publication of the first Code of Practice for LCA studies (Consoli, 1993). From that moment on, the interest towards this method has grown more and more: the first ISO standard was developed only 4 years later (ISO, 1997) and the method started to be applied to other production sectors. Although the updated principles and framework of the procedure are described by ISO 14040: 2006 and ISO 14044:2006 standards, several publications have been released over the years by international organisations (*e.g.* SETAC and the European Commission) to guide the community of practitioners and to standardize the research approach. Among them, it is worth mentioning the set of guidance documents of the European Commission's Joint Research Centre (ILCD handbook[1]), the series of five volumes published by Springer (LCA Compendium – The Complete World of Life Cycle Assessment[2]) and the handbook of Guinée et al. (2002).

LCA started to be applied to the aquaculture sector quite recently, with the first publication dating back to 2004 (Papatryphon et al., 2004). Although it was proved to be more sustainable than most of the livestock and poultry productions (Nijdam et al., 2012), aquaculture is a vast and heterogeneous

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[1] Source: https://eplca.jrc.ec.europa.eu/ilcdHandbook.html
[2] Source: https://www.springer.com/series/11776

sector and many aspects of its sustainability are still little studied or unexplored.

2. Life Cycle Assessment methodology

The main concept behind LCA approach is that any product undergoes many changes (*i.e.* processes) all along its life cycle, thus it is connected to a very large number of flows. More specifically, LCA investigates and analyses these changes in terms of matter/energy resources (inputs) and products and wastes (outputs) involved in each process (Figure 1.1).

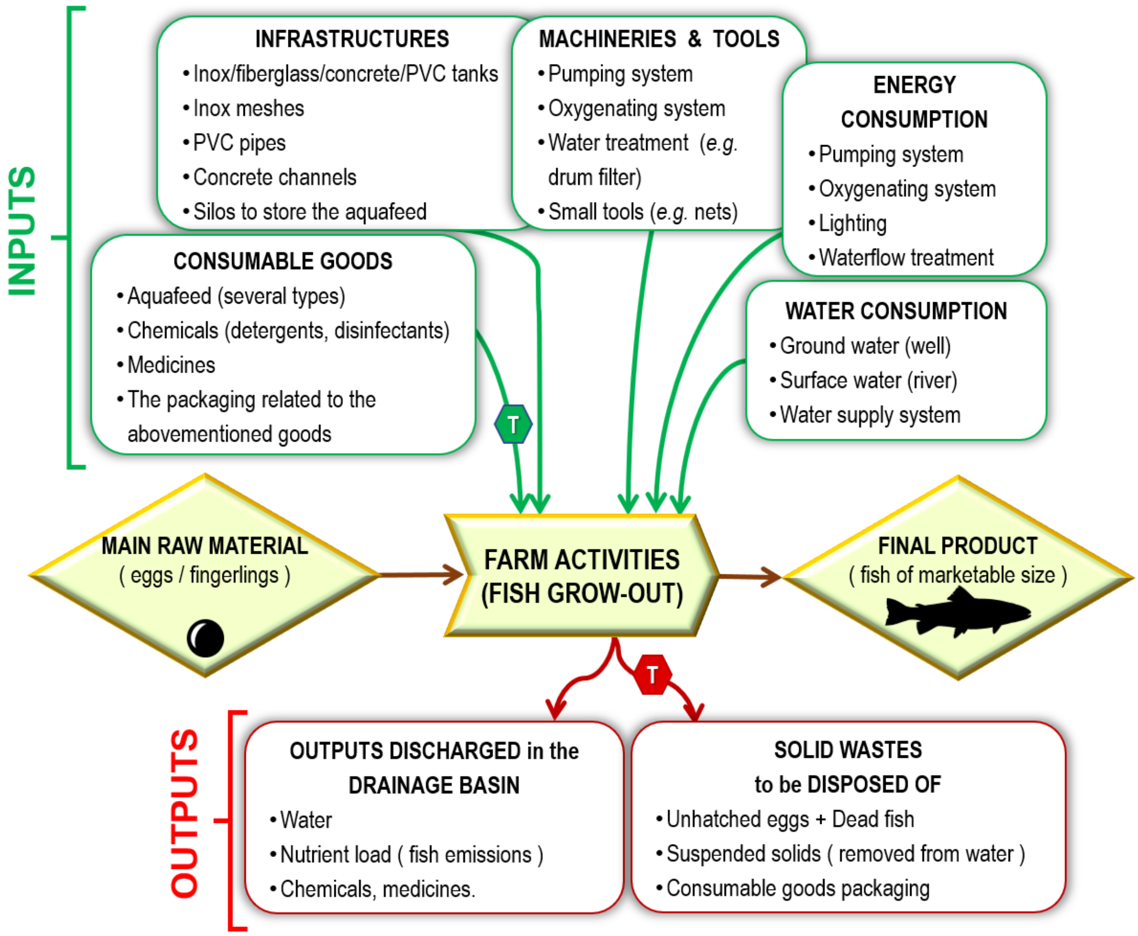

Figure 1.1 Fish grow-out process: the main raw material entering the farm (*i.e.* fish eggs) undergoes many changes (due to the farm activities) and eventually turns into the final product (*i.e.* fish of marketable size). Fish grow-out process is connected to a very large number of matter/energy resources (inputs) and waste products (outputs). T: transportation.

Once the model of the process is built, all the related flows are translated into a range of environmental impacts by means of mathematical models. Conventionally, the main phases of a product's life cycle are: raw material extraction, manufacturing/packing, use/maintenance, disposal (or recycling). Moreover, the transportation process should be considered each time the product is physically moved.

According to the ISO 14040: 2006 and ISO 14044:2006 standards, LCA includes four main steps:

Step 1. Goal and Scope

Both the purpose and all the methodological aspects of the analysis should be carefully chosen and clearly stated including, among the others, the setting of the system boundaries (*i.e.* which processes are considered in the analysis) and the reference unit (named functional unit) on which all the results will be scaled. The other crucial aspect is the selection of the impact categories (ICs), which should be appropriate to account for all the main consequences of the process on the environment: for instance, if a process releases greenhouse gases, the IC climate change must be taken into consideration. Every IC is described by a model, named 'impact pathway', which is subdivided into several consecutive steps and goes from the source of impacts (*i.e.* the environmental stressor) via quality changes to the environment (in the air, soil and water) up to the final impacts. The magnitude of each IC can be quantified by selecting, along the impact pathway, one among several alternative indicators, which are conventionally classified into mid-point and end-point indicators according to the position they occupy. With reference to the examples given above, a widely used indicator for the climate change IC is the mid-point indicator 'infra-red radiative forcing increase', expressed in terms of kg of CO_2 equivalent emitted into the atmosphere (Huijbregts et al., 2016).

Step 2. Life cycle Inventory

All the main input and output flows of matter and energy occurring along the studied process are identified, quantified and included in the list.

Step 3. Life cycle impact assessment

The inventory is processed according to the IC and the relative indicator chosen in step 1. In the mid-point approach, all the flows are classified and clustered according to the potential impact they may have on the environment. Then, all the flows contributing to the same impact are converted into quantities[3] having the same unit of measurement (*e.g.* kg of CO_2 equivalent emitted into the atmosphere) and then summed together. The resulting score is the mid-point environmental effect caused by the product with regards to the IC considered. A wide range of indicators is available at mid-point level[4]. An indicator is generally chosen by a practitioner at the point on the impact pathway where it is believed that further modelling would imply a too high degree of uncertainty or where it is possible to make a relative comparison without the need for further modelling (Finnveden et al., 2009). In the end-point approach, the entire impact pathway is taken into consideration. In this case, all these end-point indicators (such as particulate-induced effects on human beings or chemical-induced effects on nature) are usually aggregated into three 'areas of protection', which are physical elements considered worthy of protection by the society (Bare and Gloria, 2008). The areas of protection accepted by the international LCA community are: natural resources, natural environment,

[3] The flows are converted into a quantified impact on the natural environment, according to the indicator chosen to express this impact. More specifically, all the flows are multiplied by specific characterization factors, which are dimensionless numbers that expresses the impact caused by a given substance by relating it to the effect of the reference substance (which is, in the present exemplum, 1 kg of CO_2).

[4] For instance, the IC 'Aquatic Eutrophication' can be expressed in terms of Content of Degradable Organic Matter (as described in the CML-IA methodology), of Increased Nutrient Concentration (ReCiPe midpoint method), of Damage to Freshwater Ecosystems (ReCiPe endpoint method), and so on.

human health and, to some extent, man-made environment (Dewulf et al., 2015). If compared to the mid-point approach, the results of end-point approach are more uncertain, due to the further data processing[5]) but provide a comprehensive overview of the environmental consequences of the production process analysed. Therefore this approach is preferable for communicating LCA results to a generic public or to decision makers (Bare and Gloria, 2008).

Step 4. Interpretation of the results

The LCI and LCIA results are used to identify criticalities within the supply chain analysed (or to detect differences in the environmental performances of two alternative products). These findings are then interpreted by making reflections about, for instance, data consistency and results uncertainty. Finally, conclusions are drawn by highlighting limitations in the production process and by suggesting areas of improvement.

2. Research objectives and thesis outline

The first study conducted in the framework of this doctoral thesis is a critical review on aquaculture-related applications of LCA (**Chapter 2**). The purpose was both to become familiar with LCA methodology and to acquire information about the key issues of aquaculture-related LCAs. The literature search was carried out from 2017 up to the beginning of 2018 and focused on scientific papers published over the previous 5 years. The documents analysed were identified by using the same search string on Scopus and ISI-Web of Science databases and on Google Scholar web search engine. The thesis research line was developed according to the critical points highlighted by the literature review: the cascading effect of aquafeed on the environmental impacts of the entire supply chain; the different environmental impacts due to different farming

[5] See for instance: https://composite-indicators.jrc.ec.europa.eu/?q=10-step-guide

techniques; LCA methodological gaps in accounting for resource depletion.

More precisely: **Chapter 3** presents the results of an LCA on different protein sources, which could be used as partially substitutes for fishmeal within aquafeed formulations. **Chapters 4 and 5** provide new insights about the environmental performances of different fish-farming techniques: water flow-through systems and water recirculating system. More specifically, the focus was brought on a land-based freshwater system (trout production in raceways) and on an aquaponic system producing tilapia and lettuce. **Chapter 6** presents the results of an alternative accounting methodology, *i.e.* the emergy analysis, which was applied to the same production processes investigated in Chapter 3. Finally, in **Chapter 7**, conclusions are drawn in respect of the main results found.

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Chapter 2. LITERATURE REVIEW

1. Introduction

This chapter presents a comprehensive review of aquaculture LCAs which was carried out from 2015 up to the beginning of 2018. The purpose was both to become familiar with LCA methodology and to acquire information about the key issues of aquaculture-related LCAs.

At the time when this research was carried out, the two most comprehensive reviews dated back to 2013, with one paper comparing LCAs applied to farmed and wild-caught fish (Aubin, 2013) and the other one reviewing a dozen aquaculture-related LCAs until 2012 so to compare their approaches to different production systems and to examine the potential of LCA in setting criteria for certification and eco-labelling (Cao et al., 2013). Two older reviews (Henriksson et al., 2012; Vazquez-Rowe et al., 2012) focused on the methodological choices made in the aquaculture-based and fishery-based seafood production, respectively. None of the other studies published from 2013 to 2017 focused on more than one issue at a time.

Indeed, one publication tried to fill the gap related to water use in seafood supply chain (Gephart et al., 2017), while a year earlier one survey on seafood LCAs focused exclusively on the PPR impact (Primary Production Required) or its derivatives (Cashion et al., 2016) and another paper provided an insight of seafood LCA research focusing on evaluating fisheries management (Ziegler et al., 2016). Keeping going back over the years, Denham et al. (2015) analysed cleaner production strategies within the seafood industry, Pahri et al. (2015) went through many aquaculture systems so to find a way to overcome the influence of natural and anthropogenic factors and Avadì & Fréon (2013) summarized and discussed a series of studies that applied LCA approach to fisheries. Given the gap, an in-depth research on all the peer-reviewed studies published in the previous 5 years was performed.

2. Materials and methods

The research went through the recent LCA studies in aquaculture, including all the main types of aquatic products: fish, shellfish, seaweeds and microalgae from inland, marine and coastal farming. All the main related activities along their life cycle were taken into consideration.

The search was conducted by adopting the search string (‘LCA’ OR ‘life cycle assessment’) AND (‘marine culture’ OR ‘pisciculture’ OR ‘aquaculture’ OR ‘fish farm’ OR ‘fishfarm’) on Scopus and ISI-Web of Science databases and on Google Scholar web search engine. The timespan chosen ranges from 2013 to the end of 2017. The documents found – 166 publications – underwent a critical examination and the most relevant ones were included in this review. The subset of sources was selected according to the following criteria.

Fishing activities were not included in this review due to the fact that the last LCAs on fisheries were already reviewed and discussed in Ziegler et al., 2016. However, the boundary line between fisheries and aquaculture can be fuzzy and the two supply chains sometimes overlap. In these cases, only the production phases which are representative of the aquaculture field were included, as better explained below. The chosen researches had to be written in English, published on scientific journals and present original findings in terms either of methodologies or of case studies. Moreover, they had to provide thorough information concerning the methodological approach used: thus, most of the conference proceedings, reports and short communication papers were dropped, since they were not providing complete information about some details of LCA procedure.

A structured excel format was arranged to compare the following set of metrics for all the stages of LCA analysis: (i) the software used to assess the impacts; (ii) the farmed species, further subdivided into finfish, molluscs, crustaceans, microalgae & seaweeds; (iii) the geographical area where the production processes analysed are located; (iv) the production phase considered, namely aquafeed manufacturing, on-farm activities, manufacturing of both edible aquatic species and of other products (such as biogas production from microalgae); (v) the Functional Unit; (vi) the LCA databases from which background data were sourced; (vii) the System Boundaries; (viii) the allocation method used, if any; (ix) the impact assessment methods; (x) the impact categories, clustered irrespective of the indicator used to quantify them. Since the carrying out an LCA must be in compliance with the procedural guidelines described in the ISO standards (ISO 2006), the results of the present review are presented below accordingly.

3. Results

3.1 Overview of the selected subset of papers

Only 69 of the 166 documents found online (42% of the total) resulted to be consistent with the search parameters. Most of discarded documents: (i) assessed the potential environmental impacts by using methodologies other than the life cycle approach and mentioned LCA just incidentally; (ii) discussed aquaculture-related LCA as a marginal aspect of a wider life cycle research on other agrozootechnical productions. Almost all the resources came from a range of peer reviewed journals, although 3 scientific reports (Henriksson et al., 2014b; Ingólfsdóttir et al., 2013; Mungkung et al., 2014) were included too. Despite being the products of fishery activities, 4 studies on herring species (*i.e.* belonging to the *Clupeiformes* order) were included in the review: in one case (Avadí and Fréon, 2015) the research compared the sustainability of Peruvian anchoveta fisheries to that of freshwater aquaculture products; the other 3 papers were included since they centered the analysis around the manufacturing phase (Avadí et al., 2014; Laso et al., 2017; Vázquez-Rowe et al., 2014).

3.2 Goal

The goal of the found documents was to either compare different production systems or to identify strengths and weaknesses or to propose and test new methodological approaches. Within the studies which declared the species analysed, 11 studies focused on crustaceans (mainly the river prawn *Macrobrachium spp*. and the shrimp *Penaeus spp*.), 4 on molluscs (3 on *Mytilus spp*. and 1 on cockles, *Anadara granosa*), 5 on seaweeds, 3 on microalgae and 39 on finfish. The finfish species considered are better detailed in Figure 2.1 and were usually farmed in monoculture systems, being 9 polycultures (Astudillo et al., 2015; Aubin, Baruthio et al., 2015; Czyrnek-Delêtre et al., 2017; Henriksson, Zhang et al., 2014; Henriksson, Rico et al., 2015; Lazard et al., 2014; Nhu, Dewulf et al., 2015; Warshay et al., 2017; Wilfart et al., 2013) and 2 aquaponic systems (Boxman et al., 2017; Forchino et al., 2017) the only exceptions.

Fish and other aquatic organisms can be processed into either food or non-food products. 48 studies on-farm activities performed an LCA on species destined for human consumption. Among the remaining papers: 2 focused on microalgal farms aiming at recycling waste streams (Taelman et al., 2015b; Udom et al., 2013), 1 on the production of natural carotenoid astaxanthin by a farmed microalga (Pérez-López et al., 2014), 3 on biofuel production from seaweed (Aitken et al., 2014; Alvarado-Morales et al., 2013; Czyrnek-Deletre et al., 2017) and 1 on biofuel production within an Integrated Seawater Energy Agriculture System (ISEAS) combining aquaculture (tilapia and shrimp), agriculture and mangrove silviculture (Warshay et al., 2017). Finally, 4 studies investigated the processing of edible species and 6 focused on fish-feed production. Concerning the spatial distribution of researches (Figure 2.2), most studies targeted European (39%) and Asian (35%) production processes.

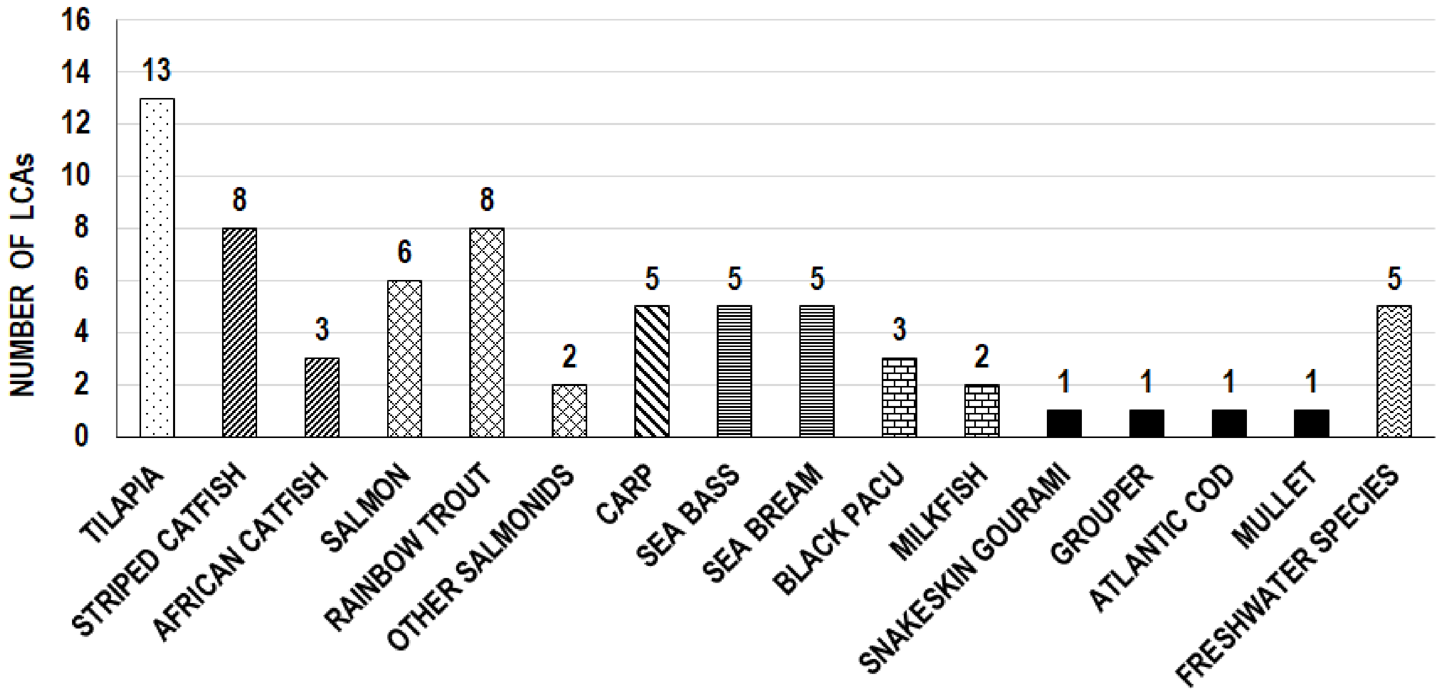

Figure 2.1 Finfish species analysed: number of occurrences. Details on species: TILAPIA (mainly *Oreochromis niloticus*); STRIPED CATFISH (*Pangasius hypophthalmus*); AFRICAN CATFISH (*Clarias spp.* + unspecified species); SALMON (*Salmo salar*); RAINBOW TROUT (*Oncorhynchus mykiss*); CARP (*Cyprinus carpio* or *Ctenopharyngodon idella*); SEA BASS (*Dicentrarchus labrax*); SEA BREAM (*Sparus aurata*); BLACK PACU (*Colossoma macropomum*); MILKFISH (*Chanos chanos*); SNAKESKIN GOURAMI (*Trichopodus pectoralis*); GROUPER (*Epinephelus spp.*); ATLANTIC COD (*Gadus morhua*); MULLET (unspecified); FRESHWATER SPECIES (tench, *Tinca tinca* – roach, *Rutilus rutilus* – perch, *Perca fluviatis* – sander, *Stizostedion lucioperca* – pike, *Esox lucius*, all belonging to a unique paper focused on polyculture ponds in France: Wilfart et al., 2013).

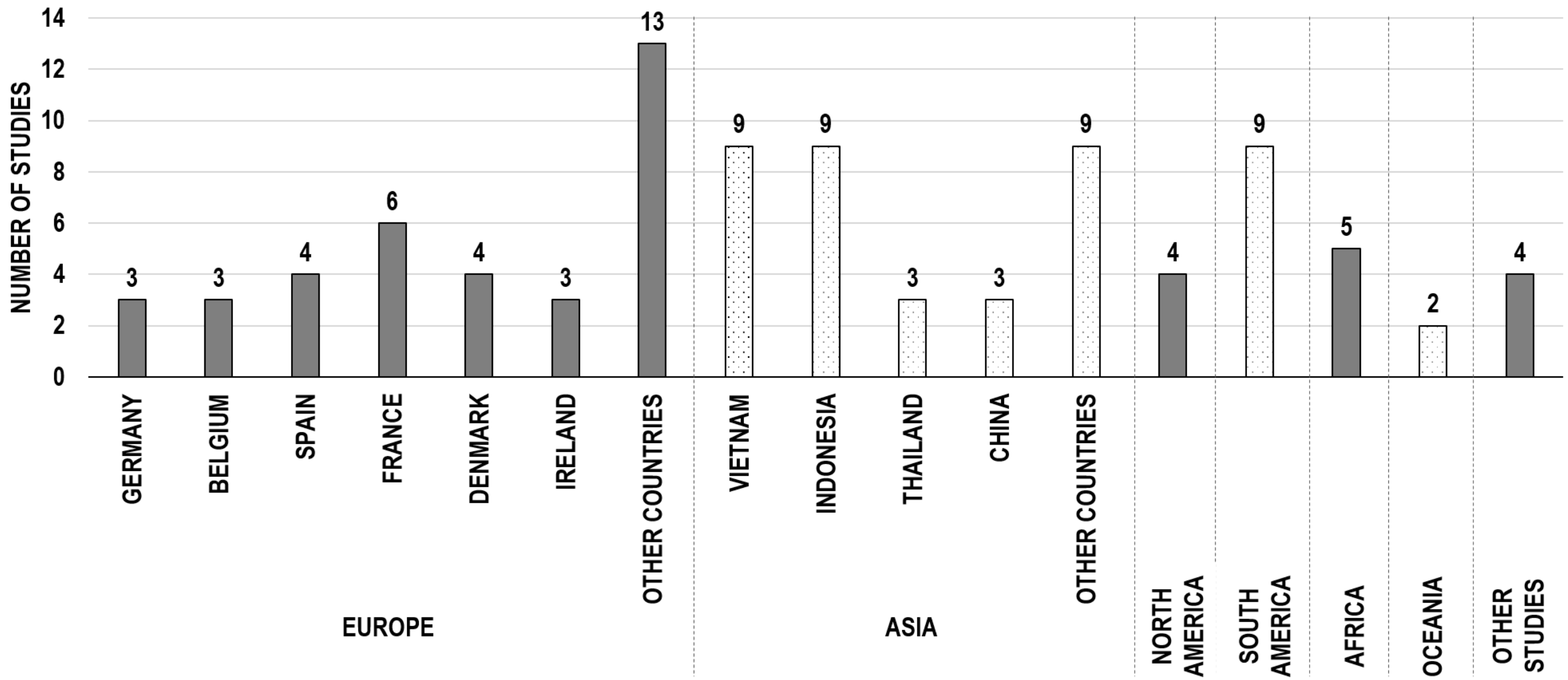

Figure 2.2 Spatial distribution of researches. 'Other countries': Cyprus, Iceland, Netherlands, Norway, Portugal, Sweden, Turkey, UK. 'Other studies': all the case-studies for which the location was not provided. Wherever two or more case-studies occurred within the same research, all of them were counted separately.

3.3 Scope

3.3.1 System Boundary

An accurate analysis of the system boundaries was not possible since the reviewed papers tackled production systems very different from one another (Figure 2.3), such as Philippine extensive pond polyculture systems in brackish water (Aubin et al., 2015) and Chilean macroalgae cultivation and processing into bioenergy (Aitken et al., 2014).

Moreover, the activities that – within each supply chain – can be included in the system boundaries are many and highly heterogeneous. Hence, a simple clustering into the main phases of the supply chain (and their combinations) was performed (see *Appendix*).

Generally speaking, 59 studies over 69 included on-farm activities within the boundaries: 55 of them analysed actually-existing farming facilities, while 4 took general data either from previous LCA studies (Farmery et al., 2015) or national/international databases and reports (Mungkung et al., 2014; Oita et al., 2016; Ziegler et al., 2013).

Pre- and post- farm phases are less represented (25 studies over 69), thus confirming the findings of a previous review (Cao et al. 2013): 6 of these papers examined in depth the aquafeed production up to the factory gate while 4 others focused specifically on post-farm activities (*i.e.* food manufacturing and transportation). Speaking of the formers, each of them investigated an important aspect of feed supply chain: (i) several types of fishmeal plants in Peru (Fréon et al., 2017); (ii) conventional and innovative feed ingredients (Basto-Silva et al., 2018; Henriksson et al., 2017b; Samuel-Fitwi et al., 2013a; Strazza et al., 2015), in one case even by adopting an unusual impact assessment methodology based on thermodynamic indicators (Draganovic et al., 2013).

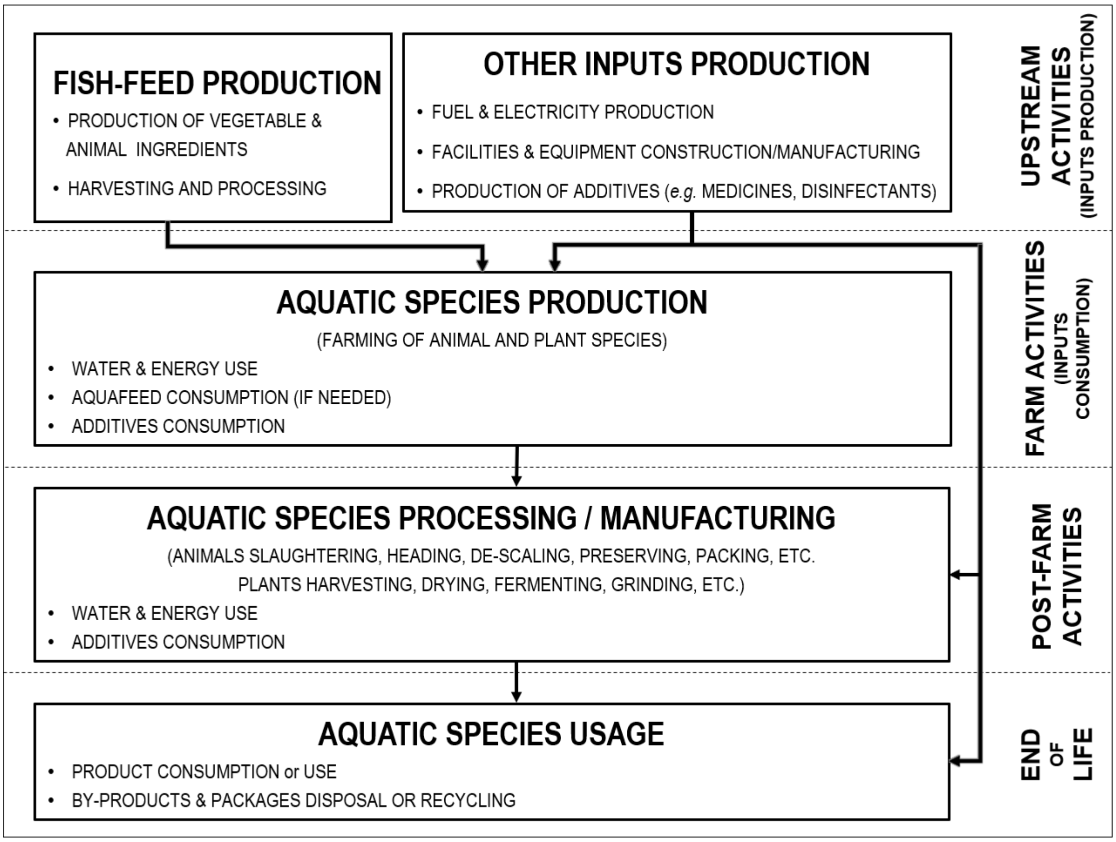

Figure 2.3 Main activities along the aquatic living resources supply chain. Arrows represent the Transportation process. Within the 'fish-feed production', 'animal ingredients' refers to either fish-captures or by-products from terrestrial livestock productions.

With regards to post-farm phase, confusion reigns over the definition of 'processing' and 'manufacturing', where the former should refer to activities such as the removal of fish head and gut and the cutting into steaks or fillets, and the latter includes subsequent processes such as preservation, packaging and labelling. The 'cradle-to-consumption' boundary was quite often used, but in these last years some interesting analyses on the 'End of Life' phase were performed too. For instance, (Spångberg et al., 2013) compared two alternative disposal scenarios for mussel shells along the Swedish coasts, in order to find out whether using cultivated mussels as fertilizer on agricultural land was more sustainable than the use of other common fertilizers. Mussel farming, transportation to the farm and the consequent treatment (composting or inertly storage under water, avoiding nitrogen losses and other emissions) were all comprised within the boundaries. A second study, targeting the sustainability of Spanish canned anchovies (Laso et al., 2017), focused not only on manufacturing processes but on the consumption and disposal of the product as well. More in the detail, it included in the analysis all the activities concerning canned anchovy transportation (from the canning factory to a logistic hub and finally to a supermarket), storage (both in small supermarket refrigerator and into household fridges), the consumption phase (which resulted to have a null environmental impact, being canned anchovies a ready-to-eat product) and finally the EoL (end of life) of the can and the cardboard box.

3.3.2 Functional Unit(s)

The Functional Unit (FU) should relate to the functions of the product rather than to the physical product. Anyway, in the aquaculture field these two aspects often coincide and thus the most common FU found was the liveweight animal biomass produced (Figure 2.4a), mainly expressed as kilograms or tons of live fish at farm gate (31 studies). The mass approach was also applied in 12 LCAs on the phases subsequent to the slaughtering (*i.e.* processing and manufacturing), in 5 researches on feed and in 3 on algae.

