Journal of Cleaner Production 294 (2021) 126266

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Ecological sustainability of aquafeed: An emergy assessment of novel or underexploited ingredients

Silvia Maiolo [a, *], Silvio Cristiano [a, b, **], Francesco Gonella [b], Roberto Pastres [a]

[a] Ca' Foscari University of Venice, Department of Environmental Sciences, Informatics and Statistics, Via Torino 155, 30170, Venezia Mestre, Italy
[b] Ca' Foscari University of Venice, Department of Molecular Sciences and Nanosystems, Via Torino 155, 30170, Venezia Mestre, Italy

ARTICLE INFO

Article history:
Received 28 July 2020
Received in revised form
29 January 2021
Accepted 2 February 2021
Available online 6 February 2021

Handling editor: Dr Sandra Caeiro

Keywords:
Aquaculture
Fishmeal substitutes
Insect larvae
Microalgae
Poultry by-product
Resource accounting

ABSTRACT

Fishmeal is the optimal source of protein for fed fish and crustacean species, but the increase in market demand and prices is pushing the aquaculture industry to test alternative protein sources. This paper provides the results of an emergy assessment performed on four partial substitutes for fishmeal – dried microalgae biomass from *Tetraselmis suecica* and *Tisochrysis lutea*, insect meal from *Hermetia illucens* larvae, and poultry by-product meal – and then compares them with the findings of a previously published Life Cycle Assessment (LCA) on the same topic. By quantifying their degree of dependence on natural resources, the research offers a complementary perspective to that of LCA, thus allowing to obtain a complete picture on the sustainability of the four production systems. Firstly, the results reveal that insect meal has the highest environmental efficiency in terms of total emergy per unit of product, followed by poultry by-product meal. The two closed microalgae cultivation systems are penalized by a low productivity, combined with a high quantity of seawater imported. Secondly, several critical aspects are highlighted by the five emergy-based indicators: in brief, all systems appear to be based on intensive industrial processes, with the imported inputs from the economy representing 99% of total emergy flow (high level of ecosystem stress). Since local renewable inputs are not significantly exploited, higher levels of production amplify the ratio between these resources and the inputs imported from the outer economies (no economies of scale are observed). Finally, the comparison with LCA results confirms a critical point already detected by the emergy assessment (*i.e.* the crucial contribution of the feed provided to insect and poultry) but also reveals new ones: (i) in the two microalgae systems, the high emergy contribution from seawater versus the high impacts of carbon dioxide and energy needs; (ii) in the insect meal system, the high emergy share represented by human labour and energy needs. In light of the numerous problems found, possible approaches are proposed to increase the environmental performance through changes to each production system and the processes that support it upstream.

1. Introduction

As already stated more than 30 years ago in the Brundtland Report (United Nations, 1987), the socio-economic development is inextricably linked not only to the current state of technology and social organisation, but also to environmental constraints. The level of renewability of natural resources and the planet's ability to absorb the effects of human activities represent a crucial point, as they have an influence on the environmental sustainability of any production process and therefore its reproducibility over time. In recent years, with the increase of public and institutional awareness of the environmental degradation at a global level, several environmental and integrated assessment tools have been developed to guide and support decision makers along the supply chain.

Assessing the environmental load of feed is crucial for evaluating the sustainability of intensive aquaculture. Within this food industry category, which reached 114.5 million t (live weight) produced worldwide in 2018, the most appreciated farmed species all over the world are salmonids (the most economically relevant product on the market since 2013), followed by shrimps and prawn (FAO, 2020). Despite the high value, their demand on the market is

* Corresponding author.
** Corresponding author. Ca' Foscari University of Venice, Department of Environmental Sciences, Informatics and Statistics, via Torino 155, 30170, Venezia Mestre, Italy.
E-mail addresses: silvia.maiolo@hotmail.it (S. Maiolo), silvio.cristiano@unive.it (S. Cristiano).