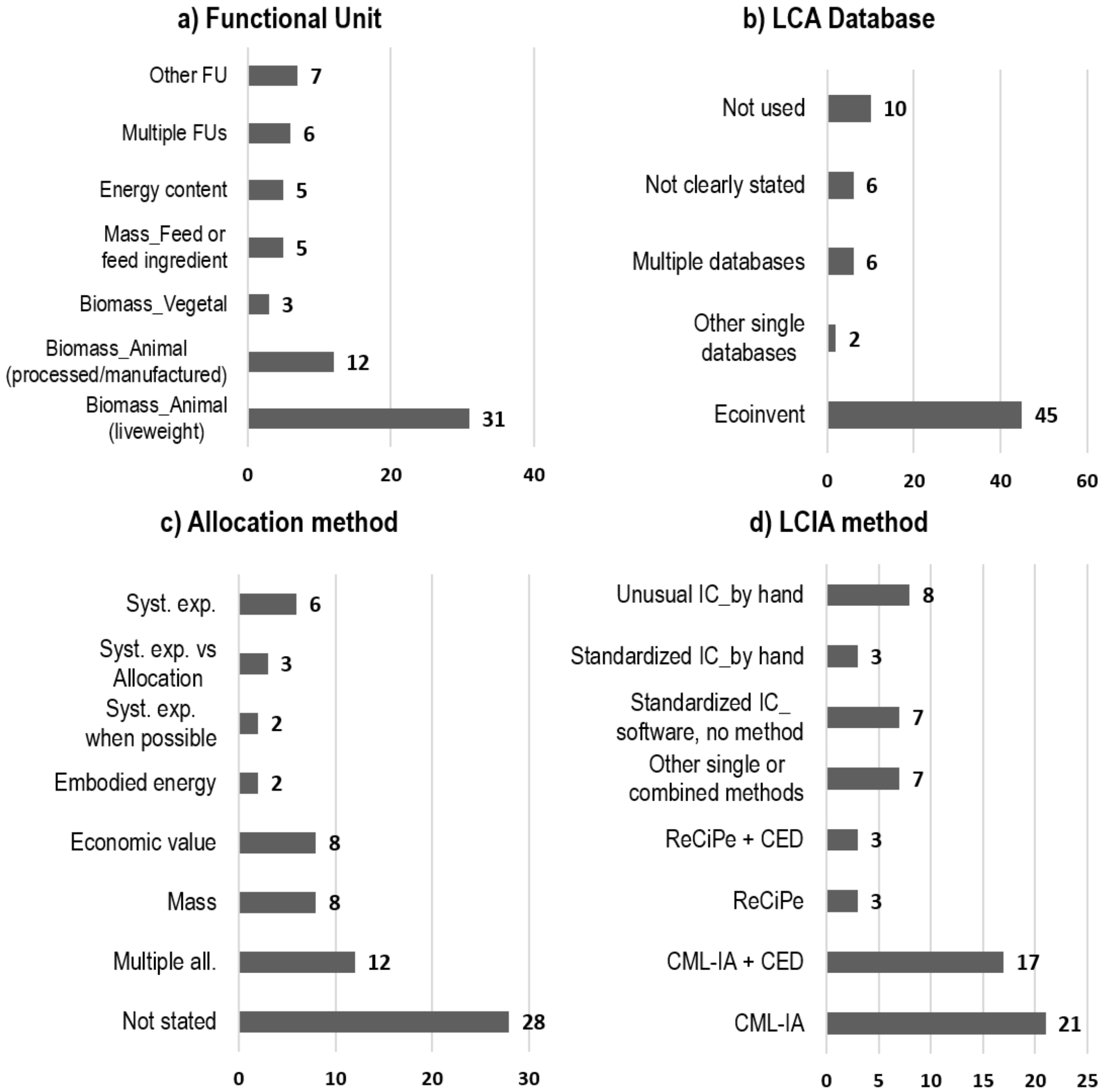

Figure 2.4 Main methodological choices. The x-axis represents the number of times a specific choice was found in the reviewed papers. Syst. exp.: System expansion. Multiple all.: Multiple allocation methods compared one another.

When energy-related FUs occurred (7% of the studies), they were related to ICs based on energy use: the exergy (MJex) embodied in the biomass was used as FU when assessing the environmental sustainability through the CEENE impact (Taelman et al., 2015a, 2015b, 2013); the energy content (MJ) either when calculating the EROI (Aitken et al., 2014) or when comparing alternative fuel sources to each other (biomethane from seaweed, gasoline and natural gas) (Czyrnek-Deletre et al., 2017).

Finally, 11% of the studies adopted less common solutions, such as the biomass entering the system, the amount of plant-available nitrogen produced, the amount of reactive nitrogen released into the environment due to the consumption of a species, 1 year of routine production.

3.4 Life Cycle Inventory (LCI)

3.4.1 Data sources

The activity of compiling the inventory represents one of the most demanding tasks in performing an LCA study, since it requires a quantification of all the flows of matter and energy moving into and out of the system boundary chosen. Primary data are usually collected through surveys and interviews with companies willing to collabourate. The collection of primary data, besides being time consuming, can be challenging when it requires the acquisition of information about: (i) upstream processes (such as the production of the main inputs used or the construction of facilities) since companies might have no information about them; (ii) certain management practices (such as the treatment of pollutant emissions or the type and quantity of detergents, disinfectants and medical products used) since they might be sensitive issues.

To fill gaps in the inventory, secondary data can be gleaned consulting specific LCA data sources such as the '*Ecoinvent*', which was used in 65% of the studies (Figure 2.4b). Among the other documents, 12% resorted to other databases – such as '*Agri-footprint*', '*ELCD*', '*LCA Food DK*' – alone or combined. 14% of the studies did not mention any LCA database but stated to have taken all the information needed from bibliography, reports, bio-socio-economic models or national statistics. Finally, 9% or the studies did not state the sources they took secondary data from.

3.4.2 System expansion and allocation

Sometimes, a production system can have more than one functional flow. In these cases, ISO standards support the expansion of the systems boundaries to include the alternative production of functions not used by the system itself. However, this procedure is not always feasible and LCA experts usually choose to proportionally share the overall impacts on two or more co-products by adopting an allocation strategy. The ISO guidelines support the use of physical allocation (either mass or gross chemical-energy content), which apportions the impacts to the mass and is an approach easily understandable by non-specialists. The economic approach is often used as well, and it consists in the apportioning of the environmental impacts to the monetary value of outputs (which is equal to the mass produced multiplied by its unit price).

Although the impact allocation can markedly affect LCA results, 41% of the studies (28 over 69) did no clearly indicated which allocation criterion was used (Figure 2.4c). On the other hand, 13% of the papers declared to have fulfilled a perfect system expansion and, within them, 3 studies compared LCA results to these obtained with different types of allocation (Astudillo et al., 2015; Laso et al., 2017; Samuel-Fitwi et al., 2013a). 2 more studies, which analysed several systems within the same research, stated to have performed the system expansion whenever possible (Henriksson et al., 2017c; Newton and Little, 2018). In 12 case-studies, multiple allocation approaches were used on the same process to compare the effects of this often-critical methodological choice and thus test the robustness of conclusions. Finally, a few adopted only one allocation method, in terms of mass (12%), energy (3%) or monetary value

(12%).

3.4.3 Useful software to perform the calculation

Concerning the tools available to automatically convert the inventory items into ICs, SimaPro software stands out as the most used one (41 of the reviewed studies), followed by CLMCA (7) and GaBi (3). In 11 researches it was decided to perform the calculations by hand using the original matrix approach, while in 5 others the choice made was not declared. The remaining 2 documents used open LCA and the IPCC Inventory Software.

The most commonly used LCIA methodology (Figure 2.4d) is by far the CML-IA (Guinée et al., 2002), applied in 38 studies, followed at a great distance by ReCiPe (Huijbregts et al., 2017) which was used 6 times. The ‘single issue’ methodology used to quantify the Cumulative Energy Demand (Frischknecht et al., 2007) was often used too (20 times), always paired with one of the two abovementioned methods. Other methods, such as the ILCD (European Commission, 2012), were less frequent. Finally, 10 papers performed LCA without either using or providing information about the assessment methodology, while 8 chose unusual ICs and assessed them by-hand.

3.5 Life Cycle Impact Assessment (LCIA)

3.5.1 Assessment methodologies: an overview

In LCIA phase, the emissions of hazardous substances and the extractions of natural resources are converted into impacts on the natural environment and, as already said in Chapter 1, the magnitude of each IC can be quantified by adopting one among (often) several alternative indicators. The results of our review on LCIA are shown in Figure 2.5.

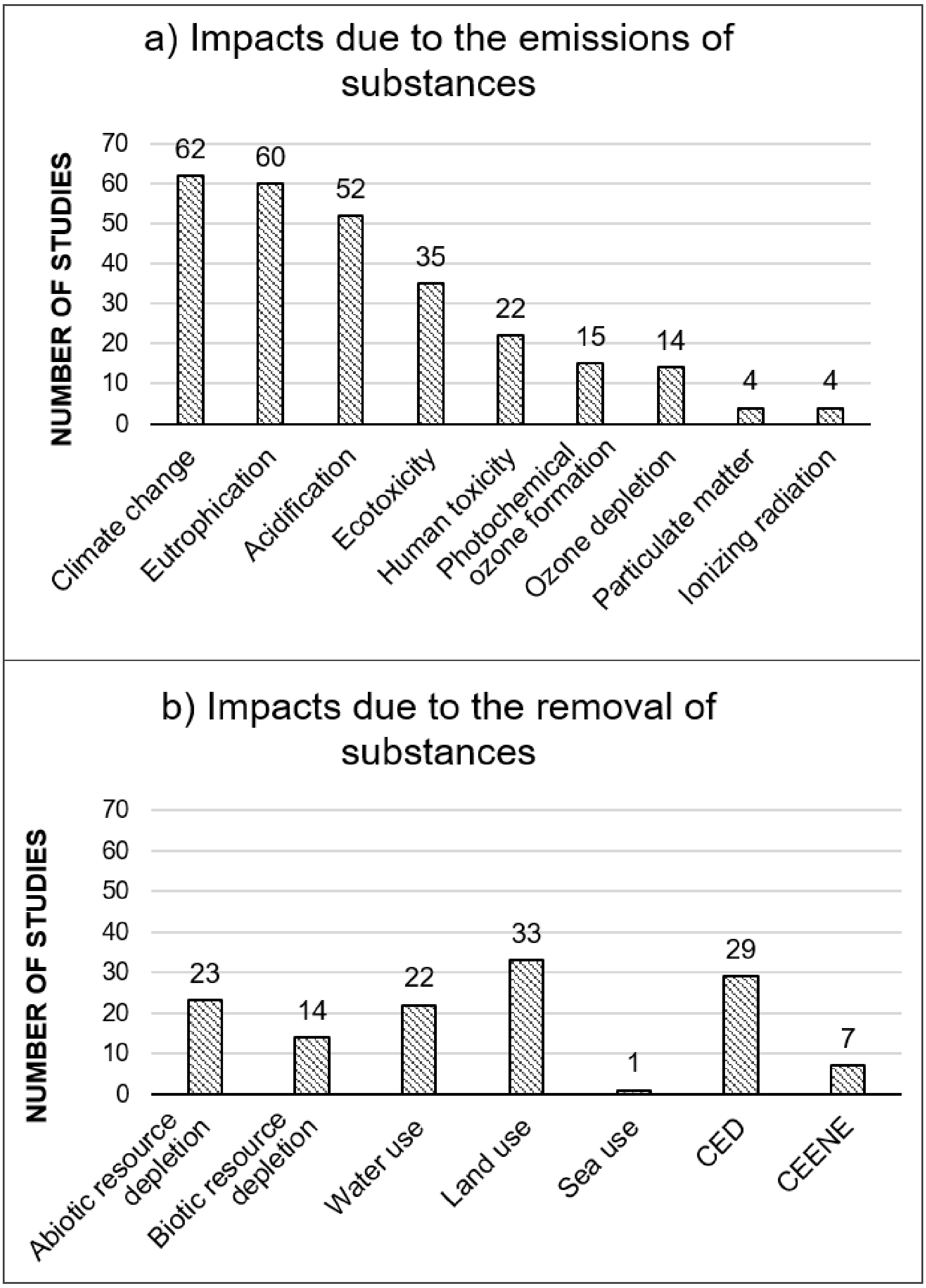

Figure 2.5 Main impact categories used. CED: Cumulative Energy Demand; CEENE: Cumulative Exergy Extraction from the Natural Environment.

Some LCIA methods that are not universally accepted and thus not included among the recommended ones by the European Platform on LCA (European

Commission, 2011) were included too. All the ICs were clustered into two groups according to the human activities that cause the impacts themselves, as better discussed in paragraphs 3.5.2 and 3.5.3.

3.5.2 Impacts due to the emissions of substances

Climate Change accounts for possible contribution of the process analysed to the global warming, which represents one of the major threat for the environment at a global scale and thus was included among the 17 Sustainable Development Goals (United Nations, 2015) as a priority concern to be tackled. It is related to the emissions of greenhouse gases to air and its characterization model, developed by the Intergovernmental Panel on Climate Change (IPCC), obtained international acceptance (European Commission, 2011). As a result, it was included in 62 case-studies over the 69 considered (Figure 2.5a).

Eutrophication assesses the impacts derived from an enrichment of macronutrients in natural ecosystems, with the difference in the characterization models between marine and freshwater eutrophication being the residence time of either nitrogen- or phosphorus-containing nutrients, respectively. With regards to aquatic species LCAs, these eutrophying agents can be released in terrestrial and aquatic ecosystems along the whole supply chain and they are mainly related to both feed ingredients production and to the metabolism of the farmed species. As a consequence, Eutrophication was considered 60 times over 69. Most of the time (36 studies) it was calculated with the characterization model available in the CML-IA methodology, which is based on the Redfield ratio between N and P (Redfield et al., 1963).

The characterization models for *Acidification* evaluate the presence of acidifying chemicals in atmosphere and soil as a result of airborne acidifying emissions. In other terms, these methods do not focus on aquatic effects since the acidification of inland water is seen as a consequence of the depletion of the acid neutralization capacity of its watershed. Being related to Climate Change, Acidification is the third most used IC in these studies (52 papers).

Ecotoxicity is a group of ICs assessing the potential impacts caused by emissions of toxic substances to air, water and soil. It was calculated by adopting either the USES-LCA model (according to Goedkoop et al., 2009) or the USEtox model of Rosenbaum et al. (2008), with the latter being developed under the UNEP–SETAC Life Cycle Initiative. It is worth saying that none of the studies which used the 'Ecotoxicity for marine ecosystems' applied it on offshore facilities (Avadí and Fréon, 2015; Ayer et al., 2016; Basto-Silva et al., 2018; Fréon et al., 2017; Henriksson et al., 2014b; Pahri et al., 2016; Pérez-López et al., 2014; Smarason et al., 2017; Vázquez-Rowe et al., 2014). This is in compliance with the advice given in the Declaration of Apeldoorn (UNEP/SETAC Life Cycle Initiative 2004), which states that "The oceans are deficient in essential metals. Therefore, additional inputs to the ocean will probably not lead to toxic effects. The characterization factor for toxicity in oceans of essential metals should be set at zero. For coastal seas, this may well be different."

The ICs *Ionizing radiation* and *Particulate matter formation* were considered 4 times each (Avadí and Fréon, 2015; Fréon et al., 2017; Henriksson et al., 2014b; Vázquez-Rowe et al., 2014) and always applied to the processing operations, in terms of either fish or fishmeal manufacturing. *Stratospheric ozone depletion* and *Photochemical oxidant formation* were used irrespective of the production processes analysed (*i.e.* feed production, fish mono- and poly-culture, algae farming, manufacturing, etc.). Most of times, no motivation for the choices taken was provided.

3.5.3 Impacts due to the removal of substances

Although a default assessment method to account for resource depletion does not exist, some indicators are particularly recommended (European Commission, 2011) and thus have been included among the available methods within LCA software. All of them are represented in Figure 2.5b under the label *Abiotic Resource Depletion*, which clustered together 13 studies using the methodology CML-IA, 8 adopting ReCiPe and 2 recurring to ILCD. In all these cases, the indicator used is related to extraction of non-renewable resources (fossil fuels and minerals) and can be expressed in many ways, such as the kg antimony equivalents per kg extraction, based on concentration reserves and rate of de-accumulation.

In regard to the *Biotic Resources* IC, it can be accounted in terms of human appropriation of the 'primary production'. The reason behind it is that this appropriation may prevent heterotroph species to be sustained by the carbon fixed in organic compounds by plants, and this would affect in turn the ecosystem health. The 'Primary Production Required' (PPR) was applied for the first time to marine products by Pauly & Christensen (1995). In that publication, PPR was used to estimate – through the calculation of target-species carbon content and the amount of energy lost through each trophic transfer – the net primary production required to yield an amount of marine biomass at a trophic level above primary production. Later, PPR also became a common IC linked to those terrestrial products which are used as inputs in aquaculture, such as crops and livestock products (Papatryphon et al. 2004).

This IC was given different names through the years, with the generic term 'Biotic Resource Use' (BRU) usually applied irrespective of the aquatic product origin (either aquaculture or fishery) and 'Net Primary Production use' (NPP-use) used only in relation to aquaculture studies (Cashion et al. 2016). With regards to the here reviewed 13 studies, the 9 publications which opted for

NPP-use were always related to on-farm aquaculture productions (Abdou et al., 2018, 2017; Aubin et al., 2015; Chen et al., 2015; Lazard et al., 2014; Medeiros et al., 2017; Mungkung et al., 2013; Santos et al., 2015; Wilfart et al., 2013). The remaining 4 studies used the term BRU to account for the environmental impacts related to pre- or post- farm activities (*i.e.* fish-feed production and fish-food manufacturing) (Avadí et al., 2015, 2014; Avadí and Fréon, 2015) with the only exception being the study of (McGrath et al., 2015), which performed a comparison between two different salmon rearing facilities. Finally, one study (Mungkung et al., 2014) accounted for the depletion of wild fish stocks simply in terms of metric tons of wild fish converted into feed and required to support the aquaculture system.

Water Use is another controversial IC, used in 22 papers. Although being a sub-category of *Abiotic Resource Depletion*, which was discussed above, it is usually treated as a separate IC (European Commission, 2011).

The most prominent approach to account for *Water Use* was the '*Water Dependence'* indicator, applied for the first time in Aubin et al. (2009). This indicator simply considers a hydric use in terms of a temporary 'loan' of water resources: no actual consumption occurs (or is taken into consideration in the studies), neither in terms of evaporation nor because of product integration or discharge into different watersheds. For instance, in land-based fish-farming systems, this indicator accounts for the volume of water removed (by diverting or pumping) from a natural body, which eventually returns to the watershed after having flown through the production system. Of the 9 papers assessing it: 6 applied this method to inland aquaculture farms (Chen et al., 2015; Dekamin et al., 2015; Medeiros et al., 2017; Mungkung et al., 2013; Santos et al., 2015; Wilfart et al., 2013); 2 papers applied it on both inland and sea farming production (Lazard et al., 2014; Mungkung et al., 2014); 1 research (Aubin et al. 2017) used it for the analysis on a mussel processing system, where seawater was pumped from and then returned to the sea without receiving treatments.

Most of the remaining studies opted for a consumption-to-availability ratio approach and accounted for *Water Use* in terms of *'Freshwater Consumption'*, also termed Consumptive Water Use or simply Water Use (see Boxman et al. 2017). This indicator is used as a proxy of the water consumed by the system and thus made unavailable for other uses and it is expressed as the share of gross consumption in the available renewable water resource, usually including in the assessment Country-specific characterization factors. Applied in 12 studies, it accounted once for the evaporated water from a recirculating aquaponic system (Boxman et al., 2017). In the other cases, it highlighted water consumption magnitude occurring either in inland fish farms (mainly ponds) (Henriksson et al., 2017a, 2017c) or in the phases of feed ingredients production and food manufacturing (Avadí et al., 2015, 2014; Avadí and Fréon, 2015; Fréon et al., 2017; Henriksson et al., 2017b; Ingólfsdóttir et al., 2013; Newton and Little, 2018; Strazza et al., 2015; Vázquez-Rowe et al., 2014). Finally, one study (Mendoza Beltran et al., 2017) applied the 'Water Footprint' concept of Mekonnen and Hoekstra (2011) in order to investigate impacts due to fish-feed production and wastewater treatments (*e.g.* wastewater from ice making) in a sea cage farming system. However, it only considered the blue water footprint, thus making its approach comparable to the 'Freshwater Consumption' above described.

Land Use (expressed as m^2 yr^{-1}) was mainly performed with the ReCiPe LCIA methodology – in terms of either land occupation or natural land transformation – and it was generally applied to case-studies that have feed production included in their system boundaries, due to the expected impacts derived from crop ingredient farming and harvesting. In some instances (like Abdou et al., 2017a, 2017b), this IC was assessed through the CML method in terms of Land Use Competition (LUC). In some others (for instance in Mendoza Beltran et al. 2017), Land Use was accounted just in terms of physical occupation (m^2), without using a specific characterization model. A case-study about sea-cages aquaculture in Tunisia (Abdou et al., 2017) adopted the *'Sea use'* IC, whose characterization model was designed for an application in the fishery-related context (Langlois et al., 2014, 2015). *'Sea use'* directly derives from the IC Land Occupation and accounts for seabed destruction and transformation caused by aquaculture activities (m^2 yr^{-1}). More specifically, it includes not only the surface occupied by the farm, but also the seabed area which is: (i) affected by farming activities through a particle-tracking model which predicts the deposition of farm solid matter on seabed; (ii) impacted by fishing activities (necessary for production of fish meal and fish oil) in terms of the area swept by fishing equipment.

The *Cumulative Energy Demand* (CED) is a measure of the energy consumption and it accounts for the use of energy at each step in the supply chain, thus including both direct and indirect consumption. This IC was considered within 29 studies, all focusing on different parts of the supply chain.

The *Cumulative Exergy Extraction from the Natural Environment* (CEENE), proposed for the first time in Dewulf et al. (2008), was applied here in 7 papers, all related to the EnVOC group (Ghent University, Belgium) and to Dewulf himself. CEENE remediates the shortcomings of the other resource-oriented method *Cumulative Energy Demand*: while the latter simply accounts for resources which may be used as energy carriers, CEENE is a most comprehensive resource indicator and it evaluates in addition non-energetic resources – like water, minerals, and metals – and land occupation. As a consequence, the 'energetic' approach highlights inefficient processes, while the 'exergetic' one quantifies the ability to cause change (being the exergy intended as a measure of the maximum amount of useful work that a resource can provide). The CEENE method distinguishes 8 different resources withdrawn from the natural environment and it expressed them in one common unit (Joules of exergy, Jex) that is physically interpretable and obviously stable with time. In regard to the reviewed documents, 3 studies investigated microalgae and seaweed cultivation systems in Europe, while 4 focused on Vietnamese productions of either pangasius (including both monoculture farming activities and the processing phases) or snakeskin gourami (within a multi-trophic aquaculture system).

3.5.4 Other sustainability indicators

Although it is not in the objective of this review to go deeply into biophysical accounting techniques other than LCA, such as energy efficiency, nutritional profiling and socio-economic performance, it is our belief that a quick mention to a couple of them might give food for thought.

In the first place, 2 studies performed an LCA on their systems just to assess the IC *Cumulative Energy Demand*, which in turn was used as denominator in the formula for computing the *Energy Return on Investment* (EROI). EROI was finally used to: (i) assess the sustainability of several fisheries and freshwater aquaculture industries in Peru (Avadi and Fréon, 2015); (ii) better investigate bioenergy production from macro-algae, considering both the cultivation phase and the processing into biofuel (Aitken et al., 2014).

The study of Draganovic et al. (2013) on salmonid fish-feed ingredients can be considered as an LCA borderline case. The research was based on the idea that the environmental sustainability of vegetable ingredients is not always superior to that of animal sources. Therefore, all the production phases involved in fish-feed production were included – namely ingredients production (*i.e.* fishing activities; crop cultivation and harvest), ingredients processing, feed manufacturing – and the impacts of different feed formulations were investigated using three *thermodynamic indicators*: (i) total energy consumption of the whole supply chain; (ii) total exergy degradation; (iii) total work energy including eco-exergy (work energy[iee]) degradation.

A new method was proposed by Oita et al. (2016) to assess *Nitrogen Footprint* (NF) caused by seafood consumption. The starting assumption was that the excess of nitrogen in the natural environment is mainly due to the fertilizers used in crop farming and to animal and human waste produced as a consequence of food consumption. Consequently, consumers' food choices have major effects on nitrogen impact. The consumer-based NF model made a distinction between fed and non-fed aquaculture systems and it was then compared with the ordinary model of (Leach et al., 2012), that provides information on how individual and collective action can result in the loss of Nr to the environment using Country-specific average per capita data on food and energy consumption.

Human labour was accounted in two case-studies. The first one analysed a Chinese dyke-pond system (Astudillo et al., 2015) by applying an idea dating back to (Giampietro and Pimentel, 1990), which consists in the expansion of the system boundaries so to account for inputs (such as food, clothes, housing) necessary to support human labour. Since this approach requires a huge effort in collecting background data, researchers opted for a simplified method and limited the impacts from labour to the energy consumed by workers to perform their specific tasks (with the energy required to meet base metabolic needs included in the calculation). Workers' energetic needs were then converted into the requisite amount of food they had to ingest – formulated according to Chinese diet – and included as input in the life cycle inventory. A different approach was adopted to analyse a Philippine extensive pond polyculture system in brackish water (Aubin et al., 2015), where human labour was accounted as the number of working days (made of 8 hours each) required to produce one ton of products. The calculation included all the main activities along the supply chain, from the production of fry at a hatchery or their catching from nature to the farm operations up to the harvesting and transportation to auction markets.

It is finally worth mentioning an attempt to *geo-localize* the impacts (Newton and Little, 2018). LCA study analysed Scottish salmon supply chain, structured in feed production, farm operation and salmon processing. Efforts were made both to detail – at each point in the value chain – the characteristics of the local environment where the emissions occurred and to represent geographically the impacts found by combining LCA with GIS methodology.

4. Discussion

4.1 Goal

Only 42% of the papers found on the scientific databases resulted to be consistent with the aim of the review. This finding reveals a frequent use of an ambiguous terminology in scientific literature on environmental sustainability, where words as 'LCA' are often mentioned in paper abstracts although being not performed below within the study.

Speaking of the 69 papers selected, the research effort seems to be rather well distributed among the main aquatic groups of species and quite consistent with a recent FAO report (FAO, 2017), which stated – for the year 2015 – a world aquaculture production clearly dominated by finfish farming (49%), followed by aquatic plants (27.7%), crustacea and molluscs (22.5%), and finally other aquatic animals such as sea urchins and frogs (0.8%). However, the comparison highlights a lower contribution to knowledge in aquatic plants LCAs. Always according to the reviewed literature, the main groups of finfish species produced from inland, marine and coastal aquaculture differ among continents but – looking at them at a global scale – tilapia (mainly *Oreochromis niloticus*), catfish (mainly *Pangasianodon hypophthalmus*), salmon and trout stand out as the most studied group. These findings reflect the economic interest for these groups of animals, known to be among the main drivers of global demand and consumption thanks to the shift from being primarily wild-caught to aquaculture-produced (FAO, 2016), a condition which in turn cause their prices to decrease and foster their commercialization. While salmonids are already a commodity in developed Countries, tilapia and catfish are becoming more and more important on the global market only in recent times, with a global production in 2014 reaching 3670, 237 and 386 thousand tonnes for the Nile tilapia (*Oreochromis niloticus*), the North African catfish (*Clarias gariepinus*) and the striped catfish (*Pangasius hypophthalmus*) respectively (FAO, 2018a). Tilapia is definitely a popular product in the United States retail sector, the largest market for this species, with the Asian and the Central America countries being the main suppliers (FAO, 2016).

Results on the spatial distribution of researches prove the increasing attention toward Asian production, neglected by the scientific community for a long time (Huysveld et al., 2013) although accounting for 89% of the global production (FAO, 2016). The importance of Asian aquaculture is even higher in a life cycle perspective, since in these regions farming practices are often less efficient than in Europe, thus leading to higher negative impact on the natural environment per production unit. Always with regard to Asian production, it is here important to mention the EU FP7 SEAT (Sustaining Ethical Aquatic Trade) project (Henriksson et al., 2014b, 2015), aiming at establishing an evidence-based framework to support stakeholder dialogues organized by third party certifiers. The project activities included detailed LCA studies on 4 farmed aquatic products (namely *Oreochromis spp*., *Pangasius spp*., *Penaeid spp*. shrimp species, *Macrobrachium spp.* freshwater prawn species) in China, Thailand, Vietnam and Bangladesh, being all major producing countries. At a continent level is also interesting to notice how low was Canadian and United States contribution to the body of knowledge in these last years: in fact, North America rates fifth in a global perspective, accounting for only 5% of the scientific production here reviewed.

4.2 Scope

With regards to the Functional Unit chosen, the live-weight biomass is surely the easiest unit to be measured but it hardly allows meaningful comparisons among organisms of different species. This is particularly the case of aquatic species having a high 'left over / live weight' ratio due to a substantial amount of trimmings and offal (such as Atlantic cod, pollack and saithe, all belonging to the *Gadidae* family). Molluscs present a similar problem, since the FU is often expressed as the total wet weight including the shell (Lourguioui et al., 2017; Pahri et al., 2016). A solution could be the one adopted by (Aubin et al., 2017) in which, after running a first LCA on 1 ton of packed 'ready-to-cook' mussels (chosen as FU), the whole analysis was rescaled on 1 ton of edible protein in order to compare the assessed impacts with those of different types of animal production. However, the conversion of the live-weight biomass into its relative edible yield without including in analysis detailed information about the manufacturing phase (*e.g.* the removal of fish offal, bones, skin, shell, etc.) might lead to an underestimation of the overall impacts. Thus, a sensitivity analysis on the functional unit would be recommended, as done in the study of Ingólfsdóttir et al. (2013) on salmon supply chain. Concerning the adoption of an energy-related FU, it was justified by the need to compare alternative fuel sources to each other (biomethane from seaweed, gasoline and natural gas). In the other cases it was necessary in order to calculate sustainability indicators related to either energy content (EROI indicator) or exergy content (CEENE indicator).

Although the processes which are included within the system boundaries were very heterogeneous, it was observed a focus on the farming phase. This is not surprising at all since, from an LCA perspective, the impacts derived from on-farm activities are generally much more important than those due to the processing and packing (Pelletier and Tyedmers, 2010). Besides, the final phases of the production are often similar to these of other agrozootechnical products and thus less representative of the specific seafood production system analysed. Since the effects of aquaculture activities on the natural environment are largely due, as for most livestock production, to both the aquafeed production (pre-farm phase) and use (on-farm phase) (Aubin, 2013; Smárason et al., 2017), aquafeed is widely regarded as becoming a major constraint to the growth of fed-species production in many developing countries. Actually, half of the world aquaculture production (by volume) is realized by farming species which do not require to be fed (FAO, 2016), with the most important non-fed animal species being bivalve molluscs, two freshwater finfish species (namely silver carp and bighead carp) and other filter-feeding animals (such as sea squirts) in marine and coastal areas. However, the farming of all the other aquatic species bears the weight of aquafeed production and use, thus it was positive to find a noticeable research effort towards the inclusion of these phases within the boundaries (see *Appendix*).

A frequent omission of information about the <u>data sources</u> used still persists, although having being already highlighted in the review of Henriksson et al. (2012) as an often neglected crucial point. Concerning data quality, the most abundant the primary data are (especially those about upstream processes), the less assumptions have to be made, the most robust the analysis is. However, the use of databases in order to get secondary data was not always stated clearly. Always speaking of the methodological choices, information about the approach adopted to handle <u>the problem of multi-products systems</u> was often disregarded too. 41% of the studies did no clearly indicate which allocation criterion was used, thus a higher transparency in the methodological choices made should be advisable. Since most of these papers analysed single-product systems (*i.e.* either monoculture farming systems or feed manufacturing productions) they probably managed to avoid allocation in the foreground system, but allocation might have been necessary in background processes. Although a sensitivity analysis (*i.e.* the comparison of the results obtained by adopting different choices) should be always performed when system expansion is not possible, several studies (26%) adopted only one allocation approach. The sensitivity analysis is always advisable since, when the by-product represents a consistent part of the total mass or energy produced, physical allocation may cause an unbalanced distribution of the environmental burdens. On the other hand, economic allocation is preferred by those who argue that industrial production systems are driven by the social preferences (*i.e.* the main product produced is the economical motivation of the whole production system under study). However, this approach may cause a magnification in the differences between valuable and low-price products in terms of environmental impacts. Moreover, the results are inevitably linked to prices fluctuation in time – due to changes in demand on the market – and in space (*i.e.* region or Country-specific prices).

Since these two methodological choices can markedly affect LCA results, a lack of information about them makes it difficult to interpret the studies and, moreover, negate the chance of a prospective comparison among papers.

4.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment phase, besides carrying the weight of all the above-mentioned methodological choices, requires further care in the decisions to take. Aquaculture activities can affect biodiversity in both a positive and negative way: while, concerning the former, the production of fish foodstuff can for instance reduce pressure on wild stocks and – in some production systems such as aquaculture in ponds – replace destructive land-use patterns, the list of potential negative impacts is quite long as well (Diana, 2009). Thus, the selection of the ICs must be comprehensive in the sense that it should reflect the full range of aquaculture activities and that it must covers all the main environmental issues related to the system.

Within the impacts due to the emissions of substances, *Climate Change, Eutrophication and Acidification* are clearly seen by the scientific community as the best proxies of aquaculture impacts, confirming previous findings (Aubin, 2013; Cao et al., 2013; Henriksson et al., 2012). The frequency at which they are used is followed at a distance by Ecotoxicity.

In regard to the evaluation of impacts due to the removal of substances from nature, the assessment approaches based on resources extraction rates and those based on exergy consumption are the most used in aquaculture-related LCAs among the six ones identified in a recent review on Resource Depletion (Klinglmair et al., 2014). However, the currently used LCIA methods are still not sufficiently comprehensive, with one of the main issues being the accounting of the consumption of some renewable resources. In fact, while the so-called renewable energies (*e.g.* wind and solar power) regenerate instantaneously, the time required for biotic resources to double their number of individual (*i.e*. their renewal time) may range from days to years (Crenna et al., 2018). This condition inevitably leads to difficulties in the identification of proxy for impact that are related to biotic resource depletion. On the other hand, the consumption of fossil fuels can be translated into an IC more easily since, despite being biotic resources, their renewal time is so wide that they can be theoretically considered as non-renewable resources, as metals and minerals.

As a result, the IC *Abiotic Resource Depletion* is the most consolidated one and already includes a series of alternative indicators recommended by the European Platform on LCA (European Commission, 2011). On the other hand, the quantification of *Biotic Resources Depletion* is a more controversial topic and it is primarily expressed with the Primary Production Required indicator. Since the adoption of the term BRU rather than NPP-use seems to be simply due to personal choices – with the research groups of Pelletier and Avadì preferring the former and that of Aubin supporting the latter – the adoption of a unique terminology would be advisable to avoid possible confusion, as already suggested by Cashion et al. (2016).

A limit of the Water Use IC is that the two most frequently used indicators are expressed simply in terms of the quantity of liquid removed from a natural waterbody. This quantitative approach can lead to biases when comparing the results obtained from different production systems. For instance, the indicator Freshwater Consumption is used as a proxy of the water consumed by the system and thus made unavailable for other uses. However, most of the reviewed studies (see *Appendix*) focused on farm activities, where the water is not consumed (it is simply the medium the farmed species grow in) and is returned to the river shortly after the derivation into the system. The other main indicator, Water Dependence, it is not very suitable either. Although the amount of water flowing through a freshwater system is far smaller than that flowing through a sea cage system (Gephart et al., 2017) still freshwater ecosystems require an adequate amount of water for their sustenance (*i.e.* the minimum flow necessary to preserve the aquatic living beings). Thus, the diversion of a quite small amount of water from a river might have big effects on the downstream aquatic environment and thus it wouldn't be a representative indicator of the actual impacts, especially in those geographical regions where water availability can be a critical parameter in assuring the survival of aquatic species. A third option is that of taking into account the degradative use of water (and not just its consumption or use) by resorting to Water Footprint, since this indicator accounts for the water required both to be consumed within the production processes (green and blue water footprint) and to be used to assimilate/dilute pollution (grey water footprint). However, one single study used this indicator and only the blue water footprint was assessed. As already highlighted by Gephart et al. (2017), this indicator is probably disregarded due to its complexities since – in addition to the amount of water used – it requires information on the location of the water withdrawal and the amount (and dynamics) of water locally or regionally available.

Although efforts were made to clarify some of the issues concerning *Land Use*, the problem of its accounting remains a very complicated one and gave rise to debate and controversy (van der Voet, 2001). In the last years, several researches have been testing different proxies (Foley et al., 2005; Lindeijer et al., 2002; Scholz, 2007) but there is still no clear consensus about which Land Use indicator would suits best in accounting aquaculture-related impacts. As a consequence, Land Use was mainly assessed with the characterization model available within ReCiPe methodology. The case-study including the *Sea use* (Abdou et al., 2017) represents an interesting attempt to transfer an IC created in a fishery-LCA context – which in turn was directly derived from the IC Land Occupation – to an aquaculture-relate context. The most interesting aspect is that this IC did not simply considered the surface area occupied by the sea-cages but included within the assessment method the characterization factors for seabed destruction and transformation as a consequence of both on-farm and fishing activities (the latter being necessary for fish-feed production).

The assessment approaches based on energy and exergy consumption are sometimes used too. CED, although being pointed out as the fourth most representative IC in aquaculture (Aubin, 2013; Cao et al., 2013; Henriksson et al., 2012), appears to have been less used in the past 5 years, with no specific motivation provided for its inclusion or exclusion from the analysis. The exergy of resources – which expresses the maximum amount of useful work the resource can provide – was sometimes accounted in terms of CEENE. As already observed for the accounting of the *Biotic Resources*, CEENE seems to be an IC whose use is intimately related to the research groups personal approach.

Besides the set of ICs that are always or often included in aquaculture LCAs, several issues – such as Genetically Modified Organisms, biodiversity loss and erosion – have already been identified but their relative impacts are seldom or never addressed, as better described in the ILCD Handbook (European

Commission, 2011). For some of them, there is still no consensus on the characterisation model proposed, while for others no characterisation models are available at all. Concerning the papers here reviewed, several research groups either paired some conventional LCIA methodologies with sustainability indicators other than LCA approach or applied controversial indicators and characterisation models.

With regards to unconventional energy-based approaches, EROI is an interesting indicator of systems energetic performance, typically used within the energy sector to determine the energy that is returned from an energy-collecting process as compared to the energy spent to run the process itself (Gupta and Hall, 2011). However, EROI can also provide very useful information when applied to food systems, since in many cases they may rely on high inputs of non-renewable resources (Pelletier et al., 2011). The 'edible protein EROI' (ep-EROI) is particularly useful as indicator of ecological sustainability, since it describes the ratio of industrial energy input to protein energy output for food production and allows for comparison of energy efficiency between different food sectors. Another energy-based approach was applied by Draganovic et al. (2013) on salmonid fish-feed ingredients, calling into question the higher sustainability of vegetable ingredients over that of animal sources. Within this study, the choice to account for *eco-exergy* to compare living organisms is particularly peculiar and it was used to describe the differences between fish, plants, crustaceans, and microalgae.

The suggestion made by Oita et al. (2016) for improvements of the Nitrogen Footprint method was interesting as well, since it took into consideration not only consumers' food choices but also the differences in nitrogen emissions between fed and non-fed aquaculture systems.

Human Labour is not directly related to any environmental impact (it is not an IC). However, it was mentioned in connection with the IC *Particulate* *matter/Respiratory inorganics*, where *work loss days* are accounted together with other parameters – such as new cases of chronic bronchitis and increased mortality risk – as an endpoint effect within the EcoSense LCIA model. It is our belief that the accounting of *Human Labour* may be useful for the interpretation of LCA results: for instance, it may enlighten the researchers about murky connections between workers' health, work loss days and the use of fossil fuel vehicles and machineries. However, farming techniques in modern, intensive aquaculture systems usually entail a low labour intensity. This is probably the reason why *Human Labour* was considered in only two papers, both concerning Asian extensive polyculture systems.

Finally, it is worth mentioning the study of Newton and Little (2017), in which an LCA on salmon supply chain was coupled with the geo-localization of the impacts by means of the GIS methodology. This topic has always represented an issue in LCA analyses, since the quantification of regional and local impacts requires a deep knowledge of the possible interactions between the system studied and its surrounding natural environment. Moreover, complex supply chains may include several activities taking place in different time and space, thus the allocation of the overall environmental impacts and their declination in their relative local context may lead to a totally different interpretation of the results.

5. Conclusion

The results of our review give the opportunity to take stock of the current general trend in aquaculture-related LCAs and provided essential information about two macro-areas.

<u>*Application of the method*</u> – The number of farmed species (fish species, molluscs, algae), the production techniques adopted (*e.g.* the type and method of feeding, the infrastructures used) and the intended use of the finished

product (human consumption but also biodiesel production and more) makes aquaculture production an extremely heterogeneous sector. Most LCAs still focus on intensive farming and on high economic value fish, but a progressive shift of the research efforts from Western to Asian culture systems was observed, thus better reflecting world aquaculture production ration. Since one of the most critical aspects of the supply chain is the aquafeed production and use, it was positive to see that its sustainability is being studied with a growing interest. Overall, an increased number of case studies is necessary to increase the level of knowledge and to direct the sector towards more sustainable production solutions.

With regards to the Functional Unit chosen, biomass is the most representative metric. However, the main purpose of fish production is human consumption, thus the coupling of mass with the edible protein as FU would be preferable (and in this case a careful evaluation should be made with regard to the opportunity of including fish manufacturing activities in the model). System boundaries are often not very wide, with most of the researches focusing on farm activities disregarding both upstream and downstream processes. A worrying observation was related to data sources and allocation method, which were often not stated although being two very delicate aspects of LCA.

With regards to the impact assessment phase, it must be borne in mind that not only the ICs but also each single indicator to assess them aims to answer to a different research questions, with the only exception being Climate Change. Thus, it is necessary to make a well-informed choice about which ones to use and to state it clearly, since the results obtained by the application of two alternative indicators to the same supply chain will be different as well.

Resource accounting models – Most of the methodological criticalities still arise from the assessment of impacts due to resources depletion and the existing lack of consensus leads to a high heterogeneity in the approaches used. Within several studies, some new or uncommon characterisation models and some sustainability indicators other than those included in LCA have been tested. Methodologies concerning several local ecological impacts are still underdeveloped and no specific improvements were suggested in the last 5 years about them.

Given the critical issues highlighted by the review, it was decided to focus the subsequent studies on three specific key issues, as already mentioned in the previous chapter:

- the aquafeed, through a focus on four candidate ingredients as potential substitutes for fishmeal (chapter 3).
- different production systems, in order to increase the level of knowledge about aquaculture sustainability. The focus was brought on land-based freshwater systems, investigating a semi-intensive flow-through system producing trout in Italy first (chapter 4) and then an aquaponic system producing tilapia in Belgium (chapter 5).
- alternative indicators for the resource accounting. The focus was brought on emergy, an indicator not included in the LCA approach (chapter 6), which was applied to the aquafeed case study of chapter 3.

Special attention was paid to fulfil, according to the ISO 14040:1997 and ISO 14044:2006 standards, several underestimated or disregarded aspects described above in this chapter, such as the coupling of different FU, the use of wider system boundaries, a clearer statement of the data-sources used and of the methodological choices made.

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Chapter 3. ALTERNATIVE PROTEIN SOURCES[6]

1. Introduction

As already discussed in chapter 1, close attention should be paid to the choice of aquafeed used, as it was already addressed as the major environmental impact source (Bohnes et al., 2018). The consumption of aquafeed is likely to increase, pushed by the increased demand for fish products (FAO 2018).

The optimal protein source for high-value carnivorous and omnivorous species, such as trout, channel catfish, common carp (freshwater) and salmon, seabass and seabream (marine) is fishmeal (FM) (NACA/FAO 2001; STECF - Scientific Technical and Economic Committee for Fisheries 2018). In the ’70s and ‘80s, the growing demand for FM caused a growing pressure on the small pelagic fish species, thus contributing to a progressive decrease in their stocks (Rana et al. 2009; FAO 2018). Concern about FM availability and market price (Tacon and Metian 2008; Naylor et al. 2009) fostered research activities aimed at replacing it with cheaper and more sustainable protein sources. This effort involved both the scientific community and the aquafeed industry.

The Italian aquafeed industry is importing about 40,000 tonnes of FM per year (Globefish 2016), mainly from Chile (more than 30%), Germany, Spain and Denmark (around 15% each). In order to reduce Italy dependence on imported FM, the project SUSHIN - SUstainable fiSH feeds INnovative ingredients, is focusing on underexploited protein sources, with the aim of designing new sustainable feed formulations. Four potential FM substitutes were identified: Poultry By-product Meal (PBM), Insect Meal (IM) and Dried Microalgae Biomass

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(DMB) from *Tetraselmis suecica* (DMB_TETRA) and *Tisochrysis lutea* (DMB_TISO). PBM is obtained from the processing of category 3 poultry by-products and, consequently, it can be fed to terrestrial farmed animals (Annex X to Regulation (EU) 142/2011). Insect Meal (IM) is obtained from the processing of fly larvae and can be used as feed ingredient, based on the current legislation (Annex II to Commission Regulation (EU) 2017/893). The feeding of fish with poultry and insect meals was authorized by the Commission Regulation (EU) 2017/893 and by the Regulation (EU) 56/2013. *Tetraselmis suecica* (DMB_TETRA) and *Tisochrysis lutea* (DMB_TISO) are two marine microalgal species farmed in outdoor photobioreactors, which are closed cultivation systems that allow to reduce the use of chemicals and optimize the use of fertilizers. According to the European Union legislation, both microalgal species are considered as safe ingredients for food and feed purposes (Enzing et al. 2014) and are included in the European catalogue of feed materials (Commission Regulation (EU) 68/2013).

According to the literature, all candidate protein sources are suitable as partial FM substitute within aquafeed formulations (Bruni et al. 2018; Zarantoniello et al. 2018; Hekmatpour et al. 2018; Henry et al. 2018a, b; Cardinaletti et al. 2018; Wu et al. 2018; Secci et al. 2019; Gong et al. 2019; Messina et al. 2019; Davies et al. 2019; Karapanagiotidis et al. 2019; dos Santos et al. 2019). PBM is already one of the main animal protein sources used in livestock and fish feed formulations (Meeker and Hamilton 2006). IM and the two DMB are emerging as valuable aquafeed ingredients only recently, despite both microalgal species have been used in aquaculture for a long time to meet specific nutritional needs of molluscs and shrimp larvae and to improve growth performance through green water techniques.

The four partial FM substitutes were investigated through the LCA methodology with the objective to identify the most environmentally sustainable one and to indicate potential improvement of their present production processes.

2. Methods

LCA was performed according to the four main steps recommended by the International Standard Organisation (ISO 2006a, b): (1) Goal and scope definition; (2) Life cycle inventory; (3) Life cycle impact assessment and (4) Results interpretation. Calculations were made using the software SimaPro 8.5.2.0 (PRé 2012). The problem-oriented approach (attributional LCA) was adopted, in order to focus on the extent of existing impacts (Tillman 2000).

2.1. Scope definition

The main characteristics of the four protein sources are presented in Table 3.1. A “cradle to plant gate” LCA was performed, thus including in the system boundaries the production of poultry by-products, fly larvae, fresh microalgae and their processing into unpackaged dried meal (Figure 3.1). One tonne of protein (*i.e.* the percentage of crude protein contained in the dried meal) was used as functional unit, since it is the nutritional property on which the partial FM substitution is based, in the formulation of new aquafeed. The set timespan is the managing of the plants for a whole year, so to include in each model the seasonal fluctuations in the production. This choice is particularly important for the microalgae production, since their growth is highly affected by outdoor environmental conditions (the available solar radiation and air temperature).

A sensitivity analysis (2 alternative scenarios per each meal) was performed in order to provide a range of the impact magnitude and to increase the robustness of the research. Furthermore, as shown in Figure 3.1, the production of insect meal and poultry by-product meal includes multifunctional processes.

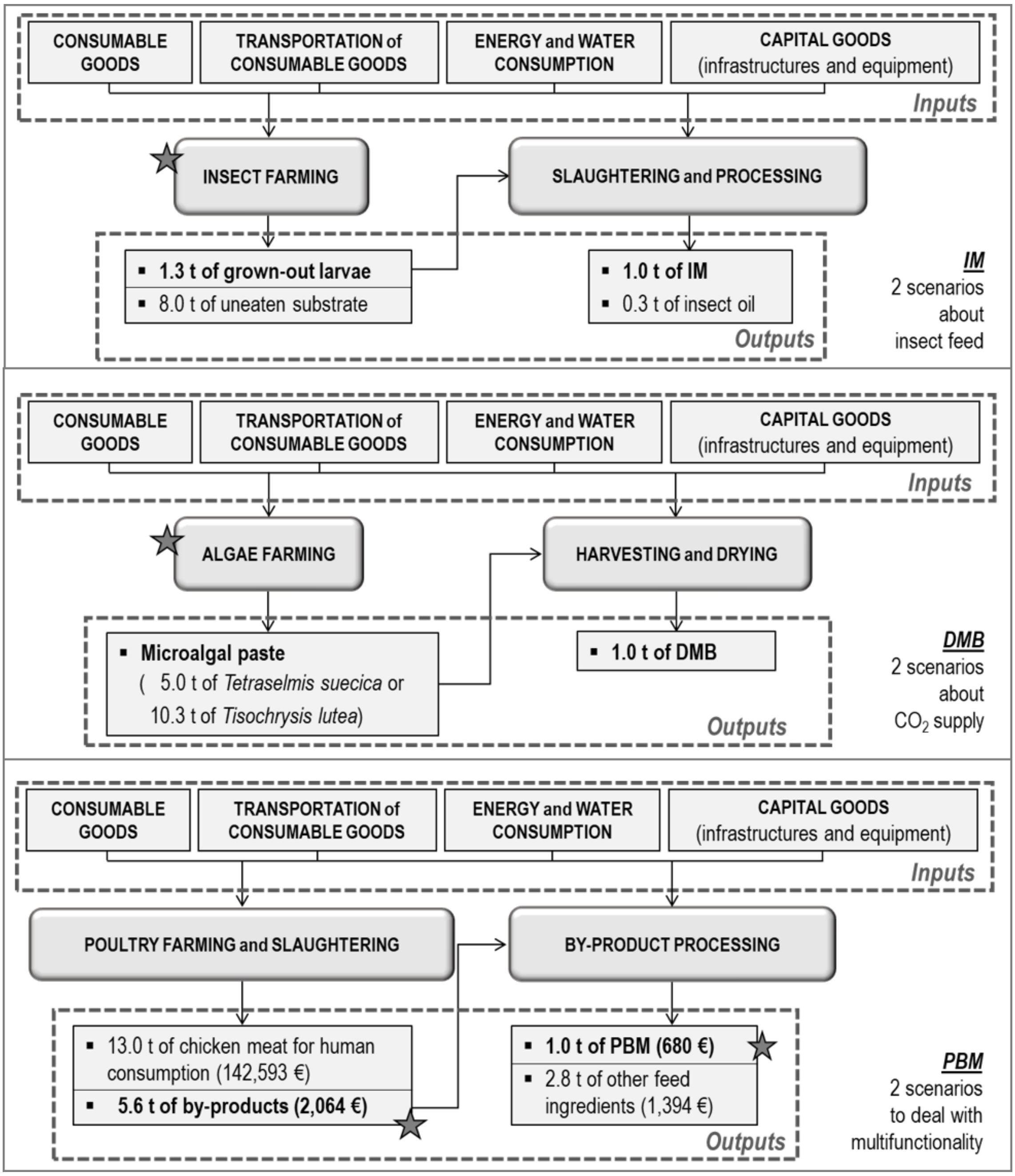

Figure 3.1 System boundaries set for each novel FM substitute modelled. They include the production of the raw material (*i.e.* chicken by-products, fly larvae, whole microalgal organisms) and its processing into meal. In each model, a star ( ) highlights the point where most of the uncertainty lies and for which 2 different scenarios were considered.

To enable a fair comparison among these meals, the mono-functional process leading to their production should be isolated from the ones related to additional system outputs (co-products). However, a subdivision into mono-functional processes cannot be performed, since in both cases the meal and the co-product(s) are obtained from a single input (raw material) entering the process.

Table 3.1 Characteristics of the novel FM substitutes (and of the related case studies analysed): Poultry By-product Meal (PBM); Insect Meal (IM); two types of Dry Microalgae Biomass (DMB_TETRA and DMB_TISO). Gross protein content was assessed by SUSHIN-project partners: CREA (Council for Agricultural Research) and the University of Udine

Novel FM substitutes	***PBM***	***IM***	***DMB_TETRA***	***DMB_TISO***
Full name	Poultry By-product Meal	Insect Meal (from black soldier fly)	Dry Microalgae Biomass – *Tetraselmis suecica*	Dry Microalgae Biomass – *Tisochrysis lutea*
Raw material	Poultry by-products	Fly larvae	Whole organism	Whole organism
Productive plant	Real	Real	Virtual	Virtual
Average annual production (tonnes of dried meal year^{-1})	48,253	109	36	25
Location	Italy	France	Italy	Italy
Crude protein content (% on a dry basis)	66	50	40	41
data source	SUSHIN project partners	SUSHIN project partners	Batista et al. (2017), Cardinaletti et al. (2018)	SUSHIN project partners, Cardinaletti et al. (2018)
Gross energy content (MJ kg of meal^{-1})	21.14	18.28	22.20	22.50
data source	SUSHIN partners	SUSHIN partners	Tredici et al. (2015)	Renaud et al. (2002)

Thus, according to ISO standard 14044 (ISO 2006a), the first solution to solve multifunctionality is the expansion of the system boundaries, in order to ensure that all the environmental burdens are taken into account. This means a change in the functional unit which, in this case, would include 1 tonne of meal plus 0.3 tonnes of insect oil (in IM production process) and 1 tonne of meal plus 2.8 tonnes of other feed ingredients (in PBM production process). As these functional units cannot be compared to each other, nor with 1 tonne of dry microalgae biomass (DMB), allocation remained as the only solution. In fact, the fourth option (the substitution method) is not perceived as correct: taking place overtime, it is not in line with the scope of the study which is, according to the attributional retrospective, to portray current production scenarios (Schrijvers et al. 2016). Details about the allocation approach used and the alternative scenarios considered are better discussed in the paragraph 2.2.2.

2.2. Life Cycle Inventory (LCI)

2.2.1. Data source

The inventories are provided in Tables 3.2, 3.3, 3.4. Data concerning the production of the two animal meals were provided by two industrial scale companies. Data concerning the production of both microalgal meals (DMB_TETRA and DMB_TISO) were based on the model of a 1 ha plant using the Green Wall Panel technology. The model is grounded on the technologies and operations of both the Green Wall Panel pilot installation at the Fotosintetica & Microbiologica S.r.l. research area (a University of Florence spin-off, Firenze, Italy) and the industrial scale plant of Archimede Ricerche S.r.l. (Camporosso, Imperia, Italy) and it was previously used for a techno-economic analysis of microalgae biomass production (Tredici et al. 2016). Despite having a different production scale (Table 3.1), the four systems can be compared to each other since they represent the state of the art of practices and technologies in their respective production field.

Foreground data were gathered by interviewing the PBM and IM companies' staff and DMB experts. Background data, such as consumable goods, production, transportation modes and energy generation (electricity, diesel fuel, etc.) were mainly derived from Ecoinvent v.3 database. However, data on crop production is poor within Ecoinvent, thus they were sourced from Agribalyse database. Poultry by-products production was sourced from Agribalyse too, since previous LCA publications on Italian poultry supply chain do not provide an exhaustive inventory. The electricity mix and water consumption in background inventory data were adapted to the Italian context for PBM and the 2 microalgal meals and French context for the IM.

Table 3.2 Dry Microalgae Biomass (DMB) inventory – Cultivation and processing of microalgae into dry microalgae biomass in an Italian virtual company. Data are scaled to 1,000 kg of meal produced.

INPUT TYPE	INPUT	UNIT	AMOUNT (DMB_TETRA)	AMOUNT (DMB_TISO)
MAIN CONSUMABLES	Fertilizer used as nutrient – Sodium nitrate ($NaNO_3$)	kg	427.7	420.1
	Fertilizer used as nutrient – Monosodium phosphate (NaH_2PO_4)	kg	27.4	26.7
	Carbon supply ▪ S1: as flue-gas (burden-free)		not considered	not considered
	▪ S2: carbon dioxide, liquid	kg	9,020.0	9,020.0
OTHER CONSUMABLES	▪ Disinfectant – Sodium hypochlorite at 15% active chlorine	kg	25.1	35.8
	▪ Disinfectant – Hydrochloric acid 36%. Both disinfectants are consumed entirely during the system washing, performed only at the beginning and at the end of the yearly production.	kg	4.1	5.8
CAPITAL GOODS	Photobioreactors metal components – Mainly composed of chromium steel 18/8, hot rolled. Lifespan: 25 years: ▪ metal frames ▪ stainless-steel serpentine (thermoregulation)	kg	94.1	134.4

	▪ water tanks ▪ pumps and air blowers ▪ centrifugation and lyophilization machines			
	Photobioreactors wood structure – Mainly composed of: Plywood, for outdoor uses Lifespan: 15 years	kg	66.8	95.5
	Photobioreactors plastic bag – Mainly composed of: polyethylene, low density, granulate. Lifespan: 1 year	kg	83.5	119.3
	Photobioreactors piping – Mainly composed of: polyvinyldenchloride, granulate. Lifespan: 15 years	kg	8.9	12.7
WATER CONSUMPTION (SEA WATER)	▪ Culture medium – Complete filling-up of the culture chambers (only the 1st day of production), plus the daily topping-up.	m^3	60.9	86.7
	▪ Cooling system.	m^3	2,105,263.2	3,007,159.9
ENERGY CONSUMPTION	Energy consumed during the: cultivation (5 pumps + 2 blowers), harvesting (centrifugation and ultrafiltration), drying (lyophilization).	kWh	12,098.8	22,716.3
TRANSPORTATION	Transportation of the consumable goods – Fertilizers, disinfectants, photobioreactors plastic bag (since their lifespan is of 1 year only) from the nearest retailer to the plant (lorry with a Gross Vehicle Weight Rating below 7.5 t), plus:			
	▪ S1: no transportation considered for the flue gas supply	t km	28.4	30.4
	▪ S2: transportation of pure CO_2 from the nearest retailer to the plant (lorry with a Gross Vehicle Weight Rating below 7.5 t)	t km	479.5	481.5

OUTPUT TYPE	OUTPUT	UNIT	AMOUNT (DMB_TETRA)	AMOUNT (DMB_TISO)
PRODUCT	Dry Microalgae Biomass	kg	1,000.0	1,000.0
EMISSIONS IN AIR	Water losses during biomass drying	m^3	4.0	9.3
	Carbon dioxide not consumed by the microalgae (that is the 80% of the CO_2 provided)	kg	7,220.0	7,220.0
EMISSIONS IN WATER (SEA WATER)	▪ Culture medium – Complete emptying of the culture chambers (once a year, on the last day of production), plus the water losses during biomass centrifugation	m^3	56.9	79.3
	▪ Cooling system	m^3	2,105,263.2	3,007,159.9

Table 3.3 Insect Meal (IM) inventory – Farming and processing of black-soldier fly larvae into insect meal and fat in a French company. Data are scaled to 1,000 kg of meal produced.

INPUT TYPE	INPUT	UNIT	AMOUNT
MAIN CONSUMABLES	Farming-substrate (feed composed of cereal by-products)	kg	6,000.0
OTHER CONSUMABLES	Chemical – Sodium chloride powder.	kg	1.7
	Chemical – Sodium hypochlorite (without water) in 15% solution state.	kg	1.7
CAPITAL GOODS	Rearing boxes of 2 kg/each, stacked on steel frame of 20 kg/each – Mainly composed of:		
	▪ polyethylene terephthalate, granulate, bottle grade. Lifespan: 15 years	kg	0.3
	▪ chromium steel 18/8, hot rolled. Lifespan: 15 years	kg	0.4
	Rendering machineries – Mainly composed of chromium steel 18/8, hot rolled. Lifespan: 25 years	kg	44.4
WATER CONSUMPTION	Tap water: ▪ added to the feed; ▪ used combined with chemicals for the essential cleaning of the facilities.	m^3	6.3

ENERGY CONSUMPTION	Energy Country mix (France) consumed by: ▪ machinery for heating & ventilation ▪ machinery for rendering ▪ other machinery (*e.g.* lighting, insect feeders)	kWh	3,366.7
TRANSPORTATION	Transportation of the consumable goods – Insect feed (cereal by-products) and chemicals from the nearest retailer to the plant (light commercial vehicle)	t km	480.0
OUTPUT TYPE	**OUTPUT**	**UNIT**	**AMOUNT**
PRODUCT	Insect meal	kg	1,000.0
CO-PRODUCT	Oil	kg	333.3
BY-PRODUCT	Field application as compost: ▪ insect growing substrate (uneaten feed, with high moisture content) ▪ dead adult flies	kg	8,016.7
EMISSION IN WATER (RIVER)	Waste-water discharge in the drainage system. It accounts for the water used for cleaning and for cooking/cooling the processed biomass.	m^3	3.0

Table 3.4 Poultry By-product Meal (PBM) inventory – Processing of poultry leftovers into poultry by-product meal and fat in an Italian company. Data are scaled to 1,000 kg of meal.

INPUT TYPE	INPUT	UNIT	AMOUNT
MAIN CONSUMABLES	Chicken feed	kg	5,556.0
OTHER CONSUMABLES	Disinfectant – A chemical product composed of Sodium phosphate (2.5%) + Ethylene oxide (1.25%) + 1-butanol (1.25%) + Isopropanol (2.5%) + Water, ultrapure (9.25%)	kg	0.2
	Detergent – A common tenside	kg	0.4
CAPITAL GOODS	Rendering machineries (pre-cooker, cooker, press, collection tanks, vibrating screens, etc.) – Mainly composed of chromium steel 18/8, hot rolled. Lifespan: 25 years.	kg	0.5
WATER CONSUMPTION	Soft water used: as live steam injected into the rendering machines; as cold water to cool down the leftovers during their processing; for hygiene reasons (*i.e.* for the essential cleaning of machinery and floors), although it represents a limited amount if compared to the volumes used daily as steam in the rendering process.	m^3	5.7

ENERGY CONSUMPTION	Energy Country mix (Italy)	kWh	282.9
	Natural gas	Nm^3	429.3
TRANSPORTATION	Transportation of the consumable goods – Poultry from the slaughterhouses to the rendering plants (lorry with a Gross Vehicle Weight Rating of 25 t), plus the chemicals from the nearest retailer to the rendering plants (light commercial vehicle)	t km	185.8
OUTPUT TYPE	**OUTPUT**	**UNIT**	**AMOUNT**
MAIN PRODUCT	Meat meal (for human consumption)	kg	1,000.0
BY-PRODUCTS	Fat	kg	833.6
	Blood meal	kg	611.2
	Feathers meal	kg	1,388.8
EMISSION IN WATER (RIVER) WATER	Waste-water discharge in the drainage system. It accounts for: water used for cleaning and for cooking/cooling the processed biomass (the virtuous recycling processes are ignored both as inputs and as outputs) the water drained from the leftovers.	m^3	7.4

2.2.2. Brief description of the production systems and of the related scenarios

DMB production. The meal is obtained through the cultivation, harvesting and processing of two unicellular marine microalgae (*Tisochrysis lutea* and *Tetraselmis suecica*) produced in a 1 ha Green Wall Panel plant close to the sea (Figure 3.1). The production of the two meals (DMB_TETRA and DMB_TISO) requires the same infrastructures and machineries, but differs in terms of consumable goods, water and energy consumption. The production at full plant size (*i.e.* in the Green Wall Panel photobioreactors) is carried out in a semi-continuous mode: every day, part of the microalgae culture is harvested and substituted with fresh culture medium. The salt water filling the system is taken and discharged into the sea. At harvesting, microalgae cells are separated from the exhausted culture medium by centrifugation. The paste thus obtained, which still contains 75-85% water, is dried, in order to get the feed ingredient. Carbon dioxide can be injected into the photobioreactors either as flue gas, which is a recycled waste-product obtained from the burning of used vegetable oils, or as pure carbon dioxide from cylinders. These two alternatives were investigated as two scenarios, S1 and S2 (Table 3.5). In the former case, the flue gas was assumed as a burden-free input, as the credits related to its production were entirely assigned to the producer. Both scenarios were modelled in accordance with Collotta et al. (2018).