https://doi.org/10.1016/j.jclepro.2021.126266

Abbreviations

%Ren	% Renewable Emergy
AEI	Areal Empower Intensity
DMB_TETRA	Dried Microalgae Biomass from Tetraselmis suecica
DMB_TISO	Dried Microalgae Biomass from Tisochrysis lutea
ELR	Environmental Loading Ratio
ESI	Emergy Sustainability Index
EYR	Emergy Yield Ratio
IM	Insect Mealobtained from black soldier fly larvae
LCA	Life Cycle Assessment
PBM	Poultry By-product Meal

growing as consumer purchasing power increases. In 2018, the production of salmonids (mainly Atlantic salmon and rainbow trout) exceeded 3.3 million t produced and about 19 percent of the total value of internationally traded fish products, while shrimps and prawn production exceeds 9 million t, equivalent to about 15 percent in terms of traded total value (FAO, 2020). All salmonids and several marine shrimp species (*e.g.* black tiger shrimp, Indian white prawn, giant river prawn) were traditionally fed with aquafeed rich in fishmeal, a high protein ingredient obtained by processing small pelagic fish species coming from lower steps of the food chain (Heuzé et al., 2015). Being wild fish stocks already fully exploited (FAO, 2018), the aquafeed industry began to search for alternative protein sources in order to reduce the dependence on fishmeal and to meet the growing demand for aquafeed. In this context, an Italian research project (SUSHIN – Sustainable fiSH feeds INnovative ingredients) explored the nutritional properties and environmental sustainability of four emerging protein sources which could be used as partial fishmeal substitutes: Poultry By-product Meal (**PBM**); Insect Meal (**IM**) obtained from black soldier fly larvae; Dried Microalgae Biomass from *Tetraselmis suecica* (**DMB_TETRA**), and *Tisochrysis lutea* (**DMB_TISO**).

A recent study applied the Life Cycle Assessment (LCA) methodology on these four protein sources (Maiolo et al., 2020), taking into consideration both the matter and energy resources (inputs) and the products and wastes (outputs) along the whole life cycle of the product. According to the LCA framework described by the ISO 14040 and 14044 standards (ISO, 2006a; 2006b), these flows were used to create a virtual model of the process and were then translated into a range of environmental impacts by means of mathematical models. LCA is a mostly anthropocentric approach focused on processes occurring in the technosphere (that comprises our economies and societies) and (even only partially) on the environment in which these are framed. Regarding the latter aspect, the effects of natural resources consumption are essentially quantified in terms of a balance between what human activities remove and what is left. However, as is more and more common in the study of systems sustainability, different analytical approaches must be put together to encompass the different perspectives to be considered for an integrated sustainability evaluation. In this respect, the emergy approach (Odum, 1996) stands out as one of the most interesting tools for environmental accounting able to address some limitations of LCA. Indeed, emergy accounting (often alongside LCA-based analyses) is increasingly used in several fields, as reported in the bibliographic analysis by Chen et al. (2017).

The present paper illustrates an emergy assessment carried out on the four abovementioned protein sources, with the aim of filling the informative gap and giving a comprehensive picture of their degree of dependence on natural resources. Therefore, while discussing potential fishmeal substitutes in aquaculture, the environmental impact of the socio-economic sphere is complemented by insights into what is required of the geobiosphere. In this way, it is possible to implicitly take into account the efficiency of both the use of naturally generated resources and the concentration through the primary sector (*i.e.* raw materials production) and secondary sector (*i.e.* raw material manufacturing).

2. Materials and methods

2.1. The emergy concept

Following thermodynamic principles, all direct and indirect energy forms (*e.g.* mechanical, thermal, electrical, chemical) participating in a process are expressed in the same unit, the Joule (J). However, in accordance with the Second Law of Thermodynamics, different energy forms can be qualitatively different in terms of the fraction of energy that can be actually converted into mechanical work. The concept of emergy (considered as an expansion of the embodied energy concept) was introduced by H.T. Odum (1996) as a way to account for all the contributions necessary to the production of something. In other terms, emergy quantifies the environmental work required to produce the product or service and thus it includes in the accounting all the energy sources and materials made available by the geobiosphere. Since solar energy is, by far, the main ecosystems input, the conventional physical units (energy, mass, etc.) are all converted through appropriate conversion factors based on solar equivalent Joule (seJ). The corresponding unit is the solar emjoule (sej). Moreover, environmental inputs are sometimes mediated by social inputs (*e.g.* labour) requiring themselves environmental inputs: consequently, these social flows must also be converted to solar emjoule. Thus, in summary, the emergy of a product represents the amount of equivalent solar energy required upstream for its manufacturing, involving both natural and artificial processes.