Table 3.5 Alternative scenarios tested on each model

	1st scenario (S1)	***2nd scenario (S2)***
PBM	Mass allocation	Economic allocation
IM	A commercial housefly diet (Barry 2004),composed of wheat bran, alfalfa meal, corn meal and tap water	A black soldier fly baseline diet (Smetana et al. 2016), made of wheat bran, rye meal and tap water
DMB_TETRA	Flue gas	Pure CO_2
DMB_TISO	Flue gas	Pure CO_2

IM production. Insect farming, slaughtering and processing are carried out in the same facility. At the end of the larval stage, most of the pre-pupae is processed, while the rest develops into the adult colony that will provide the supply of new eggs. Due to IPR protection, the exact composition of the growing substrate (*i.e.* the insect feed) was not provided by the company, who, however, communicated that the diet formulation is based on cereal by-products. Based on this information, two production scenarios were investigated, assuming two alternative diets (Barry 2004; Smetana et al. 2016) (Table 3.5). With regards to the mass balance (Figure 3.1), the use of 9.3 tonnes of growing substrate leads to the production of 1.3 tonnes of larvae (live weight) and 8 tonnes of uneaten substrate. The larvae are then converted into 1 tonne of IM and 0.3 tonnes of insect oil. According to producer’s personal communication, the uneaten growing substrate is sold on the market as fertilizer. However, if compared with the economic value of the other two products (IM and insect oil), the uneaten substrate accounts for less than 3% of the total net sales. Thus, the total environmental burdens were allocated to the production of grown-out larvae, leaving the uneaten substrate completely burden-free. The two co-products (insect meal and oil) have the same economic value (personal communication from the company), thus the allocation of impacts was based on the biomass ratio only. In summary, multifunctionality was here handled by cutting-off the uneaten substrate and by applying a mass allocation between IM and insect oil.

PBM production. The slaughter of broilers leads to the parallel production of the main product (*i.e.* broiler meat for human consumption) and of three types of by-products: meat and bones leftovers (heads, feet, skin and inedible offal); blood; feathers. Poultry by-products production was modelled starting from an Agribalyse LCI record describing broiler farming and slaughter in France. This record was then modified by substituting the nested records on poultry feed with a formulation provided by the poultry rendering company. Blood and feathers are directly processed into blood and feather meals, while the mix of meat and bones leftovers undergoes a special treatment (rendering) which separates the three animal tissue components: PBM, fat, water. For the sake of simplicity, all the products other than PBM are grouped together and named 'other feed ingredients' (Figure 3.1). The LCA model for poultry by-products processing included fine chopping, heating with added steam, press separation and it was modelled using primary data. The main assumption in this LCA model is represented by the allocation approach, based on both mass and economic value (Table 3.5), as PBM and the other feed ingredients (feather meal, blood meal and fat) significantly differ in terms of both production yield and economic value. In the system chosen as case study, 18.6 tonnes of broiler (live weight) give 13.0 tonnes of broiler meat and 5.6 tonnes of poultry by-products. The latter yields 1.0 tonne of PBM, 2.8 tonnes of other feed ingredients and 1.7 tonnes of waste water (removed from animal tissues). Thus, according to the mass balance, the by-products (obtained from poultry slaughtering) and the PBM (obtained from by-products rendering) are burdened by 30.1% and 26.3% of the impacts of the background processes, respectively (mass allocation, in the PBM S1 scenario). Alternatively, the poultry by-products and PBM are burdened by 1.4% and 31.5% of the impacts respectively, in line with their economic value (economic allocation, in the PBM S2 scenario, according to the commodities price in November 2019). An allocation approach based on nutritional characteristics (*e.g.* energy content) was not considered meaningful, as the outputs of both the multifunctional steps (the broiler slaughter and the by-product processing) are meant for very different uses and have different nutritional functions.

2.2.3. Data aggregation and other assumptions

The inventory data were aggregated into 6 sub-categories. The sub-category "Main consumables" includes either the feeds for the insect and poultry farming or the fertilizer for the microalgae. Detergents and disinfectants were included in the "Other consumables" sub-category. All systems include road "Transportation" of consumable goods, with distances calculated in terms of kilometres between the retailer of each consumable good and the facility where it is used. The lifespan of machineries and equipment, *i.e.* 'Capital goods', was estimated by assuming only an ordinary maintenance on them. Storage infrastructures and logistic, administration offices, laboratories etc. were not included in the system boundaries since they are not representative of the production processes. The sub-categories "Energy consumption" and "Water consumption and emission" track the consumption of these resources within the foreground system. Wastewater emissions from the plants producing PBM and IM are treated in accordance with the current legislation. Direct nutrient discharges from the cultivation of the two microalgal species were not taken into account, assuming that the nutrient inputs are entirely taken up by microalgae. As a consequence, no water treatments are needed here. Gas emissions directly produced by poultry and insect metabolism were not considered as a net source of CO_2: besides being lower than those of other livestock (Gerber et al. 2013; Van Huis et al. 2013; Smetana et al. 2015), they were considered as a part of a rapid biological system, in which the amount of CO_2 emitted by the animals can be considered roughly equivalent to the amount sequestered through photosynthesis by the plant material given to them as feed (Herrero et al. 2011).

2.3. Life Cycle Impact Assessment (LCIA)

Three ICs, *i.e.* Global warming (GWP, kg CO_2 eq.), Acidification (AP, kg SO_2 eq.) and Eutrophication (EP, kg PO_4^{3-} eq.) were assessed using the methodology CML-IA baseline V3.05 method (Guinée et al. 2002). The impacts Cumulative Energy Demand (CED, MJ) (Frischknecht et al. 2007) and Water Use (AWARE, m^3 m^{-2} $month^{-1}$) (Boulay et al. 2018) were selected in order to quantify cumulative impact along the supply chain (Table 3.6). The first four impacts are indicated as the best proxies of aquaculture impacts in several studies, (such as Aubin 2013; Cao et al. 2013; Henriksson et al. 2012). AWARE (a water scarcity midpoint method) was selected among the other water-footprint indicators since it is recommended by WULCA (working group under the umbrella of UNEP-SETAC Life Cycle Initiative) and it represents the state of the art of the current knowledge on how to assess impacts from water use in LCA, assessing both human and ecosystem potential deprivation.

Table 3.6 Characteristics of the impacts chosen

IC	*Short name*	*Unit of measure*	*Accounting for impacts due to:*
Global Warming	GWP	kg CO_2 eq.	The contribution of greenhouse gases to climate change
Acidification	AP	kg SO_2 eq.	The fate and deposition of acidifying substances emitted into air (which may cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials)
Eutrophication	EP	kg PO_4^{3-} eq.	The excessive levels of macro-nutrients in the environment caused by emissions of nutrients into air, water and soil
Cumulative Energy Demand	CED	MJ	The direct and indirect consumption of energy
Water use	AWARE	m^3 m^{-2} $month^{-1}$	The assessment of the Characterization Factors is based on the *Water Availability* minus *Water Demand* per unit of surface in a given watershed relative to the world average. The *Water Demand* takes into account both human water consumption and environmental water requirements.

3. Results

Impacts were assessed in terms of GWP, AC, EP, CED and AWARE. The results are summarized in Figure 3.2 and Table 3.7, which show the impacts of PBM, IM, DMB_TETRA, DMB_TISO (with 2 scenarios each) in terms of absolute values and contribution analysis. The results are presented below highlighting first the performance ranking among the four protein sources and then the contribution to impacts of the main sub-categories.

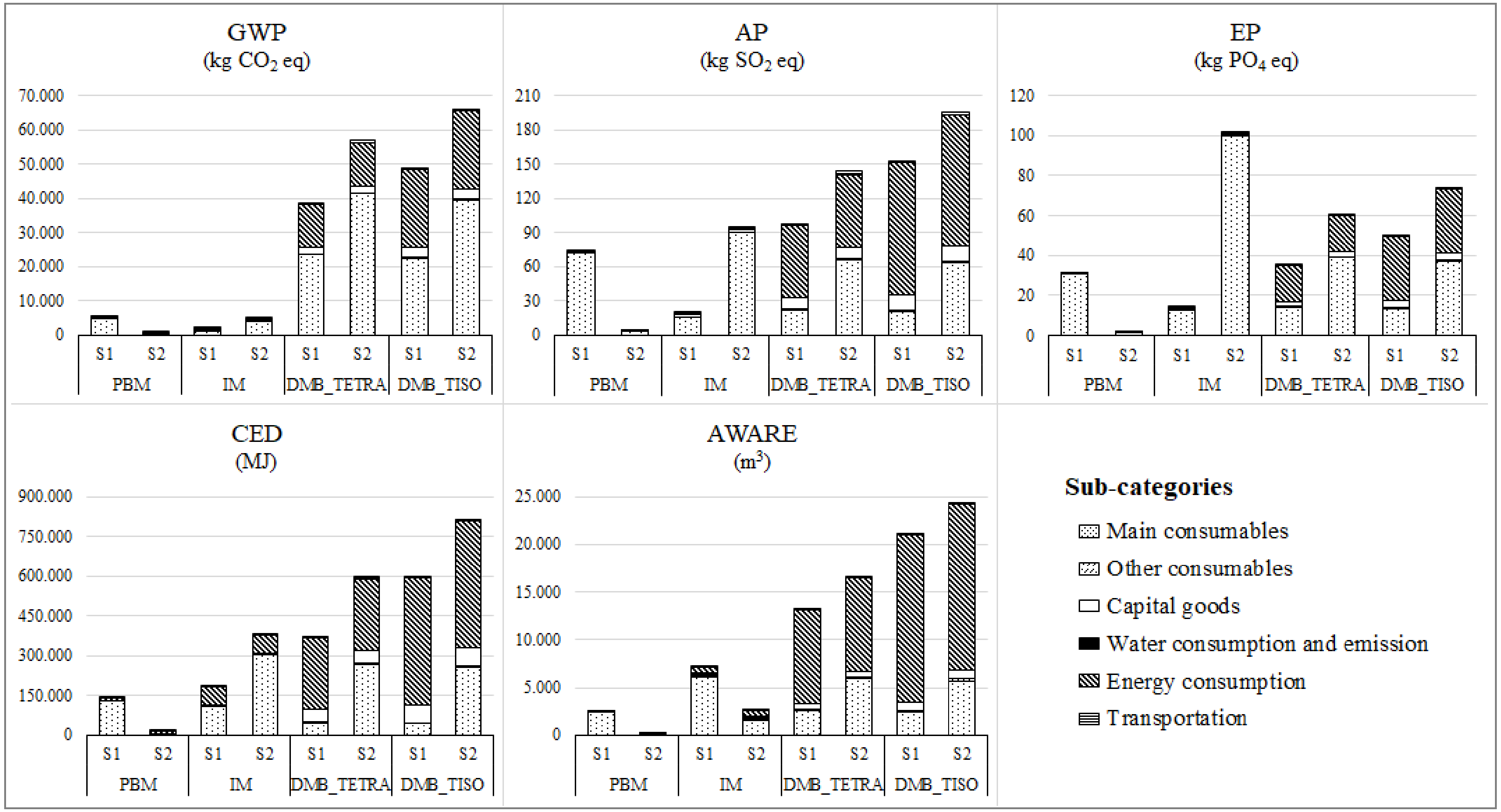

Figure 3.2 Life Cycle Impact Assessment of the four meals considered (PBM, IM, DMB_TETRA, DMB_TISO), with 2 scenarios each (S1 and S2). The 6 sub-categories contributing to the overall impact are highlighted. The FU is 1 tonne of protein contained in the meal. The impacts considered are: Global Warming (GWP), Acidification (AP), Eutrophication (EP), Cumulative Energy Demand (CED), Water use (AWARE).

Table 3.7 Life Cycle Impact Assessment of the four meals considered (PBM, IM, DMB_TETRA, DMB_TISO), with 2 scenarios each (S1 and S2). The 6 sub-categories contributing to the overall impact are highlighted. The FU is 1 tonne of protein contained in the meal.

IC	Scenario	Sub-categories: Main consum-ables (%)	Other consum-ables (%)	Capital goods (%)	Water cons. and emission (%)	Energy cons. (%)	Transportation of consum-ables (%)	Overall Impact (absolute values)
GWP (kg CO_2 eq.)	PBM S1	91.5	0.0	0.0	0.0	8.2	0.2	5,381.81
	PBM S2	26.5	0.1	0.2	0.1	71.2	1.9	738.34
	IM S1	62.0	0.3	17.2	0.5	14.3	5.8	2,046.14
	IM S2	84.1	0.1	7.2	0.2	6.0	2.4	4,899.67
	DMB_TETRA S1	61.1	0.5	5.1	0.0	33.2	0.1	38,428.04
	DMB_TETRA S2	72.7	0.3	3.5	0.0	22.4	1.1	56,872.34
	DMB_TISO S1	46.4	0.5	5.6	0.0	47.4	0.1	48,364.60
	DMB_TISO S2	59.9	0.4	4.1	0.0	34.7	0.9	66,071.12
AP (kg SO_2 eq.)	PBM S1	99.1	0.0	0.0	0.0	0.8	0.1	72.83
	PBM S2	78.7	0.0	0.2	0.2	18.9	2.0	3.65
	IM S1	79.4	0.2	9.0	0.3	8.2	2.9	20.17
	IM S2	95.6	0.0	1.9	0.1	1.7	0.6	94.87
	DMB_TETRA S1	22.4	1.0	10.0	0.0	66.4	0.2	97.06
	DMB_TETRA S2	45.7	0.7	6.7	0.0	44.8	2.0	143.79
	DMB_TISO S1	13.6	0.9	8.8	0.0	76.6	0.1	151.09
	DMB_TISO S2	32.0	0.7	6.8	0.0	59.1	1.4	195.96
EP (kg PO_4 eq.)	PBM S1	99.5	0.0	0.0	0.1	0.3	0.0	30.83
	PBM S2	87.7	0.1	0.1	1.6	9.2	1.2	1.39
	IM S1	89.2	0.1	3.9	0.5	5.2	1.0	14.18
	IM S2	98.5	0.0	0.5	0.1	0.7	0.1	101.64
	DMB_TETRA S1	40.6	1.1	7.2	0.0	50.9	0.1	34.98
	DMB_TETRA S2	64.5	0.7	4.2	0.0	29.5	1.2	60.44
	DMB_TISO S1	27.1	1.1	7.0	0.0	64.7	0.1	49.44
	DMB_TISO S2	50.3	0.7	4.7	0.0	43.3	0.9	73.88
CED (MJ)	PBM S1	94.1	0.0	0.0	0.0	5.7	0.1	138,539.21
	PBM S2	34.7	0.0	0.1	0.1	63.5	1.6	14,930.62
	IM S1	58.7	0.1	2.5	0.1	37.6	1.1	186,348.61

	IM S2	79.8	0.0	1.2	0.0	18.4	0.5	381,348.95
	DMB_TETRA S1	12.9	0.8	13.4	0.0	72.7	0.2	365,402.66
	DMB_TETRA S2	45.1	0.5	8.2	0.0	44.6	1.7	596,271.15
	DMB_TISO S1	7.5	0.7	11.3	0.0	80.4	0.1	593,616.66
	DMB_TISO S2	31.6	0.5	8.2	0.0	58.6	1.2	815,250.42
AWARE (m^3)	PBM S1	98.5	0.0	0.0	0.0	1.4	0.0	2,483.55
	PBM S2	68.8	0.4	0.2	0.5	29.6	0.6	141.38
	IM S1	86.0	0.1	1.0	4.1	8.7	0.1	7,164.23
	IM S2	62.3	0.3	2.6	10.8	23.7	0.3	2,627.81
	DMB_TETRA S1	19.4	1.5	4.7	0.0	74.3	0.0	13,052.63
	DMB_TETRA S2	36.0	1.2	3.8	0.0	58.8	0.3	16,496.90
	DMB_TISO S1	11.4	1.3	4.1	0.0	83.2	0.0	20,935.61
	DMB_TISO S2	23.3	1.1	3.5	0.0	71.9	0.2	24,242.11

The production of *Tisochrysis lutea* dry meal using pure CO_2 (DMB_TISO S2) scored the worst performances in 4 impacts over 5: GWP, AP, CED, AWARE. The same meal also appears to be the second worst option in terms of EP. A comparison between the S1 and S2 scenarios reveals that the former always performs better in both microalgae species: in DMB_TETRA, the use of S1 rather than S2 leads to an impact reduction ranging from -21% (in AWARE) to -42% (in EP); in DMB_TISO, the impacts reduction ranges from -14% (in AWARE) to -33% (in EP). The best microalgae scenario is DMB_TETRA S1, which is comparable to the animal meals in only three cases: IM S2 in AP and CED and to PBM S1 in EP. Indeed, the performances of the animal meals in all the other impacts are at least 50% smaller than those of the microalgae (with the only other exception being IM S2 in EP).

IM S2 has fluctuating performances: good results in GWP and AWARE; worse results in AP and CED, where the performances are comparable to those of the best microalgae meal (DMB_TETRA S1); the worst result among all the systems in EP. The cross-comparison of IM S1 with IM S2 reveals the former to be much more sustainable than the second, with an impact reduction of: -58% in GWP; -79% in AP; -86% in EP; -51% in CED. The only exception is AWARE, where S2 is smaller than S1 (-63%).

The other 3 animal meals appear to be the best-performing options. Among them, the production of poultry by-product meal modelled using an economic allocation of impacts (PBM S2) ranks first, as it has the lowest impacts in all the impacts considered. PBM S1 ranks second in terms of CED and AWARE, while IM S1 ranks second in GWP, AP and EP. The cross-comparison of PBM S1 with PBM S2 proves the latter to have the best performances in all the impacts considered: -86% in GWP; -95% in AP; -95% in EP; -89% in CED; -94% in AWARE.

The results in Figure 3.2 and Table 3.7 also provide the share of the 6 sub-categories to the overall impacts, thus allowing an analysis of their contributions. The performances of the two animal protein sources, PBM and IM, were similar. Indeed, the “Main consumables” sub-category, which includes either the feed for the farmed animals or the fertilizer for the microalgae, accounted for more than 50% of the total impact, with the only exceptions being GWP and CED in PBM S2 (26.5% and 34.7% respectively). As regard microalgae productions, the “Main consumables” sub-category had a high contribution on climate change and eutrophication, ranging from 27.1% to 72.7%. The other three impacts here considered (AP, CED and AWARE) were mainly influenced by “Energy consumption”, which accounted from 44.6% to 83.2% of the overall impact. Overall, the cumulative impact of the sub-categories “Main consumables” and “Energy consumption” accounts for at least 76.3% of the overall environmental burdens, regardless of the type of meal and the scenario considered.

Looking at the other sub-categories, the “Transportation” of consumable goods had a negligible effect, while the sub-category “Capital goods” affected the impact of microalgae meal, with an impact contribution range of 3.5-13.4%, and insect meal production, with an impact contribution range of 0.5-17.2%. “Water consumption and emission” sub-category had no impact on microalgae meal and small ones also for PBM and IM systems.

4. Discussion

The results presented in the previous section indicates that the 4 DMB systems ranked last, while 3 animal meals (PBM S1, PBM S2, IM S1) were the best performing ones. The interpretation of these LCA results is divided into two sections. First, considerations about the environmental performances of each meal are provided. Then, a comparison with previous literature is carried out to check if our findings are in line with previous LCA researches on these systems.

4.1 Performance analysis of microalgae meal (DMB)

DMB_TISO performed worse than that of DMB_TETRA mainly because of the lower yield of *Tisochrysis lutea* (which is more fragile and has an average annual production of 31% lower than that of *Tetraselmis suecica*). In both cases, as expected, the environmental impact decrease when flue gas is used as a carbon source, thus avoiding the impact of the production of pure CO_2 (9 tonnes of CO_2 per each tonne of DMB). However, the microalgal protein sources are less sustainable than IM and PBM irrespectively of the source of CO_2 used.

LCA results highlighted that DMB production has also other drawbacks. First, even when resorting to flue gas as carbon source (S1), the “Main consumables” contribution on climate change and eutrophication remains high (27-61%) due to the use of fertilizers. The amount of fertilizer needed (about 90 and 40 kg per tonne of fresh biomass harvested, for *Tetraselmis suecica* and *Tisochrysis lutea* respectively) leads to impacts exclusively due to fertilizer industrial production (background process). Indeed, microalgae cultivation (foreground process) does not involve a nutrient discharge in the surrounding environment, unlike what happens with soil-based agriculture (where fertilizers are partly lost through deep percolation in soil). Rather, nitrogen and phosphorus compounds are injected in the photobioreactors in controlled quantities and used with full efficiency (paragraph 2.2.3), leading to a negligible nutrient concentration in the waste water discharged in the sea. The second, and more important, reason why DMB systems are not competitive yet is represented by the high energy needs. Indeed, the four systems rely on a high amount of electricity, as shown by the inventory data: 12,000 and 22,700 kWh consumed per 1 tonne of MDB produced (for *Tetraselmis suecica* and *Tisochrysis lutea r*espectively), against 3,400 kWh consumed for 1 tonne of IM and 282 kWh plus 429 Nm^3 of natural gas needed for 1 tonne of PBM. Due to this high amount of energy, the “Energy consumption” sub-category shows impacts of one or even two orders of magnitude greater than in the animal meal systems (Figure 3.2).

The findings presented in Figure 3.2 and Table 3.7 show that the infrastructures contribution to impacts is higher than 3.5% (and up to 13.4% for CED in DMB_TETRA S1): this finding can complement those presented in Grierson et al. (2013) and Medeiros et al. (2015), who did not take the infrastructures contribution into account. The contribution of the “Water consumption and emission” sub-category is null in each of the four microalgae scenarios analysed. This is because no water treatments are required (since it was assumed that the whole amount of nutrients is used with full efficiency) and all the water used in the production of DMB, sourced directly from nature (as salt water from the sea), are fully given back to nature.

4.2 Performance analysis of fly larvae meal (IM)

In the insect meal production systems, differences between the two scenarios (S1 and S2) are due to the growing substrate used as feed. The two substrates tested here represent the “best fit” compromise between insect company’s communications and literature findings. According to the information provided by the company’s staff, the diet formulation is entirely based on cereal by-products (plus some additives) and the whole fly production cycle is quick. Moreover, the amount of water added to the ingredients is equal to their weight. With regards to literature information, a high-quality and high-protein feed is required to ensure insect fast growth (Halloran et al. 2016). Thus, although black soldier fly larvae can process almost any type of organic material (Van Huis et al. 2013), a formulation with fairly high nutritional characteristics was assumed. Despite looking quite similar, the two substrates chosen led to different environmental impacts, with IM S1 showing halved impacts compared to those of S2 in four impacts over five. The comparison of insect meal performances with those of the other protein sources confirms how important is the role played by the growing substrate. Indeed, the second scenario (IM S2) appears as the worst option among the animal meals, reaching microalgal levels in AP and CED and showing out-of-scale impact in EP (due to the high impact of rye meal production). For the same reason, IM S1 appears as more sustainable than the poultry alternative modelled with the mass allocation approach (PBM S1) in three impact over five (GWP, AP, EP). Finally, although it does not make a decisive contribution to the overall performances, the “Energy consumption” sub-category is a second important aspect and it is a sign of the high energy requirements of the company (as already mentioned in paragraph 4.1).

4.3 Performance analysis of poultry by-products meal (PBM)

Differences between the two scenarios (S1 and S2) are due to a methodological approach, *i.e.* the allocation adopted to solve multifunctionality. As explained in paragraph 2.2.2, there are two nodes where the supply chain splits into multiple outputs (Figure 3.1) and poultry by-products, which are one output of the first multifunctional process, represent the main input of the second one. In the first node, the mass allocation scenario (S1) allocates 30.1% of the background impacts (*i.e.* the impacts due to poultry farming and slaughter), to the poultry by-products, whereas the economic allocation scenario (S2) allocates to the poultry by-products a far lower share of impacts (1.4%). In the second node, both the scenarios allocate approximately the same percentage of impacts (26.3 % in S1 and 31.5% in S2) to the PBM. Thus, the poultry by-products are the key point of the whole supply chain and, when modelled by resorting to the economic allocation (PBM S2), they end up having a lower share of impacts, thus making the whole PBM S2 scenario markedly more sustainable. Therefore, the allocation methodology can make a difference, but this protein source looks in both cases as very promising (with performances on a par only with those of IM S1). These high performances are due to the ecological and economic efficiency of the production process. For instance, during the rendering process, the technical potential of both liquid and gaseous outputs is fully exploited: nutrient rich fluids are treated before flowing into wastewater and nutrients are recovered, while the gaseous phase is exploited to recover heat by means of a heat exchanger.

4.4 Literature comparison

Most papers concerning aquafeed sustainability deal with high value fish species, comparing LCA results of alternative aquafeed formulations: aquafeeds for trout and salmon (Pelletier and Tyedmers 2007; Pelletier et al. 2009; Boissy et al. 2011; Samuel-Fitwi et al. 2013); salmon aquafeed performances assessed by means of thermodynamic indicators (Draganovic et al. 2013); an aquafeed formulations based on food waste, generated and processed on board a ship (Strazza et al. 2015); feed formulations for gilthead seabream (Basto-Silva et al. 2019); salmon feeds based on methanotrophic bacteria, yeast ingredients or protein from soy, (Couture et al. 2019). Few studies deal with an evaluation of feed components on an individual basis: alternative ingredients meant for salmon aquafeed formulation (Pelletier and Tyedmers 2007); fishmeal and fish oil production in Peru (Fréon et al. 2017); several aquafeed ingredients commonly used in Indonesia; (Henriksson et al. 2017); alternative meal and fat (or oil) sources (Basto-Silva et al. 2018). Given the low number of researches on individual aquafeed ingredients, our results are also compared with LCAs on systems producing microalgae, insects and poultry for other purposes (Table 3.8).

Table 3.8 Data comparison with previous LCA studies on poultry, insect and soybean production. The functional unit is 1 ton of product, thus the impacts of the systems analysed in this study are scaled accordingly. Literature data were sourced from: poultry studies (Pelletier and Tyedmers 2007; Pelletier 2008; Leinonen et al. 2012; da Silva et al. 2014; González-García et al. 2014; Henriksson et al. 2017; Basto-Silva et al. 2018; Skunca et al. 2018; Cesari et al. 2018); insect studies (the review provided in Smetana et al. 2016; Bosch et al. 2019); microalgae studies (Sevigné-Itoiz et al. 2012; Medeiros et al. 2015; Mata et al. 2018). Outlier values, found in Basto-Silva et al. (2018), are reported in brackets.

	Data source	**GWP** (kg CO_2 eq.)	**AP** (kg SO_2 eq.)	**EP** (kg PO_4 eq.)	**CED** (MJ)
Poultry	This study (PBM)	487 - 3,552	2 - 48	1 - 20	9,854 - 91,436
	Literature	1,390 - 11,000 (305,000)	16 – 200 (5,780)	11-75 (1,570)	11,100 - 50,500
Insects	This study (IM)	1,023 - 2,450	10 - 47	7 - 51	93,174 - 190,674
	Literature	770 – 19,000	/	/	9,300 - 288,150
Micro-algae	This study (DMB)	15,371 - 27,089	39 - 80	14 - 30	146,161 - 334,253
	Literature	1,810 - 68,338	194-201	11	139,000 - 148,000

DMB. Our findings can be compare with those of Sevigné-Itoiz et al. (2012), who applied LCA to three species of marine microalgae cultivated in Spain from mid-November to the end of May in a bubble column photobioreactor under outdoor environmental conditions: 22,900 - 23,800 kg CO_2 eq. in GWP; 194 - 201 kg SO_2 eq. in AP; 10.9 - 11.4 kg PO_4^{3-} eq. in EP; 139,000 - 148,000 MJ in CED per tonne of dry microalgal biomass. Another paper (Medeiros et al. 2015) investigated the environmental impacts of Nannochloropsis sp. dry biomass production, including the cultivation in flat plate photobioreactors, the harvest (through flocculation, decantation and centrifugation) and the drying. Besides being a marine microalga, this species is supplied with flue gas and commercial fertilizers. The GWP impact was found to be of one order of magnitude smaller than ours (1,810 - 3,140 kg CO_2 eq. per tonne of dry alga). This could be due to the reduced energy consumption, based on estimates taken from literature (1,900 kWh per tonne of dry biomass, against the 12,000 - 22,700 kWh per tonne used in our model). A third LCA analysis, focusing on a real pilot-scale multi-tubular photobioreactor (Mata et al. 2018), gives GWP results much closer to ours: 68,338 kg CO_2 eq. per tonne of dry biomass. The construction materials are included in the inventory, the electricity used for both pump operation and thermoregulation is considered and data are mainly sourced from real production conditions in a Portuguese company. And, as in our systems, impacts are mainly due to the production of electricity, with nutrient production as the second main hotspot.

IM. Insects are known to cause impacts highly dependent on: (i) the species, as the gas emissions produced by their metabolism may vary considerably (Oonincx et al. 2010); (ii) the diet (Smetana et al. 2016); (iii) the life stage, temperature and level of activity (Halloran et al. 2016). As a consequence, our focus was brought on the papers which deal with LCA on black soldier fly (BSF) fed on similar substrates. The only two studies found to be suitable for a viable comparison analyse the production of BSF fed either on co-products that are generally provided to livestock (Bosch et al. 2019) or on several by-products of the food industry (Smetana et al. 2019). The impacts assessed by the former are in line with ours (Table 3.8): 3.000 kg CO_2 eq. (GWP) and 84.000 MJ (CED). With regards to the latter, despite LCA was performed by choosing the single score assessment methodology IMPACT 2002+ (thus preventing a comparison in terms of absolute values), the contribution analysis provided corroborates our findings, as feed production and energy appear to be the greatest sources of impacts. Finally, besides the studies specifically addressing BSF, a review on 8 papers (Smetana et al. 2016) reports the contribution of different insect species to GWP impact, and the results of LCAs on both our IM scenarios fall within the range.

PBM. Although this part of the model is not entirely based on primary data, this aspect does not compromise the reliability of results, since poultry supply chain has been operating on industrial-scale for a long time now and it is grounded on well-established technologies thoroughly described in literature and in the Agribalyse LCI record. Our results are comparable to published LCA studies on broiler poultry supply chain in different Countries: Italy (Cesari et al. 2017), Brazil and France (da Silva et al. 2014), Serbia (Skunca et al. 2018), Portugal (González-García et al. 2014), UK (Leinonen et al. 2012), continental United States (Pelletier 2008). Results remains comparable even when the analysis is extended up to the meat processing and packaging (da Silva et al. 2014) or beyond, to the maintenance in shops and even to the household use (Skunca et al. 2018). This can be easily explained by the fact that, in all cases, the majority of the environmental impact is due to the farming stage and to the related feed provided to the poultry, with percentage contributions varying from study to study but always ranging around 70-90% of the overall impacts. To the author's knowledge, a recent paper on the processing of poultry by-products into meal to be used as FM substitute (Basto-Silva et al. 2018) represents the only exception. The system boundaries adopted in this publication are a bit wider than those used here (as they include also the transportation of meal to the aquafeed plant) but, as done in our study, the maintenance and end of life of capital goods are not considered and the impact assessment is performed with the CML-IA methodology and scaled on 1 tonne of PBM, thus allowing meaningful comparison. Notwithstanding, results are of two orders of magnitude higher than ours. The explanation of such a huge difference probably lies entirely in the inventory used, which is not disclosed in the published paper.

5. Conclusion

The nutritional characteristics of four potential alternative dry meals – Poultry By-product Meal (PBM), Insect Meal (IM) and Dry Microalgae Biomass (DMB) obtained from two different microalgal species – make them suitable for a partial substitution of FM within aquafeed formulations. Thus, their environmental performances were here compared by means of LCA methodology in order to identify the most sustainable option and to highlight key aspects for future improvements. A sensitivity analysis (2 alternative scenarios per each candidate ingredient) was performed by introducing some changes to the key aspects of production or the system modelling approach and helped in getting a clearer picture of the likely average impacts and in interpreting the results.

The two microalgal species emerged as the less sustainable protein sources, with one insect and one poultry meal scenarios being the most sustainable options. Results about the microalgal systems also prove that the farmed species plays an important role too, since the environmental performance of *Tisochrysis lutea* dry biomass always appear worse than those of *Tetraselmis suecica*, despite being both cultivated with identical technologies.

The inventory used represents at the same time the main strength and weakness of the study. Since the present study is an attributional LCA, the inventory drawn up for each production process is based on a large number of primary data (collected directly from the companies) and it reflects the real situation and current knowledge in the field. However, nowadays the systems analysed have a different technology level and a different production scale, with PBM production already optimized and IM and DMB productions still in their infancy. It is therefore difficult to find ways to further improve the poultry supply chain, while several strategies can be adopted to increase the sustainability of the insect and microalgal productions.

The results on IM and DMB revealed that the main nutrients used (*i.e.* a growing substrate for insect and a fertilizer for both the microalgae) are the main drivers of impact, together with the amount of energy needed to power the foreground system. Therefore, a way to reduce the environmental burdens would be an increase in the growth efficiency and in the overall annual production through an improvement of the nutrient characteristics. This goal can be achieved through either a change in the nutrient formulation or by adding supplements (prebiotics and probiotics) which may act as immunostimulants and growth enhancers. However, attention must be paid when switching to new nutritional formulations. For instance, in the case of insect farming, the shift to a diet entirely composed of vegetal wastes (*i.e.* biomasses not suitable for other livestock) may have drawbacks. For sure, this option will positively affect some impacts (Bosch et al. 2019) but, in addition to being currently impracticable in Europe due to legislative constrains, it could also lead to an increased total impact due to an annual yield reduction (if the diet is not sufficiently nutritious).

The second environmental hotspot is represented by the energy consumption. The Green Wall Panel photobioreactors used for microalgal cultivation guarantee a higher control of the main variables affecting growth (*e.g.* temperature, pH) than in open cultivation systems. Moreover, they ensure to attain higher volumetric productivities (Leite et al. 2013) thus lowering harvesting operations costs. Still, they require a high amount of energy due to the mixing and cooling. With regards to the insect meal, black soldier flies are native to the warm temperate zone of America (with a growth optimum-temperature ranging from 24 to 29°C) and thus their farming requires a high amount of energy for the heating of the structures. To reduce the direct energy consumed in IM and DMB systems, an improvement of the supply chain could be achieved by using better insulating materials, so to reduce the energy consumption related to both the heating (in insect farming) and to the pumping of water into the serpentine used for the photobioreactor thermoregulation (in microalgae cultivation). Another option is a change in the source of energy, since the Italian and French Country energy mix still rely on a high amount of fossil and/or nuclear sources of energy (although renewable sources are slowly taking hold). For instance, the possibility to integrate solar panels in the microalgae plant to produce the necessary energy would have a high impact in terms of energy balance of algae production, as calculated by (Tredici et al. 2015) for *Tetraselmis suecica* and would positively affect LCA results. A commercial facility growing the green alga *Haematococcus pluvialis* for astxanthin production (Algatechnologies, Kibbutz Ketura, Israel) is already adopting solar panels to obtain energy to operate the plant, and further ways of integration may be achieved in the future. Last but not least, the environmental cost of the capital goods (infrastructures and machineries) is usually not considered within LCA analyses, but the present results prove them to partially contribute to the overall impacts in the case of both insects and microalgae production. Despite the shift from the use of finite natural resources to the recycle of waste materials is a good option also in the case of infrastructures sustainability (Bribián et al. 2011), in this case the high impact share is simply due to the low annual yield of IM and DMB systems.

In conclusion, since insect farming and microalgal cultivation in photobioreactors are not mature technologies yet, their impacts are likely to decrease with an increase in plant size, with improvement in nutrients efficiency (*i.e.* the type of feed or CO_2 source and the way it is provided) and with an optimization of the farming process and equipment used, paying particular attention to technologies capable to increase energy efficiency. On the other hand, PBM production is grounded on well-established technologies and it is not expected to substantially change in the future years. Further researches to complete the picture here outlined would be desirable, assessing for instance the impacts change due to a production scale increase or due to a shift to other energy sources. Still, the present results surely constitute a solid starting point and are a fairly faithful representation of the current situation.

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Chapter 4. FRESHWATER FLOW-THROUGH SYSTEMS

TROUT PRODUCTION IN RACEWAYS ON THE MOUNTAINS

1. Introduction

The European Union boasts a relevant production of rainbow trout (*Oncorhynchus mykiss*), with 185 thousand tonnes valued at €615 million in 2016. Italy plays an important role in this context, accounting for 19% of the European production followed by Denmark and France (17% and 14%, respectively) (STECF - Scientific Technical and Economic Committee for Fisheries, 2018). Rainbow trout production in Italy steadily increased from the 1960ies to 1990ies, reaching a peak of over 50,000 tonnes in 1997 (Iandoli and Trincanato, 2007). This positive trend was followed by a sharp decrease, due to market saturation and the consequent devaluation of the product (Roncarati and Melotti, 2007). In order to cope with this financial stress and thus to increase the value of the product (Iandoli and Trincanato, 2007), farmers began to sell processed fish (such as smoked fillets, hamburgers, fish skewers). Eventually, the annual production became stable and has been fluctuating around 40,000 tonnes in the last decade (Parisi et al., 2014; STECF - Scientific Technical and Economic Committee for Fisheries, 2018).

According to the last Italian census of aquaculture (PO FEAMP 2014-2020), nowadays the freshwater farming companies are around 310, most of which produce rainbow trout. Although this species is an anadromous fish and thus can live in almost all water bodies, from headwaters and lakes to sea water (Page and Burr, 2011), the optimum environmental conditions are represented by fast-flowing, well-oxygenated waters with temperatures below 21°C (Parisi et al., 2014). In Italy, these conditions are typical of mountainous watercourses and of karst springs, with the last one widespread in the northern Plain of the Po river. For this reason, 78% of trout companies are located in Northern Italy and in particular in Veneto, Friuli Venezia Giulia and Trentino Alto Adige (with 70, 68 and 58 farms respectively) (Fabris, 2012).

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

The environmental impact of the rainbow trout supply chain was previously investigated by means of Life Cycle Assessment (LCA) but, as pointed out by the review on salmonids LCAs of Philis et al. (2019), the findings of these studies presents some inconsistencies, due to: (i) the differences in production systems (*e.g.* marine vs land-based system) and management practices; (ii) the LCA methodology applied, in terms of system boundaries, approach to handle multi-functionality, sensitivity analysis. Bohnes and Laurent (2019) also pointed out that several of these LCA studies do not allow for a proper reproducibility of results, due to a lack of clarity about either the data used, or the methodological decisions taken. With regards to data source, the use of similar inventory data may decrease the reliability of the results, especially when they describe key aspects such as aquafeed composition: yet, several practitioners (Aubin et al., 2009; Avadí et al., 2015; Chen et al., 2015; Dekamin et al., 2015) had to recur to the aquafeed formulations provided by previous studies (Boissy et al., 2011; Papatryphon et al., 2004a, 2004b; Pelletier et al.,

2009) due to difficulties in gathering primary data.

The aim of the present paper is to both enrich the body of knowledge in the field and provide the first LCA on an Italian rainbow trout supply chain. Several critical aspects were tackled. First, in order to investigate how and where the impacts increase along the supply chain, the system boundaries were extended, including all the production phases which occur from aquafeed production up to the processing of live weight trout into foodstuff and of fish by-products into pet-food ingredients. Moreover, since the studied supply chain yields more than one product (foodstuff and pet-food ingredients), the decision of expanding the system boundaries allowed to avoid bias due to the allocation of impacts among the outputs (*i.e.* allocation approach), which often represents a forced choice for LCA practitioners. The sustainability of the by-products recycle into pet-food ingredients was assessed by including the avoided burdens in the model and by comparing the results with an alternative incineration scenario. Finally, the inventory dataset was based almost entirely on primary data gathered from the companies involved in this study and, in order to allow for a proper reproducibility of results, all the decision taken while modelling the system are here provided, together with the inventory used.

2. Materials and methods

2.1 Characterization of the rainbow trout supply chain

The study was focused on the supply chain implemented by *ASTRO – Associazione Troticoltori Trentini*, a trout farmers consortium of medium-small size companies in the mountainous province of Trentino, Northern Italy (Figure 4.1). The consortium includes 50 companies over the 58 based on the whole Trentino Alto Adige region (Fabris, 2012), thus its production can be considered representative of that of the entire geographical area.

All the production sites, 60% of which have a total water surface area smaller than 3,000 m^2 (Pontalti et al., 2006), consist in concrete raceways built close to the water courses and, with a few exceptions, their production starts with the purchase of fish seed or fingerlings from other companies and ends with the delivery of fish (in the round) to ASTRO fish processing plant. The consortium associates strictly adhere to a standardised production protocol, the *Disciplinare di produzione "Trote del Trentino"* (2015), which covers key aspects of farm management like: the aquafeed used (only feeds with specific characteristics and ingredient formulations are used); the stocking density; the quality of the water discharged in the drainage basin; the quality of the final product (condition factor and flesh chemical-physical properties). The compliance with the protocol requirements is certified by a 'geographical indication' label.

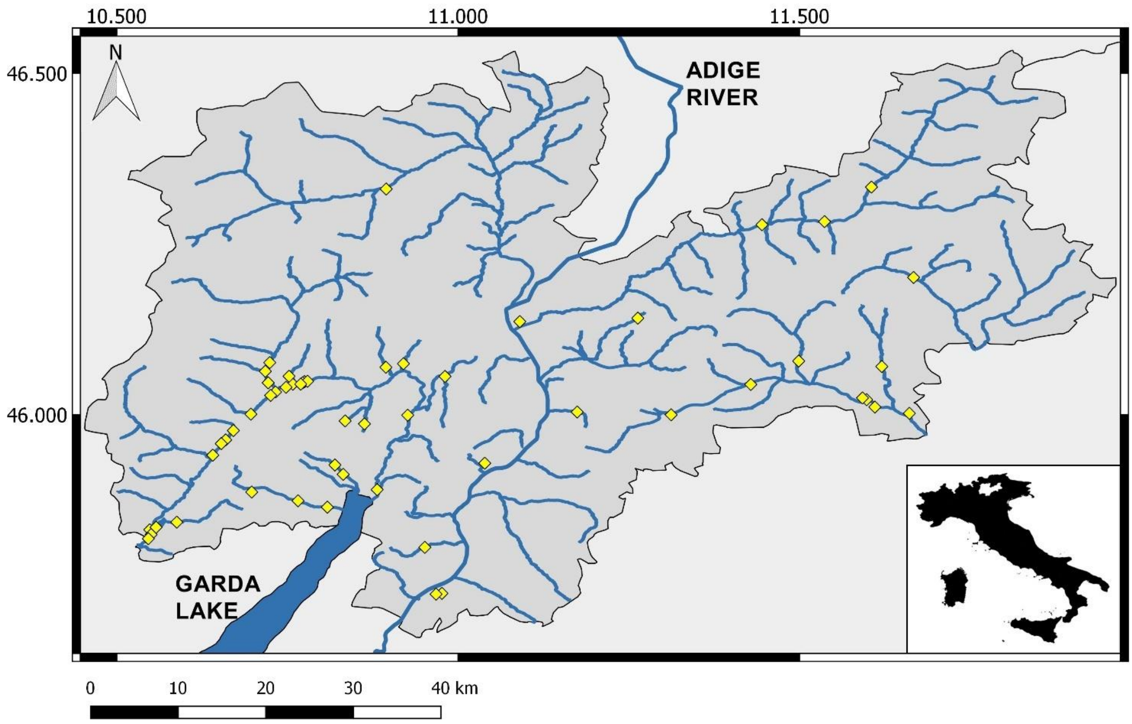

Figure 4.1 Distribution of the trout production sites (◇) belonging to the ASTRO consortium, in the province of Trentino, Italy.

Once delivered to the consortium fish processing plant, fish are processed into food for human consumption, packed and finally sold on large-scale retail trade. The consortium processes more than 1,300 tonnes of rainbow trout (live weight) each year and produces 4 main types of foodstuff (Table 4.1). Fish average yield is 55% of the live weight, with a higher yield for the degutted fish (81%) and lower yield for the other products (43-51%). All by-products (a mix of viscera, heads and frames) are sold to a company which processes them into pet-food ingredients.

Table 4.1 Details on fish processing.

	Products	Products relative abundance (in terms of biomass)	Type of raw material
Fish Processing	Head-on-gutted trout	20.2%	live-weight trout < 500g
	Fillet	51.5%	live-weight trout = 500-800 g
	Smoked fillet	5.4%	live-weight trout > 800g
	Other products (*e.g.* burgers, fish skewers)	22.9%	live-weight trout > 800g

2.2 Life Cycle Assessment

LCA was performed according to the four main steps recommended by the International Standard Organisation (ISO, 2006a, 2006b): goal and scope definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); results interpretation. Calculations were made using the software SimaPro 8.5.2.0 (PRé, 2012).

2.2.1 Scope definition

LCA was applied to the main steps of the supply chain (Figure 4.2): i) feed production, ii) grow out phase, iii) fish processing and iv) by product processing. Fish production at hatchery was not considered. The environmental impacts of the feed production, fish grow-out and by-products processing phases were scaled on a mass-based Functional Unit (FU), namely 1 tonne of product. With regards to the fish processing phase (phase 3), LCA results were scaled on the concurrent production of 1 tonne of food for human consumption plus 0.88 tonnes of fish by-products.

However, the main purpose of the supply chain and thus the main product of phase 3 is represented by the food for human consumption. Thus, in order to allow for comparison between it and literature results, the total impacts of phase 3 were then economically allocated between the food for human consumption and fish by-products. The allocation was based on: (i) the price on the Italian market of the food produced by the consortium; (ii) values about salmonid by-product utilisation in 2015 for Scotland, as reported by Stevens et al. (2018).

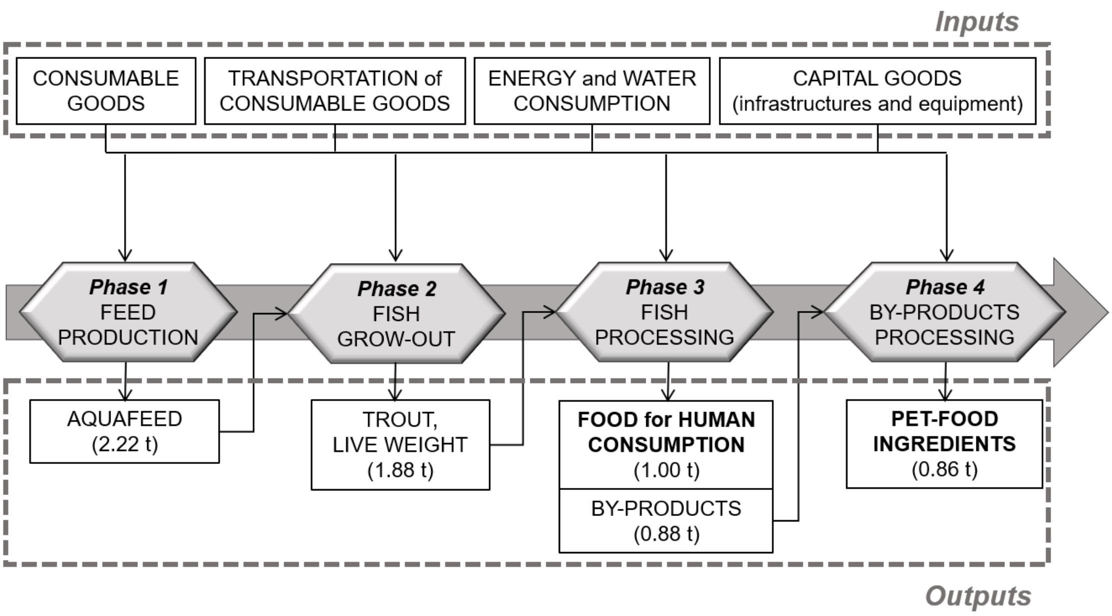

Figure 4.2 System boundaries. The two final outputs of the supply chain (*i.e.* Food for Human Consumption and Pet-Food Ingredients) are highlighted in bold. The reported mass balance of all outputs is scaled on 1 tonne of Food for Human Consumption, since this output represents the main purpose of the whole production.

With regards to the by-product processing phase (phase 4), the environmental sustainability is evaluated through the inclusion of the avoided products in the analysis. In other terms, the production of pet-food ingredients through the valorisation of fish viscera, heads and frames avoids the impacts related to the production of conventional pet-food ingredients somewhere else. The equivalence between the product actually produced in phase 4 and those whose production was avoided is shown in Table 4.2.

Table 4.2 Avoided products related to the functional unit (1 tonne of fish by-products to be treated). PAP: processed animal proteins

Recycled products			**Avoided Products**		
Material	**Amount**	**Unit**	**Material**	**Amount**	**Unit**
Animal grade hydrolysates (liquid) + fat (semi-solid)	267.00 + 44.00	kg	Fish hydrolysate from whole fishes in Chile	311.00	kg
Frozen minced fish	689.00	kg	PAP & fat, from broiler	689.00	kg
TOTAL	1,000.00	kg	TOTAL	1,000.00	kg

2.2.2 Life cycle inventory (LCI) and main assumptions

Most of the foreground data were provided by the companies involved in this study: (i) the most important feed supplier of the consortium, that is one of the main aquafeed producers in Italy; (ii) three companies of the ASTRO consortium, each managing one or more production sites (9 sites in total), (iii) the industrial manufacturing plant of ASTRO consortium, converting the whole fish in several processed products for human consumption (located in Lavis, Trento, Italy); (iv) an industrial plant which collects all fish by-products from the consortium and converts them into ingredients for the pet-food industry. Inventory data (Table 4.3) were clustered into the following sub-categories: ‘Consumable goods’ (including the use of sanitizing chemicals), ‘Transportation of consumable goods’ (from either the producer or the retail store to the plant/fish production site), ‘Capital goods’ (the various infrastructure and building materials), ‘Energy consumption’, ‘Water consumption’, ‘Emissions in water’, ‘Wastes and other emissions’.

Table 4.3 Life Cycle Inventory. The inputs and outputs data of each phase are scaled on 1,000 kg of product. BOD: Biological Oxygen Demand. COD: Chemical Oxygen Demand.

	FEED PRODUCTION			**FISH GROW-OUT**		
	Inputs	**Quantity**	**Unit**	**Inputs**	**Quantity**	**Unit**
Consumable goods	Fish ingredients (South America)	320.00	kg	Aquafeed	1,179.15	kg
	Other animal ingredients (European Union)	310.00	kg	Chemicals	3.68	kg
	Plant ingredients (European Union)	370.00	kg			
Transportation	Road transport of feed ingredients	622,960.00	kg km	Road transport of inputs (aquafeed, eggs, chemicals)	235,778.07	kg km
	Ocean transport of feed ingredients	3,739,520.00	kg km			
Capital Goods				Raceways (concrete)	748.88	kg
				Nets (nylon)	0.16	kg
Energy Consump.	Electricity (Country energy grid)	148.00	kWh	Electricity (Country energy grid)	1,032.11	kWh
	Natural gas	18.00	m^3	Diesel	26.51	L
Water Consump.	Water (from water supply system)	0.32	m^3	Water (from river and/or well)	128,462.61	m^3
	Outputs	**Quantity**	**Unit**	**Outputs**	**Quantity**	**Unit**
Product	Aquafeed	1,000.00	kg	Trout at marketable size (live weight)	1,000.00	kg
Emissions in water				Water (back to river)	128,462.61	m^3
				Chemicals (in river)	3.68	kg
				Nitrogen (in river)	57.9	kg
				Phosphorus (in river)	7.9	kg
Wastes and other emissions	Steam (in the atmosphere)	0.32	m^3	Dead biomass (incinerated)	122.58	kg
	Feed production scrap (incinerated)	1.02	kg			

	FISH PROCESSING			BY-PRODUCT PROCESSING		
	Inputs	**Quantity**	**Unit**	**Inputs**	**Quantity**	**Unit**
Consumable goods	Trout at marketable size (live weight)	1,877.61	kg	By-products (viscera, heads, frames)	1,024.67	kg
	Packaging	67.66	kg	Hydrolysis enzymes	2.62	kg
	Ingredients added to fish	26.43	kg	Chemicals	7.39	kg
Transportation	Road transport of trout	93,880.39	kg km	Road transport of by-products	245,920.84	kg km
	Road transport of the other inputs	24,387.69	kg km	Road transport of the other inputs	628.60	kg km
Capital Goods	Processing machines (stainless steel)	0.32	kg	Processing machines (stainless steel)	0.32	kg
Energy Consump.	Electricity (Country energy grid)	766.06	kWh	Electricity (Country energy grid)	7,903.50	kWh
	Electricity, self-production	139.08	kWh	Natural gas	294.64	m^3
Water Consump.	Water (from water supply system)	30.60	m^3	Water (from water supply system)	7.78	m^3
	Outputs	**Quantity**	**Unit**	**Outputs**	**Quantity**	**Unit**
Product	Food for human consumption	1,000.00	kg	Pet-food ingredients	1,000.00	kg
	By-products	880.00	kg			
Emissions in water	Water (back to river)	30.60	m^3	Water (sewerage)	6.78	m^3
	Suspended solids	2.45	kg	Suspended solids	0.54	kg
	BOD	1.22	kg	BOD	0.27	kg
	COD	4.90	kg	COD	1.08	kg
Wastes and other emissions	Semi-solid organic residuals collected from water (compost)	333.80	kg	Semi-solid organic residuals collected from water (compost)	3.25	kg
	Wasted packaging (recycled)	8.35	kg	Steam (in the atmosphere)	0.92	m^3
				Scraps from hydrolysis (incinerated)	64.27	kg
				Scraps from freezing (incinerated)	37.85	kg
				Chemicals (sewerage)	7.39	kg

Gaps in the inventory were filled with the assumptions reported in Table 4.4. Background activities, such as raw materials production, transportation modes and energy generation (electricity, diesel fuel, etc.) were mainly derived from *Ecoinvent v3*. The aquafeed ingredients and the conventional pet-food ingredients (used as avoided products) were derived from *Agribalyse v1.3*.

Table 4.4 Assumptions made to fill inventory gaps

TOPIC	DETAILS
Emissions in water	*Phase 1* – Emissions were not considered. *Phase 2* – Emissions of farm metabolic wastes (total nitrogen and phosphorous releases to water) were modelled by horizontal averaging literature data (Aubin et al., 2009; Avadí et al., 2015; Boissy et al., 2011; Dekamin et al., 2015; Grönroos et al., 2006; Samuel-Fitwi et al., 2013) according to the method described in Henriksson et al., (2014). *Phase 3 and 4* – Emissions were modelled according to the worst-case scenario, that is the concentration limits stated by the Italian legislation.
Waste water treatment	*Phase 3 and 4* – Waste water treatments lead to the separation of semi-solid organic residuals from the main stream. Being 100% organic, they are disposed of as compost and applied to field as a planting bed amendment.
Lifespan of infrastructures	Adoption of the average lifespan (assuming only ordinary maintenance): stainless steel machineries = 25 years; nylon nets = 10 years; concrete raceways = 50 year.
Infrastructures weight	Raceways – Data provided by farmers were cross-references with Google Maps measurements. The worst scenario was adopted, always considering the concrete walls of the raceways to be 1.5 m deep and 0.2 m thick (although some facilities have 0.6-0.7 m deep raceways). Concrete density was considered equal to 2,250 kg m^{-3}.
Transport distances	Road distances were calculated from Google Maps; ocean distances (transport of aquafeed ingredients from South America to a Dutch harbour) were assessed from marinetraffic.com

2.2.3 Life Cycle Impact Assessment (LCIA)

The impact assessment was performed using ReCiPe 2016 Midpoint (H) V1.02 (Huijbregts et al., 2016), since ReCiPe is a follow up of Eco-indicator and CML methods and it represents the most recent and harmonized indicator approach available in life cycle impact assessment (European Commission/JRC, 2010).

The following ICs were selected: climate change (GWP, expressed in kg of CO_2 eq. to air); terrestrial acidification (TAP, expressed in kg SO_2 eq. to air); freshwater eutrophication (FEP, expressed in kg P eq. to fresh water); terrestrial ecotoxicity (TETP, expressed in kg 1,4-DCB eq. to industrial soil); freshwater ecotoxicity (FETP, expressed in kg 1,4-DCB eq. to fresh water). Furthermore, one single issue method (Frischknecht et al., 2007) was applied to evaluate the Cumulative Energy Demand (CED, expressed in MJ). According to the literature (Aubin, 2013; Cao et al., 2013; Henriksson et al., 2012; Philis et al., 2019), these ICs are the best proxies of aquaculture impacts.

Finally, the methodology CML-IA baseline V3.05 (Guinée et al., 2002) was used as an alternative to ReCiPe in order to facilitate the comparison with previous LCA studies on trout systems (Aubin et al., 2009; Avadí et al., 2015; Boissy et al., 2011; Chen et al., 2015; D’Orbcastel et al., 2009; Dekamin et al., 2015; Papatryphon et al., 2004b; Samuel-Fitwi et al., 2013). The CML-IA impacts maintain the unit of those assessed with ReCiPe, except for the eutrophication impact (FEP), which in CML-IA is assessed in terms emissions in water (without discerning between marine and freshwater nutrient limitation) and is expressed in kg of PO_4^{3-} eq. However, it is worth mentioning that the results obtained with CML-IA and ReCipe methodologies cannot and should not be compared due to significant methodological differences (with ReCiPe including a wider set of emissions in the characterisation model and presenting a refined classification of substances).

3. Results

An overview of the sustainability of the whole supply chain is provided through a contribution analysis (Figure 4.3). Then, in order to gain a thorough understanding of the key issue in each phase, the hotspots highlighted in Figure 4.3 are cross-checked with the absolute values provided in the four tables (Tables 4.5, 4.6, 4.7, 4.8), where the impacts of each sub-category are detailed.

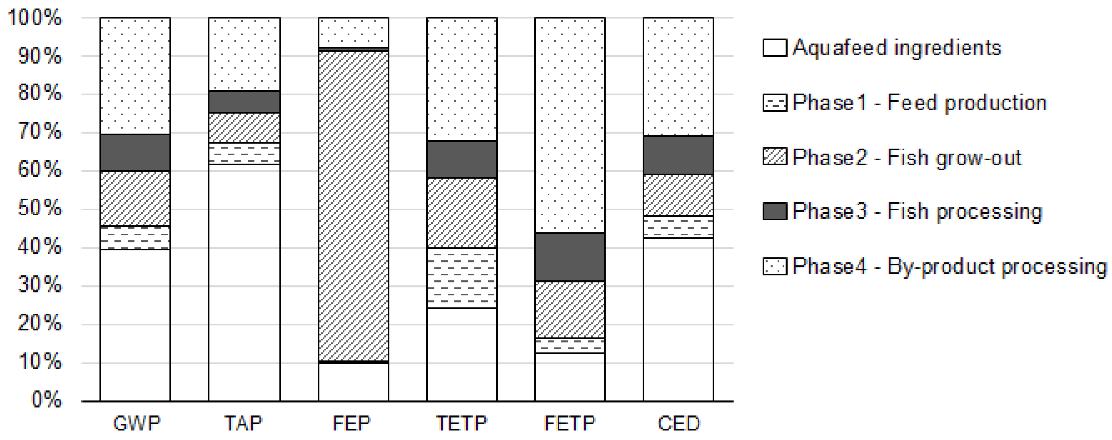

Figure 4.3 Contribution analysis. Each column represents the contribution of the four phases to one of the six ICs. Aquafeed ingredients are represented as a separate segment (although belonging to phase 1) since they are the main raw material entering the supply chain. Phase 4 includes the contribution of the avoided burdens.

Table 4.5 LCIA on Feed Production (phase 1). Impacts are scaled on 1 tonne of aquafeed produced. Where not specified, impacts are assessed with the ReCiPe H method.

SUB-CATEGORIES	GWP kg CO_2 eq. to air	TAP kg SO_2 eq. to air	FEP kg P eq. to fresh water	TETP kg 1,4-DCB eq. to industrial soil	FETP kg 1,4-DCB eq. to fresh water	CED MJ
Fish ingredients	358.36	1.23	0.02	281.40	1.40	5,382.12
Other animal ingredients	603.78	9.50	0.19	1,045.78	8.10	13,913.83
Plant ingredients	535.27	5.33	0.62	1,055.68	12.55	15,177.01
Transportation	145.83	1.10	0.01	1,434.18	1.87	2,351.43
Energy consumption	75.20	0.29	0.02	139.88	4.67	2,111.54
Water consumption	0.12	0.00	0.00	0.29	0.00	2.28
TOTAL	**1,718.57**	**17.46**	**0.86**	**3,957.20**	**28.60**	**38,938.21**
TOTAL (CML-IA methodology)	**1,655.16**	**16.68**	**12.36**	**142.13**	**860.06**	

Table 4.6 LCIA on Fish Grow-out (phase 2). Impacts are scaled on 1 tonne of trout (live weight) produced. The values reported are the average of the 3 farm companies LCA results. Where not specified, impacts are assessed with the ReCiPe H method.

SUB-CATEGORIES	GWP kg CO_2 eq. to air	TAP kg SO_2 eq. to air	FEP kg P eq. to fresh water	TETP kg 1,4-DCB eq. to industrial soil	FETP kg 1,4-DCB eq. to fresh water	CED MJ
	Average	Average	Average	Average	Average	Average
Aquafeed	2,002.49	20.34	1.00	4,610.97	33.32	45,371.21
Chemicals	8.09	0.06	0.00	18.65	0.47	155.33
Transportation	39.58	0.15	0.00	506.48	0.62	650.95
Capital goods	87.17	0.21	0.02	381.46	2.11	819.56
Energy consumption	531.18	2.30	0.16	1,241.28	27.74	9,337.24
Water consumption	0.00	0.00	0.00	0.00	0.00	0.00
Emissions in water	0.00	0.00	7.90	0.00	0.00	0.00
Dead biomass disposal	4.46	0.02	0.00	9.01	1.04	31.33
TOTAL	**2,672.97**	**23.08**	**9.08**	**6,767.85**	**65.31**	**56,365.62**
TOTAL (CML-IA methodology)	**2,587.64**	**22.78**	**63.86**	**169.16**	**1,292.68**	

Table 4.7 LCIA on Fish Processing (phase 3). Impacts are partly allocated to 1 t of the main product, that is the food for human consumption (99.64%) and partly to 0.88 t of by-products produced alongside (0.36%). Where not specified, impacts are assessed with the ReCiPe H method.

SUB-CATEGORIES	GWP kg CO_2 eq. to air		TAP kg SO_2 eq. to air		FEP kg P eq. to fresh water		TETP kg 1,4-DCB eq. to industrial soil		FETP kg 1,4-DCB eq. to fresh water		CED MJ	
	Main products	By-products	Main products	By-products	Main products	By-products	Main products	By-products	Main products	By-products	Main products	By-products
Trout (whole fish)	5,248.89	18.83	44.52	0.16	17.08	0.06	13,160.83	47.20	139.43	0.50	110,971.78	398.00
Chemicals	194.87	0.70	0.53	0.00	0.02	0.00	242.43	0.87	1.95	0.01	4,879.74	17.50
Transportation	54.23	0.19	0.19	0.00	0.01	0.00	362.12	1.30	2.00	0.01	860.10	3.08
Capital goods	1.70	0.01	0.01	0.00	0.00	0.00	29.28	0.11	0.09	0.00	22.32	0.08
Energy consumption	374.38	1.34	1.44	0.01	0.11	0.00	995.32	3.57	26.78	0.10	8,007.37	28.72
Water consumption	11.14	0.04	0.04	0.00	0.01	0.00	21.39	0.08	0.54	0.00	171.46	0.61
Emissions in water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid wastes disposal	-28.10	-0.10	-0.06	0.00	0.00	0.00	-2.96	-0.01	-0.04	0.00	-674.32	-2.42
TOTAL	**5,857.11**	**21.01**	**46.66**	**0.17**	**17.24**	**0.06**	**14,808.42**	**53.11**	**170.74**	**0.61**	**124,238.44**	**445.58**
TOTAL (CML-IA methodology)	**5,676.12**	**20.36**	**46.68**	**0.17**	**120.87**	**0.43**	**324.91**	**1.17**	**2,833.03**	**10.16**		

Table 4.8 LCIA on By-product processing (phase 4). Impacts are scaled on 1 tonne of pet-food ingredients produced. Where not specified, impacts are assessed with the ReCiPe H method.

SUB-CATEGORIES	GWP kg CO_2 eq. to air	TAP kg SO_2 eq. to air	FEP kg P eq. to fresh water	TETP kg 1,4-DCB eq. to industrial soil	FETP kg 1,4-DCB eq. to fresh water	CED MJ
By-products	201.94	1.62	0.59	509.31	5.83	4,302.16
Chemicals	42.05	0.29	0.10	170.55	1.63	852.66
Transportation	155.68	0.56	0.02	1,121.77	5.53	2.413.17
Capital goods	1.72	0.01	0.00	29.62	0.09	22.58
Energy consumption	4,127.51	14.70	1.08	7,390.59	248.25	83,065.46
Water consumption	2.84	0.01	0.00	5.46	0.14	43.74
Emissions in water	0.00	0.00	0.00	0.00	0.00	0.00
Solid wastes disposal	3.55	0.01	0.00	7.17	0.83	24.93
Avoided burdens contribution	-1,561.81	-4.34	-0.08	-961.57	-5.18	-26,192.89
TOTAL	**2,973.48**	**12.88**	**1.71**	**8,272.90**	**257.12**	**64,531.81**
TOTAL (CML-IA methodology)	**2,903.15**	**14.52**	**8.34**	**33.52**	**2,133.56**	

The environmental impact related to the production of food for human consumption (the main purpose of the whole production) is reported in Table 4.7 and is scaled on 1 tonne of final product: 5,857.11 kg CO_2 eq. to air (GWP), 46.66 kg SO_2 eq. to air (TAP), 17.24 kg P eq. to fresh water (FEP), 14,808.42 kg 1,4-DCB eq. to industrial soil (TETP), 170.74 kg 1,4-DCB eq. to fresh water (FETP), 124,238.44 MJ (CED). The impacts of the whole supply chain are those caused by the production of 1 tonne of foodstuff plus 0.86 tonnes of pet-food ingredients (in compliance with the mass balance reported in Figure 4.2): 8,414.30 kg CO_2 eq. to air (GWP), 57.74 kg SO_2 eq. to air (TAP), 18.71 kg P eq. to fresh water (FEP), 21,923.11 kg 1,4-DCB eq. to industrial soil (TETP), 391.86 kg 1,4-DCB eq. to fresh water (FETP), 179,735.79 MJ (CED). These impacts are not explicitly shown in a table, but they can be assessed by summing 100% of the impacts provided in Table 4.7 with 86% of the total impacts in Table 4.8.

The overview of the whole supply chain (Figure 4.3) highlights the critical aspects of each production phase. First, it is evident the key role of the aquafeed ingredients, accounting for 40, 62 and 43% of the whole GWP, TAP and CED respectively. The subsequent processing of the ingredients into aquafeed (phase 1) increases the share of terrestrial ecotoxic impacts (40% of the TETP of the whole supply chain). Fish grow-out (phase 2) is the main responsible of the eutrophication impacts (accounting for 81% of the total FEP) but affects other ICs as well (14, 18 and 15% of GWP, TETP and FETP respectively). The impacts contribution produced by phase 3 (the processing of live weight trout into food products) never exceed 12%, while the environmental burdens caused by phase 4 (the processing of trout by-products) are again quite high, accounting for 30, 32, 56 and 31% of GWP, TETP, FETP and CED respectively.

A closer examination of each phase revealed that, within phase 1 (Table 4.5) the main hotspot is represented by the production of ‘plant ingredients’ and of ‘other animal ingredients’ (*i.e.* poultry and livestock by-product meals). Indeed, their individual contribution to the three critical impacts identified in phase 1 is always higher than 30%: at least 535 kg CO_2 eq. over the total 1,719 kg emitted in the atmosphere (GWP); at least 5 kg SO_2 eq. over the total 17 kg emitted in the air (TAP); at least 13,914 MJ over the total 38,938 MJ consumed (CED). Moreover, if summed together, the impacts of ‘plant ingredients’ and ‘other animal ingredients’ account for no less than 55% in all the six ICs here considered. In phase 2 (Table 4.6), apart from the contribution to impacts due to the main raw material (the ‘aquafeed used’), other sub-categories require attention. With regards to freshwater eutrophication (FEP), which is the most critical impact of this phase, the ‘emissions in water’ account alone for 7.90 kg of P eq. over the total 9.08 kg emitted in freshwater. Another important sub-category is that of ‘energy consumption’ since it accounts, in the other three critical ICs of phase 2, for at least 18% of the total impacts: 531 kg of CO_2 eq. over the total 2,673 kg emitted in the atmosphere (GWP); 1,241 kg of 1,4-DCB eq. over the total 6,768 kg emitted into industrial soil (TETP); 28 kg of 1,4-DCB eq. over the total 65 kg emitted into freshwater (FETP). In phase 3 (Table 4.7) the impact contribution of the main raw material (that is, trout at marketable size) overcomes the share of all the other sub-categories, as they account together for less than one fifth of the total impacts in all the 6 ICs considered. Finally, in phase 4 (Table 4.8), the high values observed in the four critical ICs (GWP, TETP, FETP, CED) are mainly due to the 'energy consumption' sub-category.

4. Discussion

4.1 General considerations and comparison with literature

To the author's knowledge, this study is the first LCA performed on most of the rainbow trout supply chain by means of a conventional impact assessment methodology. Indeed, the only two studies with similar system boundaries (Grönroos et al., 2006; Silvenius et al., 2017) adopted unconventional characterization models, making it difficult to compare results with other LCA studies on trout.

Our results assessed through the CML-IA methodology and CED (Tables 4., 4.6, 4.7, 4.8) are consistent with those found in literature (Table 4.9). More specifically, our results in phase 1 fall within the ranges of previous studies specifically addressing salmon feed (Pelletier et al., 2009) and trout feed (Boissy et al., 2011) and, once again, confirm the aquafeed to be one of the major environmental impact sources along the supply chain (Aubin, 2013; Bohnes et al., 2018; Newton and Little, 2018; Smarason et al., 2017).

Table 4.9 LCIA results (assessed with the CML-IA methodology) found in literature. Values for phase 1 were taken from: Pelletier et al. (2009); Boissy et al. (2011). Values for phase 2 were taken from: Papatryphon et al. (2004b); Samuel-Fitwi et al. (2013a); Chen et al. (2015); Aubin et al. (2009); Dekamin et al. (2015); supplementary materials of Boissy et al. (2011); supplementary materials of Avadí et al. (2015); D'Orbcastel et al. (2009). Impacts are scaled on 1 tonne of product.

	Climate change	**Acidification**	**Eutrophication**	**Terrestrial ecotoxicity**	**Freshwater ecotoxicity**	**CED**
	kg CO_2 eq. to air	kg SO_2 eq. to air	kg PO_4^{3-} eq. to fresh water	kg 1,4-DCB eq. to industrial soil	kg 1,4-DCB eq. to fresh water	MJ
Phase 1	1,450 - 3,060	9 - 28	6 - 10	//	//	18,070 - 44,700
Phase 2	1,760 - 3,561	10 - 33	29 - 76	17 - 19	//	30,000 - 78,200

Eutrophication impacts in phase 2 (fish grow-out) are consistent with those in scientific publications on flow-through freshwater systems (Table 4.9), both in terms of absolute values (Table 4.5) and as percentage contributions (Figure 4.3). Our results for the ICs climate change (GWP), acidification (AP) and cumulative energy demand (CED) are in line with literature results as well. However, with regards to fish metabolic wastes and eutrophication impacts, some of these scientific publications totally omitted the specific source of information, while the others calculated N and P emissions by using a mass-balance approach: (i) a revised model of Cho and Kaushik (1990), as in the case of Aubin et al. (2009), Avadí et al. (2015), Boissy et al. (2011); (ii) the models developed by INRA-National Institute for Agricultural Research (Papatryphon et al., 2005, 2004a), as in the case of D'Orbcastel et al. (2009), Dekamin et al. (2015), Papatryphon et al. (2004b). This is due to the difficulties in getting primary data, since an accurate quantification of phosphorus and nitrogen trout emissions into the aquatic environment requires a time and money consuming monitoring (throughout a whole day and repeated several times throughout the year).

With regards to phases 3 and 4, our results on the whole supply chain cannot be compared with trout literature. Of the 2 papers which expanded the system boundaries beyond the farm gate (Grönroos et al., 2006; Silvenius et al., 2017), the first one provided a single-score impact obtained by normalising and weighting results, while the second one stated a climate change impact of 5,470 kg CO_2 eq. per t of product after having performed an economic allocation with an unspecified share of impacts between the main products and trout by-products. A comparison with LCAs on other salmonids supply chains may induce a misleading interpretation of results, since key aspects (*e.g.* feed ingredient composition and efficiency, on-farm operations, the allocation approach adopted between product and by-products) were proved to highly affect the results.

4.2 Performances of the four phases

As already explained in paragraph 2.1, the results can be considered representative of the ASTRO consortium and in general of the entire regional production, as all the associated companies (which represent 86% of trout farms in Trentino Alto Adige) use the same type of aquafeed and follow the same production protocol. This aspect is not frequent in trout LCA literature, as most of the studies published are limited to one production site (Philis et al., 2019).

With regards to phase 1, the most interesting result is that each of the three ingredients sub-categories (namely, ‘fish ingredients’, ‘other animal ingredients’, ‘plant ingredients’) accounts for around one third of the aquafeed in terms of biomass, but they affect the aquafeed environmental performances in a completely different way (Table 4.5). More specifically, the impacts of ‘fish ingredients’ are markedly smaller than those of the ‘other animal ingredients’ and of ‘plant ingredients’ simply because of the methodological choices made. The ‘fish ingredients’ are modelled by considering the infrastructures, water and energy used plus the wastes emitted along the fishing and processing activities:

the potential impacts caused to the marine ecosystem and to wild fish stocks, which are natural resources that self-regenerate in the oceans, are thus disregarded. In fact, some scientific research groups already developed a few indicators to cope with this problem (*e.g.* Biotic Resource Depletion, Sea Use and Biodiversity Loss), and more detailed aquafeed LCAs were already published. However, a deep focus on all the nuances of aquafeed sustainability assessment was not among the purpose of the present aquafeed model, which simply aimed at providing a quite reliable impact assessment of this phase so to trace its contribution along the supply chain.

All the activities carried out in phase 2 (fish grow-out) were included in the analysis, with the only exception being the fish production at hatchery. The decision was supported by the fact that the biomass of a fry never exceeds 2.9% of that of an adult animal (10g against a minimum weight of 350g for the fish at a commercial size), thus the amount of inputs and emissions related to the carrying out of this step was assumed to be negligible. Looking at LCA results, the major environmental impact caused by phase 2 is in term of freshwater eutrophication, which in turn is almost entirely due to fish metabolic wastes. Considerations about the quantification of these wastes were already made in paragraph 4.1. Yet, phase 2 has also some effects on climate change (GWP) and ecotoxicity (TETP and FETP). This is due to both the 'aquafeed' sub-category (in terms of the feed formulation and the amount used) and to the on-farm 'energy consumption'. A shift towards more sustainable energy sources, such as the hydropower used to replace the electricity from the national grid, would surely help improving this aspect.

With regards to the performances of phase 3, the impacts contribution due to fish processing activities is definitely low (Figure 4.3). The reasons are several. Almost no fish delivered to the trout processing plant is discarded: all animals are in good sanitary conditions (fresh and free of parasites and/or diseases, affecting internal quality), and those in noncompliance with morphological quality standards (*e.g.* size, shape, colour) are used to get fish skewers and minced fish products (Table 4.1). Good practices (such as the recycle of part of the wasted packaging) and technical improvements (*e.g.* photovoltaic panels installed on the roof) further improve the environmental sustainability (Table 4.7).

Despite this fact, the impacts related to the production of 1 tonne of food for human consumption (the main product of phase 3) double those related to the backstream process due to the efficiency rate of fish processing. Indeed, the amount of foodstuff obtained in phase 3 (1 tonne) represents on average 53% of the raw material consumed (1.88 tonnes of live-weight trout): yet, it is charged with 99.64% of the total impacts of phase 2 due to the economic-based allocation approach.

As a consequence, in phase 4 (Table 4.8) the environmental impacts caused by the raw material (fish by-products) are very low. However, the overall impacts of by-product processing phase are quite high in four ICs over six (Figure 4.3), due to the extensive use of electricity and natural gas. The reason of these high values lies in the fact that the company must keep the products at a constant low temperature, from the time it is purchased until the time it is sold. Thus, the energy needed for the cold chain management is consumed not only by the refrigerated cold stores, but also by the fully automated transport system and, obviously, by the machineries involved in the enzymatic hydrolysis and freezing processes (from the initial grinding of the raw material to the packaging and labelling of the final products).

4.3 Food for thought: LCA methodological aspects and possible improvements

The aquafeed formulation here used was based on primary data and the related impacts found were in line with those in literature but, as previously discussed, they were assessed by resorting to official LCI databases and standardised ICs, which still have room for improvement. In this regard, a joint research effort involving food industry professionals and several LCA practitioners is underway to develop a Seafood LCI database (Hognes et al., 2018) and other open inventories such as the Thai LCI database and the here used Agribalyse database, while in parallel several fishery-related LCAs have already been carried out (Avadí et al., 2019; Ziegler et al., 2016) and characterization models capable to include impacts on the oceans ecosystems have already been suggested by previous literature in this field (Cashion et al., 2016). Thus, more comprehensive inventories and ICs are expected to be integrated within the International Life Cycle Data system (https://eplca.jrc.ec.europa.eu/ilcd.html) in the near future.

Despite eutrophication due to nutrient emissions from trout farms appeared clearly as the main hotspot of phase 2, our study (together with most of the literature) still uses inventory data based on mass-balance models, due to a lack of field data. Another key aspect is that freshwater eutrophication is a local-scale IC and the actual negative effects on the environment depend on the assimilative capacity of the receiving water bodies. Indeed, according to the environmental mechanisms underlying the assessment of FEP impact, the addition of a considerable amount of nutrients in watercourses may affect the river vegetal community by favouring more nutrient-demanding species, with cascade effects on the whole aquatic ecosystem. However, environmental monitoring in the ASTRO production area did not show marked changes of the Extended Biotic Index (APAT-IRSA, 2003) upstream and downstream trout farms, in line with scientific literature findings (Fabrizi et al., 2010; Pontalti et al., 2006). This is probably linked to the lower water temperatures in mountain farms and the consequent: reduced trout growth rate (when compared to growth rate in plain lands); reduced nutrients load; increased oxygen concentration (available for the bacterial degradation of nutrients). Given the crucial importance of freshwater eutrophication IC, further researches on trout emissions under different environmental and farming conditions would certainly improve the degree of reliability of the inventory data used. This, coupled with some kind of quantification of the potentially altered area at the bottom of the river, as already suggested in Ford et al. (2012), would help gaining a more complete picture of the nutrients contribution to local scale effects.

The expansion of the system boundaries up to phase 4 allowed to include in the analysis both the products of the supply chain (foodstuff and pet-food ingredients), thus avoiding bias due to the use of the allocation approach. The inclusion of phase 4 also proves that system boundaries broader than the cradle-to-farm-gate perspective can reveal unexpected hotspots. In this specific case, the automated manufacturing process speeds up the production and increases the control on product quality, but at the same time it dramatically increases the energy requirement. In order to investigate to which extent this aspect negatively affects the environmental sustainability, results of phase 4 were compared with those of a simple incineration scenario. This alternative scenario includes both by-products transportation and municipal incineration (with fly ash extraction), and the incineration LCI data were sourced from Ecoinvent database. Results proved that the recycle of by-products into pet-food ingredients is as competitive as their incineration only if the former has almost null energy requirements. Indeed, after the removal of ‘energy consumption’ contribution (see Table 4.8), the environmental impacts of the recycling and of the incineration scenarios are respectively of: -1,154.03 and 634.81 kg CO_2 (GWP), -1.82 and 0.85 kg SO_2 (TAP), 0.63 and 0.12 kg P to freshwater (FEP), 882.31 and 261.27 kg 1,4-DCB to freshwater (TETP), 8.87 and 902.76 kg 1,4-DCB to industrial soil (FETP), -18,533.65 and 2,484.44 MJ (CED).

5. Conclusions

An assessment of the whole supply chain is very important from a LCA perspective, as it provides a full picture of the product sustainability. In this specific case study, the setting up of more comprehensive system boundaries was crucial in showing how and where the impacts increase along the supply chain. Our results where compared with previous literature whenever possible and always appeared consistent with it, despite some differences in the methodological choices made.

Several areas for improvement along the supply chain were pinpointed, with regards to choices in both the managing of the companies and in the modelling of the system according to LCA procedure. First, the modelling of aquafeed production (phase 1) could be further improved, and further research is needed to tailor LCA inventories and impact assessments methods capable of providing more precise and accurate measurements. Though not extremely accurate, yet the values obtained confirm the feed as an important aspect to consider in reducing the environmental impacts. With regards to fish grow-out (phase 2), the surge in eutrophication values is definitely a key issue, which makes it urgent to both increase the knowledge on trout emissions and to improve/develop impact assessment methods capable to better describe the effects of an increased nutrient release on freshwater ecosystems. Although the 'aquafeed' sub-category is the second main contributor to impacts, the 'energy consumption' needed to carry out farm activities appeared not to be negligible as well. In this regard, ways to improve the environmental sustainability include the use of an increased share of energy produced from renewable sources (either purchased or self-produced) and further efforts towards better management practices (*e.g.* sedimentation basins instead of energivorous filter machines at the outlet of the farm).

Finally, more attention must be paid towards the amount and source of energy used in the by-product processing (phase 4), since the energy impacts appeared high to the point that the incineration of fish by-products would be more sustainable. In order to improve the sustainability of this last phase, the use of renewable energy sources (rather than electricity from the Country energy grid) might be coupled to an improved insulation of the facilities and to the use of less energivorous machineries.

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Chapter 5. FRESHWATER RECIRCULATING SYSTEMS

TILAPIA AND LETTUCE PRODUCTION IN AN AQUAPONIC SYSTEM[7]

1. Introduction

Eco-design can be defined as the integration of environmental considerations into a planned production process, with the purpose of identifying critical aspects and improving the environmental performance before its actual realization (Brones et al., 2017). The eco-design approach has never been applied to aquaponics (Figure 5.1), that is an innovative practice which integrates the culture of aquatic animals (mainly fish) with the hydroponic production of plants (Tyson et al., 2011). Consumers are generally neutral or favourable to aquaponics (Short et al., 2017). Indeed, the food produced using aquaponic techniques is perceived as similar to the organic one and, as such, more healthy and tastier than its equivalent produced with conventional systems (Prada et al., 2017). Despite aquaponics uses less water than conventional aquaculture systems and markedly reduces waste emissions (da Silva Cerozi and Fitzsimmons, 2017; Danaher et al., 2013; Timmons and Ebeling, 2010), this type of production is still in its infancy and its environmental sustainability has not been fully investigated yet. Therefore, LCA is here applied to the project of a future aquaponic facility in order to get an overview of its environmental burdens and thus propose less impacting technical solutions prior to its actual building.

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[7] The contents of this chapter represent a substantial part of the conference paper:

Forchino A.A., Gennotte V., Maiolo S., Brigolin D., Mélard C., Pastres R. 2018.
Eco-designing Aquaponics: a case study of an experimental production system in Belgium. Procedia CIRP, 69:546-550. https://doi.org/10.1016/j.procir.2017.11.064

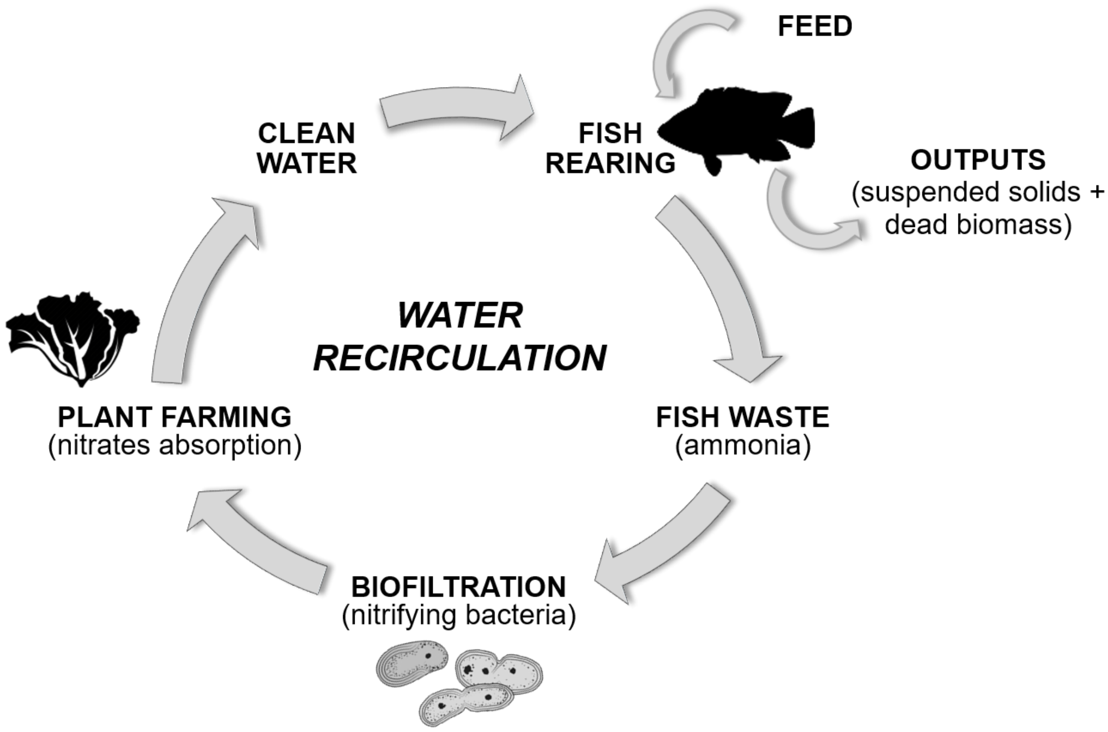

Figure 5.1 General scheme of an aquaponic system. The suspended solids include faeces and uneaten feed

2. Material and methods

2.1 System description

The pilot aquaponic system (Figure 5.2) will be hosted inside an insulated room, constructed in aerated concrete blocks (thermal transmittance U = 0.31 W m^{-2} K^{-1}) and with a surface of 104 m^2. The building is equipped with a double flow ventilation system. The fish culture equipment includes 6 rearing tanks (total volume = 6.4 m^3), a sump tank (0.6 m^3), a drum filter (250 W); a backwash pump (1 kW), a moving bed biofilter (1.5 m^3), a brushless circulation pump (0.5 kW), an air blower (1.5 kW), a UV sterilizer (95 W) and electrical heating (9 kW). The mechanical filtration is complemented by a swirl separator (3 m^3).

The water exiting the fish culture is conveyed to the mechanical filtering station (a swirl separator plus a drum filter) to remove most of the suspended solids discharged from the system as sludge. Hydroponic cultures are arranged on 3-level shelves lighted by artificial LED lighting (6 kW). The cultivated area (50 m^2) is composed of:

- 16.7 m^2 of 'Nutrient Film Technique' structures (where a shallow stream of water is recirculated beyond the bare roots of the plants);
- 33.3 m^2 of 'Deep Water Culture' tanks (where plants are inserted in polystyrene slabs, floating on a water layer deeper than 5 cm).

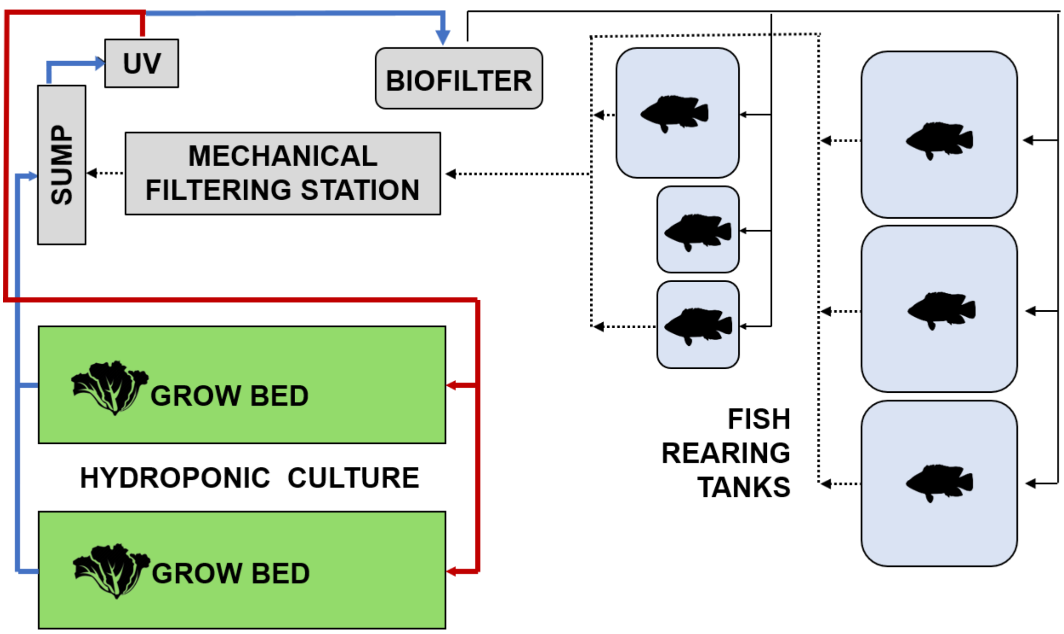

Figure 5.2 Outline of the aquaponic facility. The different pattern of the arrows highlights the direction of water flows

The daily water losses are exclusively due to drum filter backwashing and to the evapotranspiration from plants and the water surface. According to the technical characteristics of the system, they are expected to be 1.7% of the total water volume and will be partly compensated with rain water collected outside the facility. The quantity of rain water potentially collectable is estimated according to the local climate conditions and will reduce the consumption of water from the water mains. Always according to the technical design features, infrastructure lifespan was set at 25 years.

The system is designed to farm tilapia (Oreochromis niloticus) and lettuce (Lactuca sativa), which are among the species most frequently farmed by commercial aquaponic growers (Love et al., 2015). Tilapia is an internationally traded fish species (FAO, 2018), mainly farmed in Asian and North American countries and not well known in Europe yet. It is characterized by a rapid growth and by low operating costs. Lettuce is a leafy vegetable with a short growing period and low nutrient requirements (Yep and Zheng, 2019) and it is commonly consumed in Europe (Miličić et al., 2017; Villarroel et al., 2016).

2.2 Scope of the study

The main activities to be carried out in a year of production were taken into consideration. To facilitate the understanding and interpretation of the results, the input and output flows were organized into 5 sub-categories: 'Consumables', 'Capital goods', 'Water consumption', 'Energy consumption', 'Transportation' of consumables from the closest retailer to the pilot system (Figure 5.3).

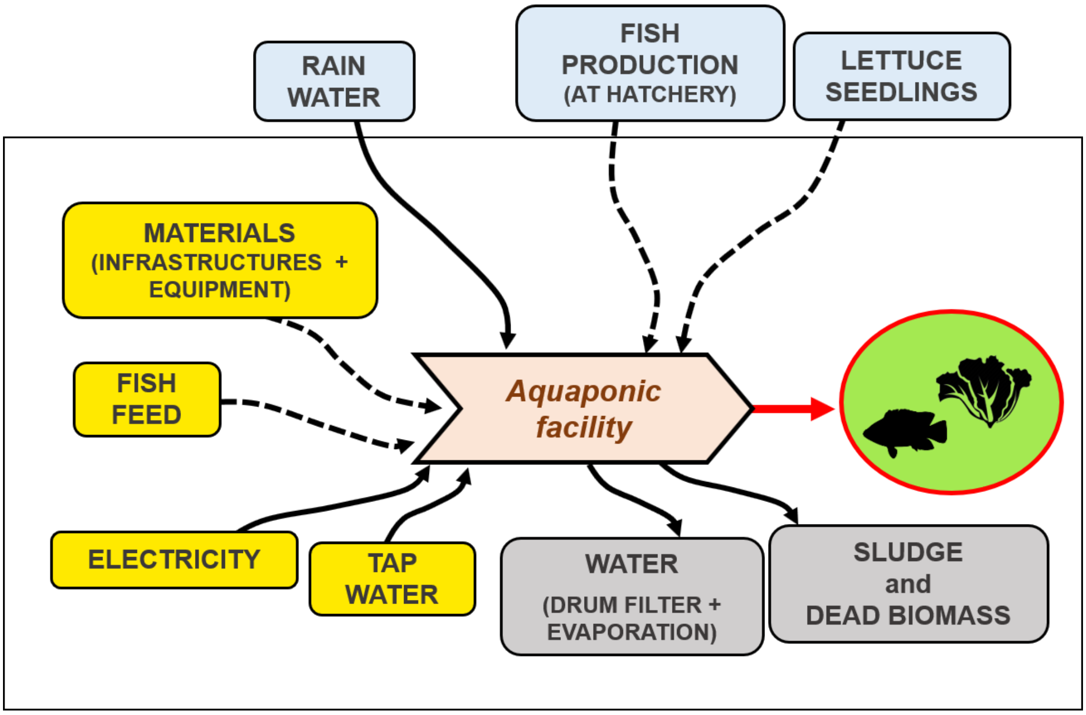

Figure 5.3 System boundaries of the considered aquaponic system. Dot arrows indicate processes for which transportation was considered

Lettuce and tilapia wastes (*i.e.* dead biomass and fish sludge in water) are included in the 'Consumables' sub-category. Being a natural resource, rain water was left out of the system boundaries, together with the production of lettuce seedlings and tilapia fingerlings. The functional unit is 1 kg of product. Since the expected yearly production is of 0.7 and 4 tons of fish and vegetable, respectively, the functional unit is composed of 0.85 kg of lettuce and 0.14 kg of tilapia.

2.3 Life Cycle Inventory (LCI)

To run the analyses, data collected were integrated with others derived from literature and experts' judgment. The main system features and consumptions are reported in Table 5.1.

Table 5.1 Aquaponic system design and main yearly expected flows of energy and matter.

Energy	
Water pumping + LED (kWh)	63,000
Heating (kWh)	15,000
Water	
Input - Tap water (m^3)	870
Input - Rain water (m^3)	200
Output - Water evaporation (m^3)	70
Output - Drum filter backwashing (m^3)	1,000
Production	
Fish feed (kg)	840
Fish production (kg)	700
Plant production (kg)	4,000

Lettuce and tilapia wastes are represented by accidental deaths and by suspended solids (faeces and uneaten feed) which must be removed from the system. Dead fish and lettuce were considered in terms of nitrogen and phosphorous released in the soil, assuming for them a landfill disposal scenario, while the removed suspended solids were quantified in terms of nitrogen and phosphorous released in the sewer system. The full list of the assumptions based on literature data is provided in Table 5.2.

Table 5.2 List of the assumptions based on literature data.

ASSUMPTION	REFERENCE
Mortality was set at 3% for tilapia.	(Akekapot Khammi et al., 2015)
Mortality was set at 10% for lettuce.	(Brault et al., 2002)
Fish faeces production was set at 193.68 g kg^{-1} of feed.	(Keramat Amirkolaie and Schrama, 2013)
Tilapia total fillet and carcass (skin + bones) were set at 279.9 g kg^{-1} and 720.1 g kg^{-1}, respectively.	(Gonzales and Brown, 2006)
Total nitrogen and phosphorous percentages in sludge (faeces + uneaten feed) were set at 18.37 and 5.6,	(Rafiee and Saad, 2005)

respectively.	
Total proteins and total phosphorous in Tilapia fillet were set at 834 g kg^{-1} and 0.03 g kg^{-1}.	(Gonzales and Brown, 2006)
Total proteins and total phosphorous in Tilapia carcass were set at 481 g kg^{-1} and 0.35 g kg^{-1}.	(Gonzales and Brown, 2006)
N and P contents in lettuce were 10.11% and 2.34%.	(Hamilton and Bernier, 1975)
Tilapia aquafeed formulation.	(Situmorang et al., 2016)

2.3 Impact Assessment methodology

All the calculations were performed using SimaPro® version 8.0.3.14 (PRé, 2012). The methodology CML-IA baseline V3.05 method (Guinée et al., 2002) was used to evaluate the ICs Global warming (kg CO_2 eq.), Acidification (kg SO_2 eq.) and Eutrophication (kg PO_4^{3-} eq.), while the method of Frischknecht et al. (2007) was used to assess the Cumulative Energy Use (MJ) impact. These four impacts were chosen since they are considered as representative of the main aquaculture environmental burdens (Aubin 2013; Cao et al. 2013; Henriksson et al. 2012).

3. Results

LCA results are reported in Table 5.3 and Figure 5.4. The analysis shows 'Energy consumption' to be by far the main source of impacts for the aquaponic system. In fact, this sub-category has a contribution higher than 85% in all the ICs here considered. 'Consumables' is the only other relevant sub-category, since it is responsible for 13% of the total Eutrophication impact. The contribution of 'Transportation', 'Water consumption' and 'Capital goods' to the overall impacts appears limited.

Table 5.3 LCIA results of the aquaponic system. The functional unit it 1 kg of product (0.85 kg of lettuce + 0.14 kg of tilapia)

	Global warming	Acidification	Eutrophication	Cumulative Energy Use
SUB-CATEGORY	kg CO_2 eq.	kg SO_2 eq.	kg PO_4^{3-} eq.	MJ
Consumables	0.25	0.00	0.01	3.13
Capital goods	0.75	0.00	0.00	11.60
Energy consumption	11.99	0.08	0.07	218.01
Water consumption	0.07	0.00	0.00	1.04
Transportation	0.09	0.00	0.00	1.43
Total	13.15	0.09	0.09	235.22

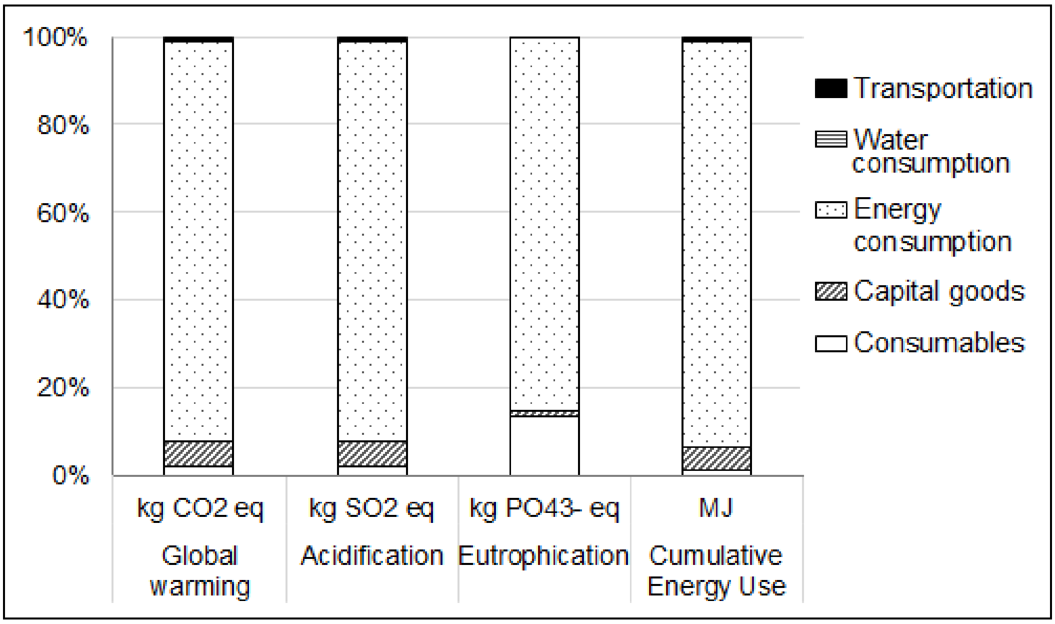

Figure 5.4 LCIA: contribution analysis

4. Discussion

The results reported in Table 5.3 and Figure 5.4 proved that 'Energy consumption' will surely represent a critical issue to achieve the sustainability of this future aquaponic facility. Since the growth rate of Tilapia is optimized in a narrow temperature range 28-32°C (D'Orbcastel et al., 2009), about 19% of the total energy consumed would be used to heat the water (up to 25°C) in order to meet the thermal needs of the species. According to Ecoinvent database, the Belgian electricity mix is mainly composed of fossil and nuclear sources, thus possible improvements could be made by implementing renewable energy sources. Moreover, according to the results, the design of the aquaponic system could be reviewed in terms of walls insulation-layer and energetic efficiency of the chosen equipment. However, the major part of energy consumed (81%) is due to water pumping (including the running of the drum filter) and artificial lighting. These impacts could be mitigated by reviewing the system equipment, opting for smaller and less 'energivorous' machineries. For example, an implementation of sedimentation tanks and/or skimmer to reduce the energy consumption linked to the drum filter should be evaluated.

The effects of the 'Consumables' sub-category on eutrophication are not negligible (13% of EU impacts). These results, mainly due to the aquafeed used and to the disposal of wastes in landfill and in the sewer system, are in line with previous findings (Forchino et al., 2017; Xie and Rosentrater, 2015). However, it is worth mentioning that in terms of absolute values the expected EU impact appears low, with only 0.01 kg PO_4^{3-} eq. emitted per kg of product (see Table 5.3). 'Capital goods' are not a source of concern, since infrastructures contribution to the environmental impacts represents 6% of the Global warming and Acidification and 5% of the Cumulative Energy Use.

'Water consumption' has a low contribution to impacts too (always below 1%). Even though at first sight this contribution seems minimal, the aquaponic system needs about 1070 m^3 $year^{-1}$, which are equivalent to a hydric consumption of about 250 L kg^{-1} of lettuce. This value is 10 times higher than the water demand calculated for hydroponic lettuce production (20 L kg^{-1}) and it is comparable to the one of conventional lettuce production (Barbosa et al., 2015). The critical point in the system design is clearly the drum filter, which accounts for more than 90% of the overall hydric consumption.

5. Conclusion

The research carried out, providing an overview of the strengths and weaknesses of the facility prior to its actual construction, proved the importance of LCA as an eco-design tool. Results indicated that the sustainability of fish and vegetable production using aquaponics techniques could sensibly increase by lowering the energy needs. With regards to the water requirements, although they do not significantly affect any of the impacts considered in this study, they turned out to be unexpectedly high and comparable to those of lettuce production in conventional soil-based agriculture. Several design improvements were suggested, but the use of a drum filter with better energy and water performances surely represents the key point.

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Chapter 6. EMERGY ANALYSIS: AN ALTERNATIVE RESOURCE ACCOUNTING TOOL

1. Introduction

As already stated more than 30 years ago in the Brundtland Report (United Nations, 1987), “The concept of sustainable development does imply […] limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities”. This increased attention to the natural resource management led towards a more conscious planning of the production processes and LCA is surely a powerful tool in this regard. However, as emerged from the critical review of the literature (chapter 2), to date the impact assessment of biotic and abiotic resource consumption is not fully integrated within LCA framework (Klinglmair et al., 2014). One of the crucial aspects is the renewability of the resources.

For instance, the characterisation model included in the CML-IA methodology (Guinée et al., 2002) expresses the non-renewable abiotic resource depletion of a given resource in terms of the ratio of the extracted mass to the natural existing reserves. This method is operational both for actual abiotic resources (*i.e.* metals, minerals, radioactive elements) and for fossil fuels which (although being formed from decayed organic matter) are considered as non-renewable due to the extremely long time needed to regenerate them. A key issue in this model is the fact that, although the abiotic resources from the geosphere are finite (or can be considered as such), still most of them can actually be stock in the technosphere and thus recycled several times. On the other hand, the abiotic resources which regenerate instantaneously (*i.e.* sunlight, electricity from wind power) are completely disregarded within the LCA approach.

As regards biotic resource depletion, their assessment obliges to consider, within the impact pathway, their renewal time (*i.e.* the time required for biotic resources to double their number of individuals). However, despite being renewable, these resources are highly affected by the surrounding environmental conditions and by the level of awareness and attention paid by humans while exploiting them. A negligent management of these resources could therefore lead to their exhaustion.

A general classification of the natural resources is shown in Figure 6.1. All biotic resources are obtained from the biosphere, while abiotic resources are those that come from non-living, non-organic material and they can be obtained mainly from the geosphere but also from the atmosphere and hydrosphere.

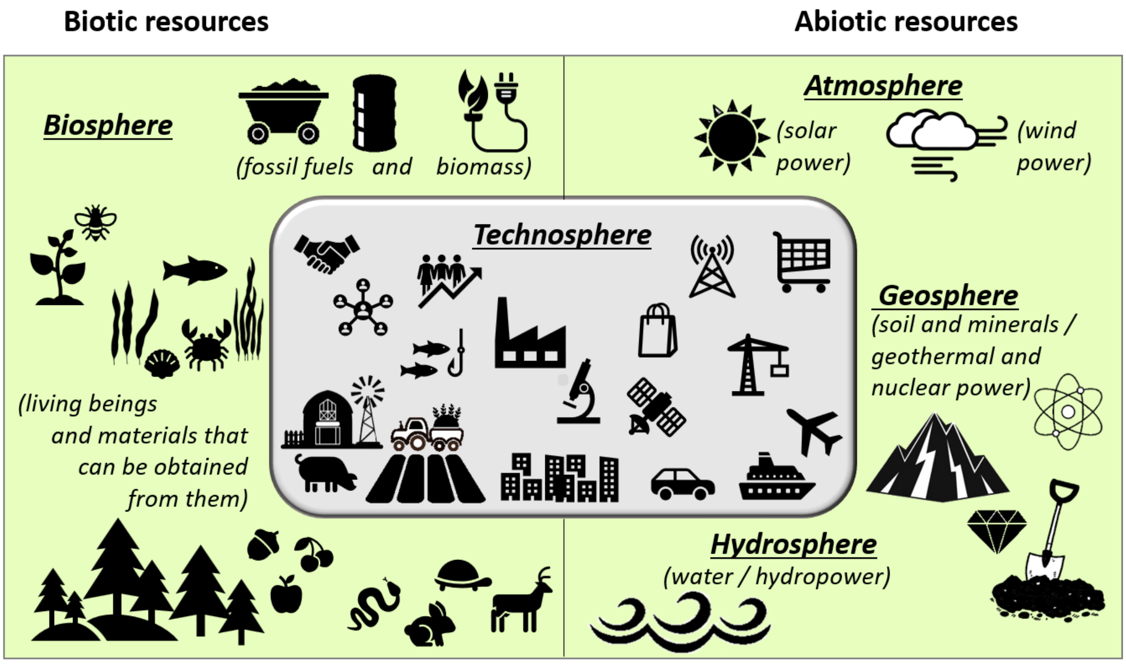

Figure 6.1 General classification of the natural resources.

The picture shows that all the matter and energy sources used by the technosphere (which comprises our economies and societies) ultimately depend on the availability of ecological goods and services in the geo-biosphere (including the provision of primary energies and materials, as well as the dilution and recycling of emissions).

However, LCA methodology has a utilitarian (*i.e.* anthropocentric) focus and, at present, it considers only the processes occurring in the technosphere. Thus, a huge scientific effort is being made to find a way to consider the total work that, within the geo-biosphere, underpins the resources used by human activities. Among the tools for environmental accounting, emergy stands out as one of the most interesting approaches.

2. The emergy approach

All energy forms (*e.g.* mechanical, thermal, electrical, chemical), are expressed with the same unit, *i.e.* the Joule (J). However, in accordance with the Second Law of Thermodynamics, different energy forms can be markedly different in terms of their 'quality'. Energy quality is taken into account by its entropy content, which sets an upper limit to the fraction of energy which can actually be converted into mechanical work. This concept can be restated in terms of Exergy, or available energy, which can be defined as "the shaft work or electrical energy necessary to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged only with the environment" (Riekert, 1974).

The concept of emergy (contraction of the English term embodied energy) was introduced by Odum in the early 1980s (Odum, 1996, 1988) as another way of taking into account the consequences of the Second Law, with a more explicit link to ecosystem theory. Emergy is defined as the available energy that is directly or indirectly required by a process in order to generate a product or a service. In other words, emergy quantifies all the energy sources, materials and ecosystem services along the whole production process and it represents the environmental work required to produce the product (or service), thus revealing hidden energy needs. Since solar energy is, by far, the main exergy inputs for terrestrial ecosystems, emergy is expressed in joule of solar energy (sej). Therefore, the emergy of a product represents the amount of solar energy required for manufacturing it.

The emergy method was applied to the alternative substitute for fishmeal described in chapter 3, in order to take into consideration both economic resources (from the technosphere) and environmental resources which support human economy (from the geo-biosphere).

3. The emergy approach

Unlike the Life Cycle Assessment performed in chapter 3, a single scenario for each meal was here considered. Both the Dry Microalgae Biomass (DMB) systems were modelled using liquid CO_2 as carbon source. The Insect Meal (IM) system was modelled using as substrate a compound made of corn and wheat residues, used in a small plant that produces 1 tonne of black soldier fly per day (Allegretti et al., 2018). As regards the Poultry By-product Meal (PBM) system, the emergy analysis is subjected to algebra rules different from those of the Life Cycle Assessment (as better explained in paragraph 3.3), thus it was not necessary to allocate the flows among co-products.

3.1 Overview of the emergy-algebra rules and of the emergy analysis

The emergy analysis is subjected to specific rules (Odum, 1996). Unlike what happens in an energy analysis, were there is a clear distinction between energy output and dissipated energy, here all the emergy sources needed by a process are entirely assigned to the output (first emergy-algebra rule). The second and third rules specifically relate to the type of process outputs. The third rule is similar to LCA allocation approach and is applied to processes having only one output, which can however be used for various purposes (Figure 6.5A). For example, the DMB could theoretically be used partly as a feed ingredient and partly for human consumption purposes (*e.g.* as a food supplement). In this case, each 'leg' of the split is charged with a share of the total emergy flow proportional to the energy content of each product fraction. When (as in the case of both IM and PBM) a process produces different types of outputs (Figure 6.5B), the emergy flow is entirely assigned to each of them (second rule). The reason lies in the fact that each product cannot be produced without producing the other, and thus it requires the total emergy input to be produced.

The fourth emergy-algebra rule, which however does not apply in the current context, states that emergy cannot be counted twice: if two co-products must be used together, their sum cannot be greater than the total emergy inflow.

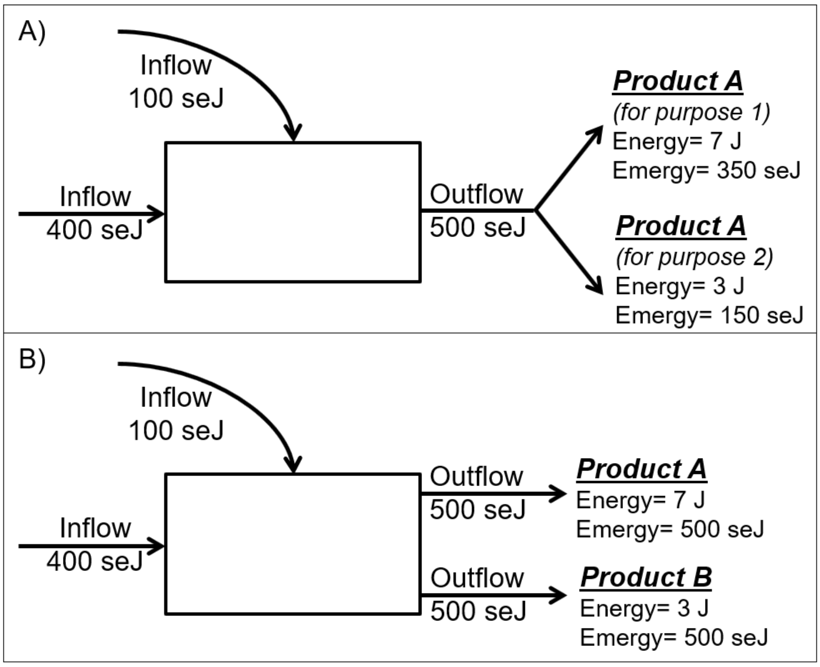

Figure 6.5 Emergy flows in a dual output system, illustrating both a pathway 'split' (A) and the allocation between co-products (B). The figure is adapted from Brown and Herendeen (1996)

The emergy analysis presented in this chapter is organized, according to the recommended method (Odum, 1996), into three steps: (i) all the main components within the system boundary must be identified and drawn in a systems energy flow diagram; (ii) the components are organized in an emergy evaluation table and converted into the equivalent sej content; (iii) emergy indicators are calculated and results are interpreted and discussed.

3.2 Step 1 – Systems emergy flow diagrams

Systems diagramming helps in identifying all the energy flows involved. The complex systems analysed through the emergy method are in some respects similar to the production processes considered while applying LCA. However, the resources belonging to the geo-biosphere are added in the former. The diagrams describing the production of the four protein sources are reported in Figure 6.2 (dry microalgae biomass), Figure 6.3 (insect meal) and Figure 6.4 (poultry by-product meal). The inputs from nature (renewable energies and local non-renewable sources) are positioned on the left side of the flow diagram, while the inputs from the economy are situated at the top and all the outputs on the right side.

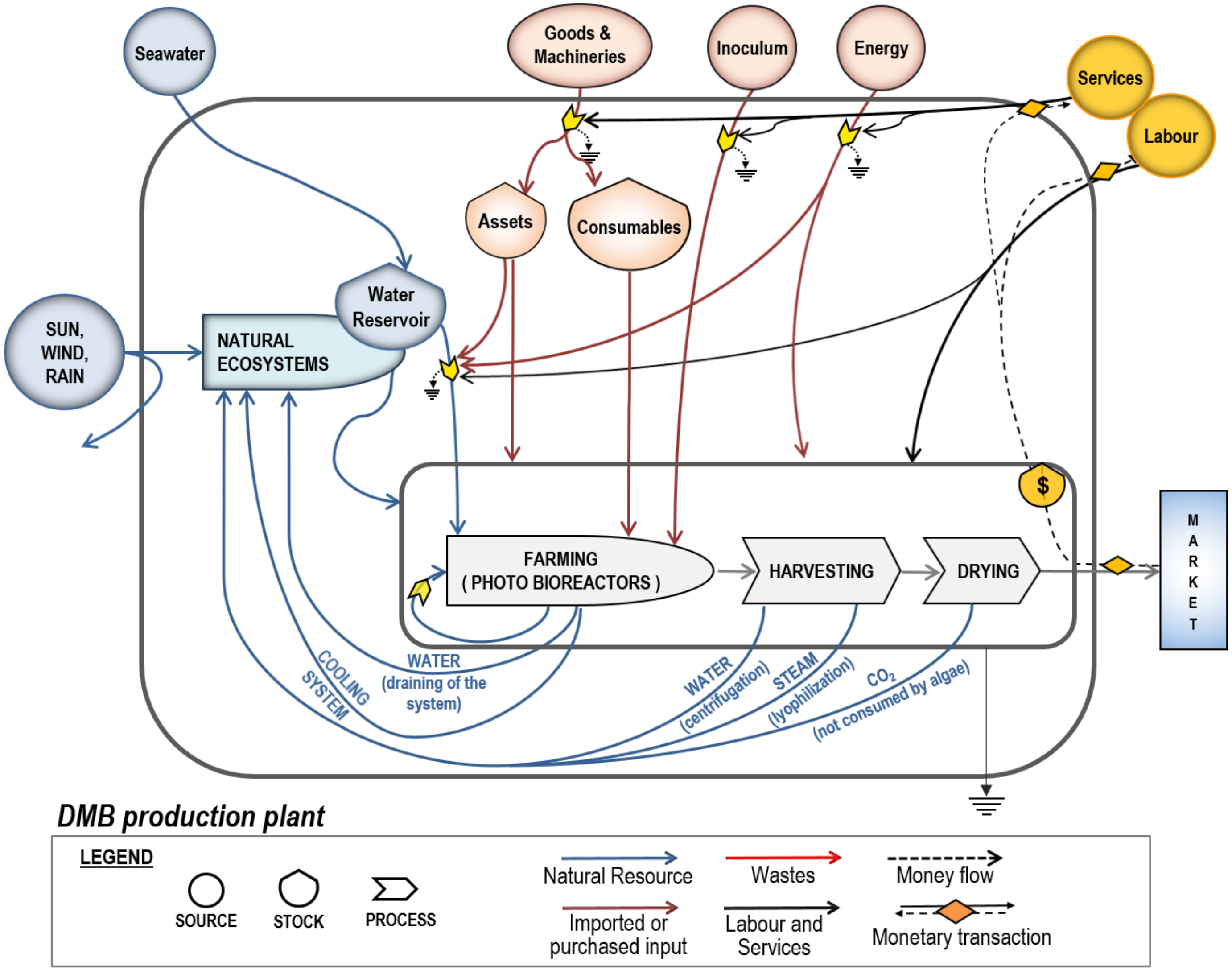

Figure 6.2

Emergy flow diagram of dry microalgae biomass (DMB) production plant.

The diagram is valid for both *Tetraselmis suecica* and *Tisochrysis lutea* production.)

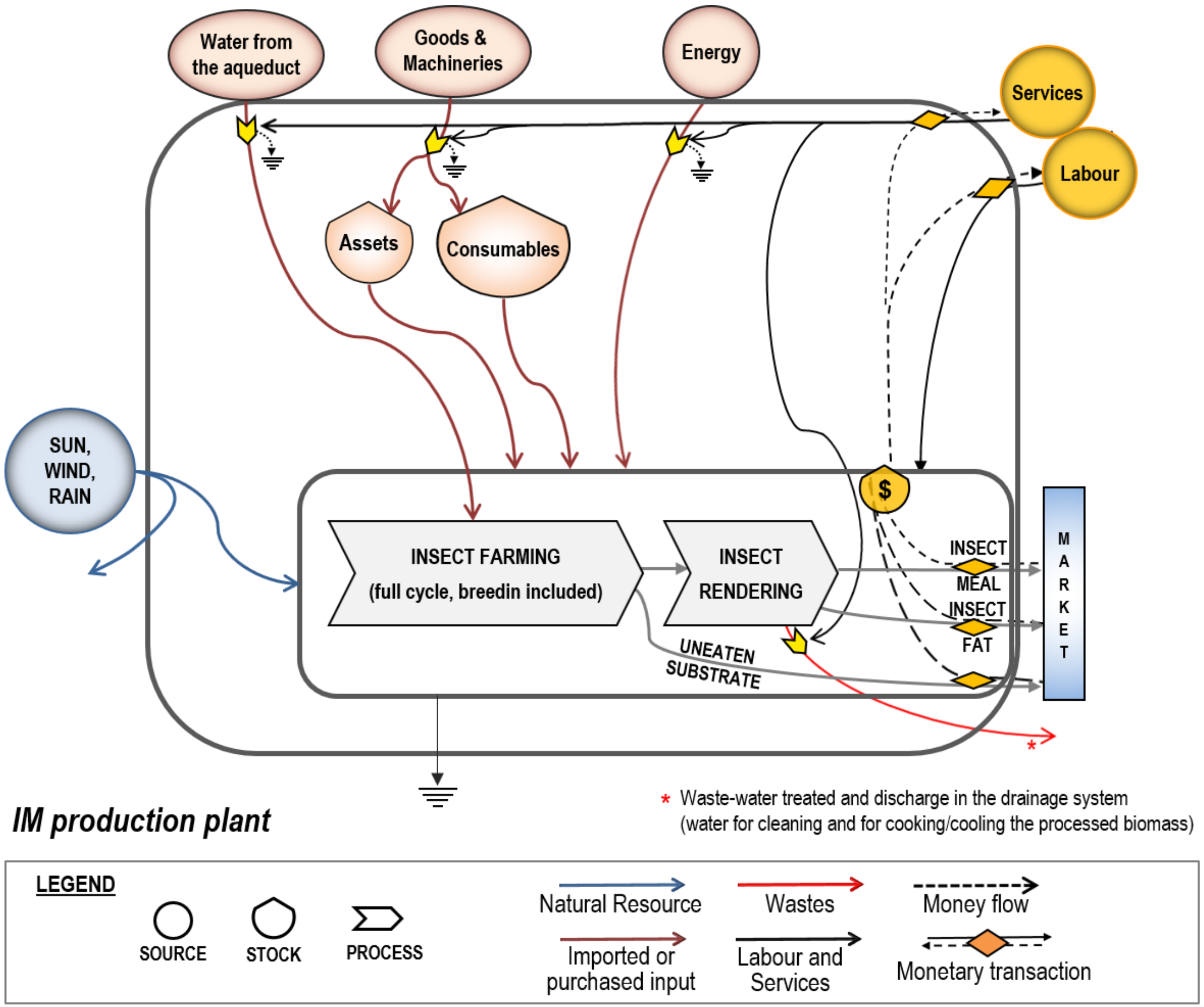

Figure 6.3

Emergy flow diagram of insect meal (IM) production

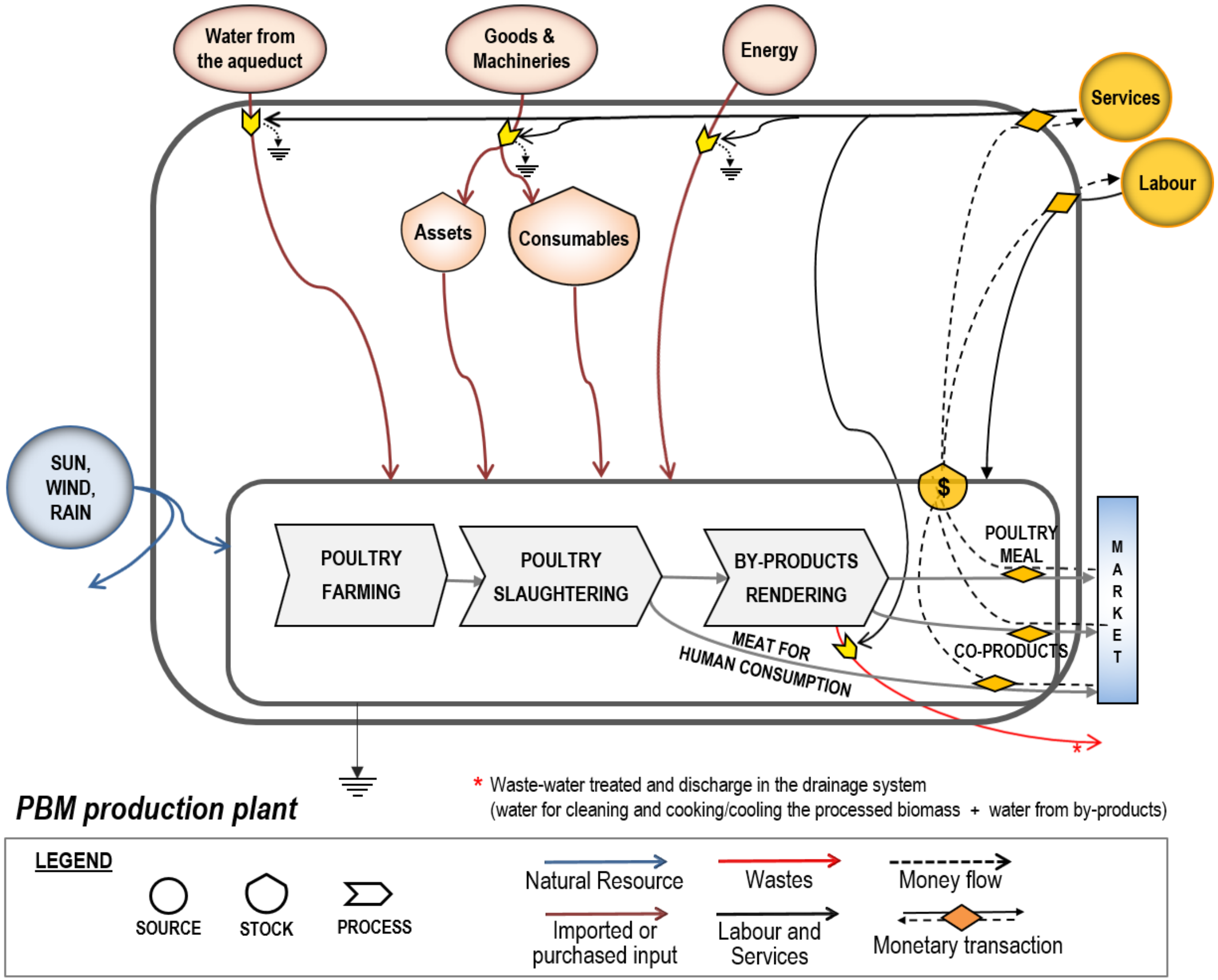

Figure 6.4

Emergy flow diagram of poultry by-products (PBM) production

3.3 Step 2 – Emergy evaluation tables and emergy-based indicators

The quantification of the inputs from nature requires several data. First, the surface area occupied by the production plant must be estimated, since these resources cannot reach the ground (and thus the geo-biosphere) precisely because of the presence of the plant. Then, site- and time- specific data must be gathered from a number of different data sources (Table 6.1).

Table 6.1 The assessment method for the renewable energy sources dissipated on land

RENEWABLE ENERGY	FORMULA	MAIN DATA SOURCES
Solar energy (from sunlight)	(plant surface area) x (annual solar radiation) x (1 - albedo) x (Carnot efficiency)	PBM and DMB annual solar radiation: http://www.solaritaly.enea.it/CalcComune/Calcola.php IM annual solar radiation: http://ines.solaire.free.fr/gisesol.php
Kinetic energy (from wind)	0.5 x (plant surface area) x (air density) x (drag coefficient for land) x (geostrophic wind velocity for land)^3 x (time)	PBM wind velocity and annual precipitation: http://www.arpa.veneto.it/dati-ambientali/dati-ambientali#-strong-dati-validati--strong- DMB wind velocity and annual precipitation: http://www.sir.toscana.it/ricerca-dati IM wind velocity and annual precipitation: https://donneespubliques.meteofrance.fr/?fond=produit&id_produit=117&id_rubrique=39
Chemical potential (from rain)	(plant surface area) x (annual precipitation) x (average evapotranspiration) x (water density) x (Gibbs energy of rain)	

Seawater is another natural resource that has been taken into consideration while modelling the DMB production system: seawater pumping is among the activities carried out during the microalgae farming phase, and the water collected is used both as culture medium and, by flowing through a heat exchanger, for the cooling of the system. In both cases, the water is pumped and returned to the sea within a year and it does not require any treatment. Given the wide availability of the resource within the spatial and temporal boundaries of the system, seawater was here considered as a secondary renewable energy. On the other hand, the emergy of the surface area occupied by the plants (thus, a local non-renewable sources) was assumed negligible compared to the other natural resources included in the model.

The inputs from the economy include both the ‘imported or purchased inputs’ and the ‘labour & services’ used. The purchased inputs are essentially the material and energy resources needed to carry out the process (and they represent the full LCA inventory used in chapter 3). The ‘labour & services’ category includes labour, the other operating costs and capital costs. Their flows were quantified as follows. A techno-economic analysis of microalgae production in photobioreactor (Tredici et al., 2016) was used to assess the labour and services needed by both the microalgal species (DMB_TETRA and DMB_TISO production). With regards to the production of insect and poultry-by-product meal, the quantification of goods and services was based on their current price on the European market. Since no information in this regard was provided by the companies producing IM and PBM, the number of full-time employees was assumed on the basis of the author's knowledge of the management of the two plants.

Once quantified, all the inputs are converted into emergy. The conversion factors used in emergy analysis are named Unit Emergy Values (UEVs) and can be assessed in several ways. For instance, the 'transformity' is the ratio of the emergy content (sej) to the energy content (J) of a product, while the 'specific emergy' is the emergy content (sej) divided by the product mass (kg). UEVs can be sourced from literature and from national and international databases. The sum of all the inputs from nature and the economy gives the total emergy of the system, that is the solar emjoules required annually for the ordinary management of the company (sej year-1). The major emergy flows of the four systems (DMB_TETRA, DMB_TISO, IM, PBM) are summarised in Tables 6.2, 6.3, 6.4, 6.5: the inputs converted into their equivalent amount of solar joules are given on the last column on the right (Odum, 1996).

Table 6.2 DMB_TETRA system – Annual emergy flows of *Tetraselmis suecica* farming and processing by means of the Green Wall Panel technology.

#	ITEM	AMOUNT*	UNIT	REFINED UEV (sej unit^{-1}) **	UEV REFERENCE ***	SOLAR EMERGY (sej year^{-1})
Primary renewable energy						
1	Sun	3.55E+13	J year^{-1}	1.00E+00	By definition	3.55E+13
Secondary renewable energy						
2	Wind (kinetic energy)	4.55E+11	J year^{-1}	7.92E+02	(a)	3.60E+14
3	Rain (chemical potential)	3.62E+10	J year^{-1}	6.93E+03	(a)	2.51E+14
4	Pumped seawater - medium	2.18E+03	m^3 year^{-1}	1.00E+11	(b)	2.18E+14
5	Pumped seawater - cooling	7.58E+07	m^3 year^{-1}	1.00E+11	(b)	7.58E+18
				RENEWABLE INPUT (R)****		***7.58E+ 18***
Local non-renewable sources						
	Land use (not relevant)					
				TOTAL NON-RENEWABLE INPUT (N)		***0.00E+ 00***
				TOTAL INPUT FROM NATURE		**7.58E+18**
Imported or purchased input						
Main consumables						
6	Fertilizer 1 – $NaNO_3$	1.54E+07	g year^{-1}	3.89E+09	(c)	5.98E+16
7	Fertilizer 2 – NaH_2PO_4	9.86E+05	g year^{-1}	3.89E+09	(c)	3.83E+15
8	Carbon dioxide, liquid	3.25E+08	g year^{-1}	1.06E+09	(d)	3.44E+17
Chemicals: disinfectants						
9	Sodium hypochlorite at 15% active chlorine	1.36E+05	g year^{-1}	3.58E+09	(c)	4.85E+14
10	Hydrochloric acid 36%	5.31E+04	g year^{-1}	3.58E+09	(c)	1.90E+14
Photobioreactor: main structure						
11	LDPE culture chamber	4.29E+06	g year^{-1}	8.51E+09	(e)	3.65E+16
12	Steel frame	3.12E+06	g year^{-1}	2.26E+09	(f)	7.05E+15
13	Wood base	3.44E+06	g year^{-1}	5.96E+09	(e)	2.05E+16
Photobioreactor: others						
14	PVC Tanks (2)	5.20E+04	g year^{-1}	7.43E+09	(e)	3.86E+14
15	PVC manifolds, piping and valves	4.57E+05	g year^{-1}	7.43E+09	(e)	3.40E+15
16	PVC blowers (2) and related piping	5.00E+04	g year^{-1}	7.43E+09	(e)	3.71E+14
17	Steel Pumps (5)	2.00E+04	g year^{-1}	2.26E+09	(f)	4.52E+13
18	Steel Heat exchanger	3.20E+04	g year^{-1}	2.26E+09	(f)	7.23E+13
19	Steel centrifugal	8.00E+04	g year^{-1}	2.26E+09	(f)	1.81E+14

	separators (2)					
Energy						
20	Electric power	4.36E+05	kWh year^{-1}	4.15E+11	(g)	1.81E+17
				TOTAL PURCHASED INPUT (F)		***6.58E+17***
Labour and Services						
21	Capital Costs + operating costs	4.76E+05	€ year^{-1}	7.58E+11	(h)	3.61E+17
				TOTAL INPUTS FOR LABOUR and SERVICES		***3.61E+17***
				TOTAL INPUT FROM THE ECONOMY		**1.02E+18**

NOTES

* Data sources – Items 1-5: this study (see paragraph 3.2 in this chapter) ; items 6-20: this study (see chapter 3); item 21: adaption from a techno-economic analysis (Tredici et al., 2016).

** Calculated/converted from previous works based on the GEB2016 of 1.20E+25 sej (Brown et al., 2016).

*** UEV References: (a) Brown and Ulgiati, 2016; (b) De Vilbiss and Brown, 2015; (c) Campbell et al., 2005; (d) Nimmanterdwong et al., 2017; (e) Buranakarn, 1998; (f) Odum, 1996; (g) Brown and Ulgiati, 2002; (h) Buonocore et al., 2015

**** Only the driving renewable energy input is used in final calculation, as per Brown and Ulgiati (2016).

Table 6.3 DMB_TISO system – Annual emergy flows of *Tisochrysis lutea* farming and processing by means of the Green Wall Panel technology.

#	ITEM	AMOUNT*	UNIT	REFINED UEV (sej unit^{-1}) **	UEV REFERENCE ***	SOLAR EMERGY (sej year^{-1})
Primary renewable energy						
1	Sun	3.55E+13	J year^{-1}	1.00E+00	By definition	3.55E+13
Secondary renewable energy						
2	Wind (kinetic energy)	4.55E+11	J year^{-1}	7.92E+02	(a)	3.60E+14
3	Rain (chemical potential)	3.62E+10	J year^{-1}	6.93E+03	(a)	2.51E+14
4	Pumped seawater - medium	2.18E+03	m^3 year^{-1}	1.00E+11	(b)	2.18E+14
5	Pumped seawater - cooling	7.58E+07	m^3 year^{-1}	1.00E+11	(b)	7.58E+18
					RENEWABLE INPUT (R)*****	***7.58E+18***
Local non-renewable sources						
	Land use (not relevant)					
				TOTAL NON-RENEWABLE INPUT (N)		***0.00E+00***
					TOTAL INPUT FROM	**7.58E+18**

					NATURE	
Imported or purchased input						
Main consumables						
6	Fertilizer 1 – $NaNO_3$	1.06E+07	g year^{-1}	3.89E+09	(c)	4.11E+16
7	Fertilizer 2 – NaH_2PO_4	6.73E+05	g year^{-1}	3.89E+09	(c)	2.62E+15
8	Carbon dioxide, liquid	2.27E+08	g year^{-1}	1.06E+09	(d)	2.41E+17
Chemicals: disinfectants						
9	Sodium hypochlorite at 15% active chlorine	1.35E+05	g year^{-1}	3.58E+09	(c)	4.84E+14
10	Hydrochloric acid 36%	5.26E+04	g year^{-1}	3.58E+09	(c)	1.88E+14
Photobioreactor: main structure						
11	LDPE culture chamber	3.01E+06	g year^{-1}	8.51E+09	(e)	2.56E+16
12	Steel frame	3.12E+06	g year^{-1}	2.26E+09	(f)	7.05E+15
13	Wood base	2.41E+06	g year^{-1}	5.96E+09	(e)	1.43E+16
Photobioreactor: others						
14	PVC Tanks (2)	5.20E+04	g year^{-1}	7.43E+09	(e)	3.86E+14
15	PVC manifolds, piping and valves	3.20E+05	g year^{-1}	7.43E+09	(e)	2.38E+15
16	PVC blowers (2) and related piping	5.00E+04	g year^{-1}	7.43E+09	(e)	3.71E+14
17	Steel Pumps (5)	2.00E+04	g year^{-1}	2.26E+09	(f)	4.52E+13
18	Steel Heat exchanger	3.20E+04	g year^{-1}	2.26E+09	(f)	7.23E+13
19	Steel centrifugal separators (2)	8.00E+04	g year^{-1}	2.26E+09	(f)	1.81E+14
Energy						
20	Electric power	5.72E+05	kWh year^{-1}	4.15E+11	(g)	2.38E+17
				TOTAL PURCHASED INPUT (F)		***5.73E+17***
Labour and Services						
21	Capital Costs + operating costs	5.03E+05	€ year^{-1}	7.58E+11	(h)	3.81E+17
				TOTAL INPUTS FOR LABOUR and SERVICES		***3.81E+17***
				TOTAL INPUT FROM THE ECONOMY		**9.55E+17**

NOTES

* Data sources – Items 1-5: this study (see paragraph 3.2 in this chapter) ; items 6-20: this study (see chapter 3); item 21: adaption from a techno-economic analysis (Tredici et al., 2016).

** Calculated/converted from previous works based on the GEB2016 of 1.20E+25 sej (Brown et al., 2016).

*** UEV References: (a) Brown and Ulgiati, 2016; (b) De Vilbiss and Brown, 2015; (c) Campbell et al., 2005; (d) Nimmanterdwong et al., 2017; (e) Buranakarn, 1998; (f) Odum, 1996; (g) Brown and Ulgiati, 2002; (h) Buonocore et al., 2015.

**** Only the driving renewable energy input is used in final calculation, as per Brown and Ulgiati (2016).

Table 6.4 IM system – Annual emergy flows of black soldier fly farming and processing.

#	ITEM	AMOUNT*	UNIT	REFINED UEV (sej unit-1) **	UEV REFERENCE ***	SOLAR EMERGY (sej year-1)
Primary renewable energy						
1	Sun	5.38E+12	J year-1	1.00E+00	By definition	5.38E+12
Secondary renewable energy						
2	Wind (kinetic energy)	1.19E+12	J year-1	7.92E+02	(a)	9.43E+14
3	Rain (chemical potential)	8.12E+09	J year-1	6.93E+03	(a)	5.63E+13
				RENEWABLE INPUT (R)*		***9.43E+14***
Local non-renewable sources						
	Land use (not relevant)					
				TOTAL NON-RENEWABLE INPUT (N)		***0.00E+00***
				TOTAL INPUT FROM NATURE		**9.43E+14**
Imported or purchased input						
Main consumable						
4	Farming substrate	1.22E+13	J year-1	3.32E+09	(b)	5.57E+17
Chemicals						
5	Sodium chloride powder	1.86E+05	g year-1	3.58E+09	(c)	6.65E+14
6	Sodium hypochlorite	2.79E+04	g year-1	3.58E+09	(c)	9.98E+13
Equipment & Machineries						
7	PET insect rearing boxes	3.29E+04	g year-1	0.00E+00	(d)	0.00E+00
8	Steel insect rearing boxes	4.38E+04	g year-1	2.26E+09	(e)	9.90E+13
9	Steel rendering machines	4.86E+06	g year-1	2.26E+09	(e)	1.10E+16
Water & Energy						
10	Tap water	3.47E+09	J year-1	2.86E+06	(f)	9.91E+15
11	Electric power	3.69E+05	kWh year-1	4.15E+11	(g)	1.53E+17
				TOTAL PURCHASED INPUT (F)		***7.32E+17***
Labour and Services						
12	Farming substrate	1.03E+05	€ year-1	7.58E+11	(h)	7.78E+16
13	Sodium chloride powder	2.98E+02	€ year-1	7.58E+11	(h)	2.26E+14
14	Sodium hypochlorite	1.88E+02	€ year-1	7.58E+11	(h)	1.42E+14
15	Tap water	2.76E+03	€ year-1	7.58E+11	(h)	2.09E+15
16	Energy (country mix)	6.64E+04	€ year-1	7.58E+11	(h)	5.03E+16
17	Labour (2 workers)	2.00E+00	person year-1	2.74E+16	(f)	5.47E+16
				TOTAL INPUTS FOR LABOUR and SERVICES		***1.85E+17***
				TOTAL INPUT FROM THE ECONOMY		**3.60E+17**

NOTES

* Data sources – Items 1-3 and 12-17: this study (see paragraph 3.2 in this chapter); items 4-11: this study (see chapter 3).

** Calculated/converted from previous works based on the GEB2016 of 1.20E+25 sej (Brown et al., 2016).

*** UEV References: (a) Brown and Ulgiati, 2016; (b) Allegretti et al., 2018; (c) Campbell et al., 2005; (d) Buranakarn, 1998; (e) Odum, 1996; (f) Ascione et al., 2009; (g) Brown and Ulgiati, 2002; (h) Buonocore et al., 2015.

**** Only the driving renewable energy input is used in final calculation, as per Brown and Ulgiati (2016).

Table 6.5 PBM system – Annual emergy flows of poultry farming and processing

#	ITEM	AMOUNT*	UNIT	REFINED UEV (sej unit^{-1}) **	UEV REFERENCE ***	SOLAR EMERGY (sej year^{-1})
Primary renewable energy						
1	Sun	3.47E+13	J year^{-1}	1.00E+00	By definition	3.47E+13
Secondary renewable energy						
2	Wind (kinetic energy)	4.62E+11	J year^{-1}	7.92E+02	(a)	3.66E+14
3	Rain (chemical potential)	5.44E+10	J year^{-1}	6.93E+03	(a)	3.77E+14
				RENEWABLE INPUT (R)****		*3,77E+14*
Local non-renewable sources						
	Land use (not relevant)					
			TOTAL NON-RENEWABLE INPUT (N)			***0,00E+00***
			TOTAL INPUT FROM NATURE			**3,77E+14**
Imported or purchased input						
Main consumable						
4	Live weight chicken (conventional poultry production)	8.02E+11	g year^{-1}	5.66E+09	(b)	**4.53E+21**
Chemicals						
5	Disinfectant	4.84E+05	g year^{-1}	3.58E+09	(c)	1.73E+15
6	Detergent	4.20E+06	g year^{-1}	3.58E+09	(c)	1.50E+16
Equipment & Machineries						
7	Steel - Rendering machineries	2.16E+07	g year^{-1}	2.26E+09	(d)	4.89E+16
Water & Energy						
8	Soft water	2.45E+11	g year^{-1}	2.86E+06	(e)	7.00E+17
9	Electric power	1.22E+07	kWh year^{-1}	4.15E+11	(f)	5.08E+18
1	Natural gas	1.86E+07	Nm^3	5.66E+04	(g)	1.05E+12

0			year^{-1}			
				TOTAL PURCHASED INPUT (F)		***4.54E+21***
Labour and Services						
11	Live weight chicken (conventional poultry production)	9.46E+05	€ year^{-1}	7.58E+11	(h)	**7.2E+17**
12	Disinfectant	2.52E+04	€ year^{-1}	7.58E+11	(h)	1.91E+16
13	Detergent	3.63E+04	€ year^{-1}	7.58E+11	(h)	2.76E+16
14	Soft water	9.86E+05	€ year^{-1}	7.58E+11	(h)	7.48E+17
15	Electric power	3.00E+06	€ year^{-1}	7.58E+11	(h)	2.28E+18
16	Natural gas	2.02E+07	€ year^{-1}	7.58E+11	(h)	1.53E+19
17	Labour (1 worker)	1.00E+00	person year^{-1}	2.74E+16	(e)	2.74E+16
				TOTAL INPUTS FOR LABOUR and SERVICES		***1.92E+19***
				TOTAL INPUT FROM THE ECONOMY		**4.56E+21**

NOTES

* Data sources – Items 1-3 and 12-17: this study (see paragraph 3.2 in this chapter); Items 4-10: this study (see chapter 3); item 11: adaption from (Castellini et al., 2012).

** Calculated/converted from previous works based on the GEB2016 of 1.20E+25 sej (Brown et al., 2016).

***UEV References: (a) Brown and Ulgiati, 2016; (b) Castellini et al., 2006; (c) Campbell et al., 2005; (d) Odum, 1996; (e) Ascione et al., 2009; (f) Brown and Ulgiati, 2002; (g) Bastianoni et al., 2009; (h) Buonocore et al., 2015.

**** Only the driving renewable energy input is used in final calculation, as per Brown and Ulgiati (2016).

The total emergy of each system can be used to assess several emergy-based indicators (Table 6.6). The indicator considered here is the '*specific emergy*' (sej kg^{-1}), which is the total emergy of the system (sej year^{-1}) divided by the mass of the main product, that is DMB_TETRA, DMB_TISO, IM and PBM annual yield (kg year^{-1}). According to the formula, the indicator assumes lower values when less emergy is needed to produce a given amount of product: in other terms, the lower the specific emergy, the greater the efficiency of the process. This indicator was calculated using as a numerator both the total emergy of the system and the emergy net of '*Labour and Services*'.

Table 6.6 Annual yield and related emergy-based indicator

	Total emergy (sej year^{-1})	**Annual yield** (kg year^{-1})	**Specific emergy** (sej kg^{-1})	
			Total emergy / yield	(Total emergy - labour and services) / yield
DMB_TETRA	8.60E+18	36,000	2.39E+14	2.29E+14
DMB_TISO	8.53E+18	25,200	3.39E+14	3.23E+14
IM	9.18E+17	109,500	8.38E+12	6.69E+12
PBM	4.56E+21	43,286,022	1.05E+14	1.05E+14

3.4 Step 3 – Results and discussion

The results revealed that the most efficient system (*i.e.* the one with the lowest specific emergy) is IM, followed by PBM, DMB_TETRA and finally DMB_TISO (Table 6.6). The specific emergy of the four meals does not change markedly if the contribution of 'Labour and Services' is removed from the calculation. The only exception is IM system, where a consistent reduction (-20%) is mainly due to the cost of labour, farming substrate and electricity. While the contribution of 'Labour and Services' can be high but not decisive, the greatest emergy share is provided by either the natural resources or the purchased inputs (Tables 6.2, 6.3, 6.4, 6.5). Indeed, the major contributor in both DMB systems is represented by the seawater used for the cooling (88% in DMB_TETRA and 89% in DMB_TISO), in IM system by the farming substrate provided to insects (61%) and in PBM system by the background production of live weight chicken (99%).

Results showed that the contribution from nature differs among the systems. The two microalgal systems, despite being the less emergy efficient, are almost entirely dependent on renewable natural resources, while the production of the two animal meals is clearly disconnected from the surrounding environment and depended mainly on external resources from the economy. Thus, although at first sight DMB_TETRA and DMB_TISO systems appear as the less sustainable ones (since they consume the highest level of emergy sources per kg of product), they actually have a high capacity to persist through time. Indeed, within the food chain, microalgae are primary producers, which means that they self-produce complex organic compounds (necessary for their growth) from simple substances (CO_2 and chemical fertilizers) and from sunlight. On the other hand, insects and chicken are consumers and thus their growth is supported by the consumption of other living source of energy. Thus, despite being more emergy efficient, both IM and PBM systems rely mainly on non-renewable emergy inputs and thus cause, in proportion, a higher environmental stress.

However, the renewability percentage of the economic resources was not considered in this analysis, and the considerations made above are valid only because the contribution of renewable natural resources is extremely high in both the DMB systems. If the renewability percentages were known, it would be possible to divide the emergy of each economic resource into its renewable (R) and non-renewable (N) component, thus allowing more thorough considerations on the permanence of the four systems through time.

In conclusion, the values discussed in this chapter cannot be considered as final results. To improve the analysis, the emergy assessment of some economic inputs should be reviewed, the renewability percentage of economic resources could be included in the emergy tables and more emergy-based indicators could be used to analyse the emergy results. Furthermore, externalities such as steam and CO_2 emissions could be determined and incorporated into the calculation. However, the results obtained so far revealed a higher renewability of the DMB systems compared to the one of the two animal meals, which was an aspect not detectable with LCA analysis.

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Chapter 7. CONCLUSION

This chapter summarizes the main findings of the thesis and presents some concluding remarks on the efficiency of fish supply chain.

1. *Main findings*

This thesis focused on the environmental sustainability of aquaculture, using LCA as the main assessment tool and in one case coupling it with a complementary resource accounting methodology, *i.e.* the emergy analysis.

Aquaculture has a prominent role in the agri-food industry, and it is characterised by a global growing trend. However, it is a vast and heterogeneous sector and, despite previous LCA studies proved it to be more sustainable than other branches of animal husbandry, several informative gaps still exist, both from a methodological point of view and as regards the number of production processes analysed.

The thesis research line was developed according to several critical points highlighted by the literature review (chapter 2): the cascading effect of aquafeed on the environmental impacts of the entire supply chain; the different environmental impacts due to different farming techniques; methodological gaps in accounting for resource depletion. These aspects were investigated by applying LCA and emergy analysis to aquaculture supply chains that are relevant in a national and European context.

First, given the high impact contribution of the aquafeed, LCA was applied to four protein sources which can partially substitute fish meal within aquafeed formulations: two dry microalgae biomasses; insect meal (from black soldier fly larvae fed with cereal by-products); poultry by-product meal (chapter 3). Poultry by-product meal and insect meal appeared as the best option in terms of environmental sustainability, although fluctuations in the performances of the latter were observed and attributed to the type of substrate provided to insects. On the other hand, the systems for the production and processing of the two vegetable sources appeared as not competitive.

Chapters 4 investigates the whole rainbow trout supply chain, as it is managed by an Italian trout farmers consortium which is very attentive to fish welfare and sustainability issues. All trout farms are raceways (*i.e.* flow-through freshwater systems), they are supplied almost exclusively by a single aquafeed producer, adhere to a production protocol that standardizes their production and deliver the grown-out trout (in the round) to the same processing plant. Moreover, fish by-products obtained from trout processing are given to a company that converts them into pet-food ingredients. This is a quite uncommon practice in aquaculture, since currently fish trimming is mostly considered waste and discharged in local waterways (Pelletier et al., 2018). LCA results showed that, with regards to the grow-out phase, the environmental performances were mainly affected by the aquafeed. Thus, improvements could be achieved through an increased aquafeed efficiency, which can be attained by improving feed characteristics (nutritional properties, digestibility, palatability). Another option to improve the sustainability of this phase could be an increased focus on management practices, since less feed is wasted if fish is not overfed and is in good health conditions. On the other hand, fish processing appeared as a highly efficient production system, which already optimizes the resources used. Indeed: (i) the environmental and economic burdens of the processing plant are shared among the consortium associates; (ii) to minimize fish rejection rate, the harvested trout is delivered to the processing plant within a short period of time, thus guaranteeing the cold chain compliance (and the preservation of the fish); (iii) when fish is seen as not fit for market (due to odd shape or blemishes), still it is not discarded but simply processed into minced fish. The last phase of the supply chain provided an unexpected result.

According to the EU Waste Framework Directive, recycling of materials has the preference over energy recovery (that is to say, biomass incineration). However, our results indicated that recycling fish by-product involves a high energy input: therefore, though desirable, it may not be the most environmentally friendly option when energy is sourced by fossil fuels, as already highlighted by previous studies (Schrijvers et al., 2016).

Chapter 5 focused on an aquaponic pilot plant (a freshwater recirculating system) producing tilapia and lettuce. Aquaponics is a production technique that has gradually spread worldwide over the past decade and that is being studied by various research groups, among which that of the University of the Virgin Islands was the pioneer (see for instance Danaher et al., 2013). However, aquaponics is still struggling to establish itself in Europe, where both research activities and operating production facilities are not fully investigated yet. Thus, the chapter explored the potential of LCA as an eco-design tool, since it was applied to the project of a future aquaponic facility in order to get an overview of its environmental burdens and thus propose less impacting technical solutions prior to its actual building. Unlike fish farming in raceways, the sustainability of the aquaponic facility was mainly dependent on the energy needs of the system. Moreover, despite appearing quite small at a first glance, water consumption turned out to be far higher than that of conventional hydroponic systems. Among the suggested improvement actions, the substitution of the drum-filter with one having better performances (*i.e.* a reduced energy and water consumption) undoubtedly represents the key point.

One last aspect highlighted by the literature review is that LCA quantifies the environmental sustainability of a product throughout its complete life cycle, but it adopts a utilitarian (*i.e.* anthropocentric) perspective. On the other hand, the emergy analysis extends the boundaries beyond the technosphere, including in the resource accounting all the energy sources, materials and ecosystem services involved in the production process. In other terms, it accounts for the environmental work required to produce the product. Thus, chapter 6 was dedicated to the application of the emergy analysis to the same supply chains analysed in chapter 3 (*i.e.* the four protein sources). Results of the emergy analysis provided a second perspective, albeit partial, on the environmental performance of the four protein sources. Indeed, the less efficient production system (*i.e.* microalgae farming and processing) turned out to be the one with the highest capacity to persist through time, as it relies mainly on renewable resources from nature.

Overall, results show that sustainable issues can occur at several point along aquaculture supply chain: from feed ingredients production, to fish grow-out phase, up to the processing of fish by-products into pet-food ingredients. The impacts found were mainly due to:

- the resources used to feed the farmed organisms, be they microalgae, insects, chickens (the protein sources of chapter 3) or fishes (trout farming in chapter 4);
- the energy consumed, linked both to the energy needs of the machinery and to the maintenance of adequate thermal conditions (observed mainly during the farming of microalgae and insects and during the processing of fish by-products).

2. Concluding remarks

As any other food production sector, aquaculture development is influenced by several, intertwined factors (Bush et al., 2019): political elements, such as land use regulations; economic elements, such as consumption levels (which are expected to increase dramatically in developing countries); social elements, such as changes in diet behaviour; environmental elements, such as climate change.

All these factors make it difficult to predict changes in aquaculture supply chain in the medium-long term and would require extensive environmental and economic modelling. However, the results summarized in the previous paragraph suggests the following observations

Poultry production is grounded on well-established technologies and it is not expected to substantially change in the future years. On the other hand, insect farming and microalgal cultivation in photobioreactors are not mature production processes and surely have large margin for technological improvements. This could affect their nutritional quality, their potential scalability and, consequently, their environmental sustainability. With regards to their scalability, currently there are no large-scale facilities for microalgae cultivation in photobioreactors: the largest microalgae facilities in the world, located in China and in the United States, are based on open ponds. With regards to the insect farming industry, the current production remains dependent on manual labour, irrespectively of the production scale and the species farmed. Since labour cost in Europe is high, current insect prices on the market are high as well. In addition, the current farming of black soldier fly is characterized by a small-scale production.

With regards to the ongoing climate change, it is now widely accepted that it represents one of the most pressing issues of our time. However, an increase in temperature could positively affect microalgal cultivation (Tredici et al., 2016). The production of black soldier flies could take advantage of the temperature increase as well, since that fly is a species typical of the warm temperate zone of America and whose farming in Europe can only take place in closed and thermoregulated environments. The supply of a proper substrate (to feed the larvae on) may not represent a problem either: as already discussed in chapter 3, this species can process almost any type of organic material (Van Huis et al., 2013), thus allowing to recover and recycle in the supply chain several co-products which otherwise would have been disposed of as waste.

On the other hand, climate change could damage trout farming activities (Cianfrani et al., 2015). For instance, the diverted rivers which flow through the trout raceways analysed are glacier-fed and the climatic variability could negatively affect both dissolved oxygen levels and water availability. In this case, a shift towards a recirculating system (such as RAS or even aquaponics) would guarantee a better control on the production.

In this context of growing uncertainty and climate instability, a further push towards monitoring how climate change impacts are generated and distributed along food supply chain is required, together with the promotion of any positive interaction between producers, consumers, government and technical/scientific actors towards the adoption of circular economy strategies. With respect to the latter, the processes analysed in this thesis show encouraging results. Indeed, circular processes were already found within several phases of aquaculture supply chain: the eco-design requested on the aquaponic plant; the generation of resources from by-products and wastes; resource sharing practices (the processing plant shared by the whole consortium of trout farmers). Perhaps the growing adoption of good practices towards an increasingly circular economy is mainly due to the need for competitiveness. Nevertheless, these measures are paving the way to an economy that is not only more competitive but also more environmentally sustainable.

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APPENDIX_CHAPTER 2

Phase of the supply chain	N. of publications	Publications	
Only Feed	6	(Silva et al., 2018) (Henriksson et al., 2017b) (Fréon et al., 2017)	(Strazza et al., 2015) (Draganovic et al., 2013) (Samuel-Fitwi et al., 2013a)
Feed + Farming	1	(Samuel-Fitwi et al., 2013c)	
Only Farming	44	(Abdou et al., 2018) (Parker, 2018) (Abdou et al., 2017) (Aubin et al., 2017) (Badiola et al., 2017) (Besson et al., 2017) (Boxman et al., 2017) (Forchino et al., 2017) (Henriksson et al., 2017c) (Henriksson et al., 2017a) (Järviö et al., 2017) (Lourguioui et al., 2017) (Medeiros et al., 2017) (Mendoza Beltran et al., 2017) (Smarason et al., 2017) (Ayer et al., 2016) (Besson et al., 2016) (Pahri et al., 2016) (García García et al., 2016) (Liu et al., 2016) (Nhu et al., 2016) (Oita et al., 2016)	(Yacout et al., 2016) (Aubin et al., 2015) (Avadí et al., 2015) (Chen et al., 2015) (Dekamin et al., 2015) (Jonell and Henriksson, 2015) (McGrath et al., 2015) (Nhu et al., 2015a) (Nhu et al., 2015b) (Santos et al., 2015) (Taelman et al., 2015a) (Teah et al., 2015) (Lazard et al., 2014) (Mungkung et al., 2014) (Huysveld et al., 2013) (Ingólfsdóttir et al., 2013) (Mungkung et al., 2013) (Pongpat and Tongpool, 2013) (Samuel-Fitwi et al., 2013b) (Taelman et al., 2013) (Wilfart et al., 2013) (Ziegler et al., 2013)
Farming + Processing into Foodstuff	5	(Astudillo et al., 2015) (Avadí and Fréon, 2015) (Farmery et al., 2015)	(Henriksson et al., 2015) (Henriksson et al., 2014)
Farming + Processing	8	(Czyrnek-Deletre et al., 2017) (Warshay et al., 2017)	(Pérez-López et al., 2014) (Alvarado-Morales et al.,

into Other Products		(Taelman et al., 2015b) (Aitken et al., 2014)	2013) (Spångberg et al., 2013) (Udom et al., 2013)
Feed + Farming + Processing	1	(Newton and Little, 2018)	
Only Processing	4	(Laso et al., 2017) (Rodrigues et al., 2016)	(Avadí et al., 2014) (Vázquez-Rowe et al., 2014)
Total	**69**		

The 69 publications are grouped according to the production phases included in their system boundaries. Publications within each group are listed in chronological order.