According to Odum (1996), emergy accounting is organised in three steps: (i) the conceptual model of the process, including the identification of system boundaries and the drafting of the emergy flow diagram; (ii) the inventory of matter and energy flows and their conversion by means of an emergy evaluation table and (iii) the calculation and interpretation of a set of environmental sustainability indicators. These indicators are meant to compare the relative contribution of different groups of input sources, for example, renewable vs non-renewable, local vs non-local, imported vs already available, natural vs human-made, and so on. In brief, emergy accounting and the related emergy-based indicators take into account the socio-ecological contributions required to generate, concentrate, and extract a certain resource, including human labour and economic services (that are often left out of the more traditional evaluation methods).

2.2. Case studies description and systems diagramming

At present, the protein sources considered in this study are being produced at different technology levels and production scales (Table 1), with IM and DMB productions still in their infancy. However, the analysis on the four productions is based on a large number of primary data (collected directly from the companies) and reflects the current knowledge in the field. As such, the comparison between the four productions can be considered as consistent.

The system diagrams of the production plants are reported in Figs. 1–3 and are extensively described in the following paragraphs. Within each diagram, the inputs from nature (renewable energies and local non-renewable sources) are positioned on the left side,

Table 1
Annual yield. DMB: Dried Microalgae Biomass from *Tetraselmis suecica* (TETRA) and *Tisochrysis lutea* (TISO); IM:Insect Meal (IM); PBM: Poultry By-product Meal.

	DMB_TETRA	DMB_TISO	IM	PBM
Product (kg/y)	36,000	25,200	99,000	43,286,022
By-products (kg/y)	–	–	Fat + substrate residues (825,000)	Blood meal + Feather meal + Fat (122,643,729) Chicken for human consumption (561,115,100)

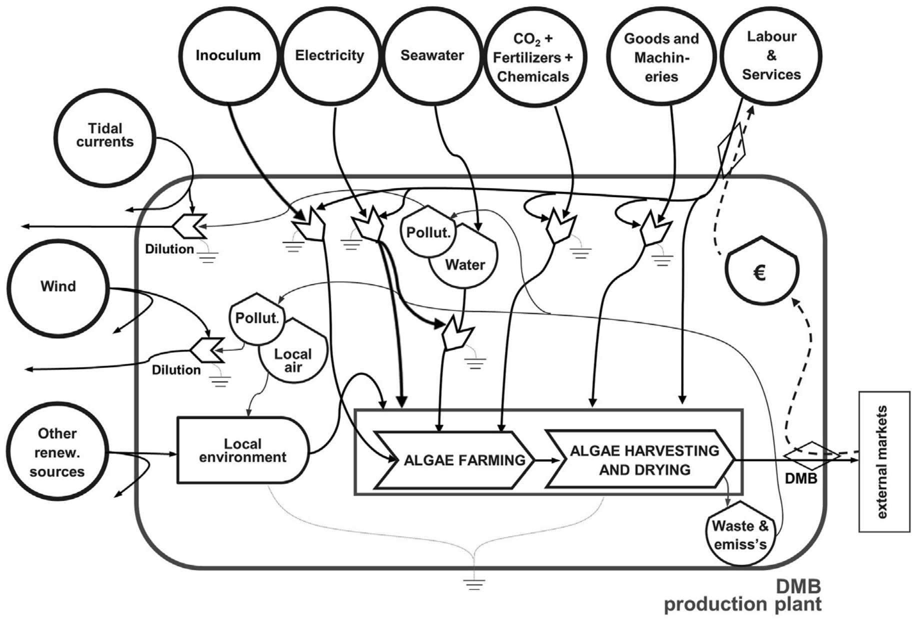

Fig. 1. System diagram of the dry microalgae biomass (DMB) production plant. The diagram is valid for both *Tetraselmis suecica* and *Tisochrysis lutea* production. Dashed lines represent money flows.

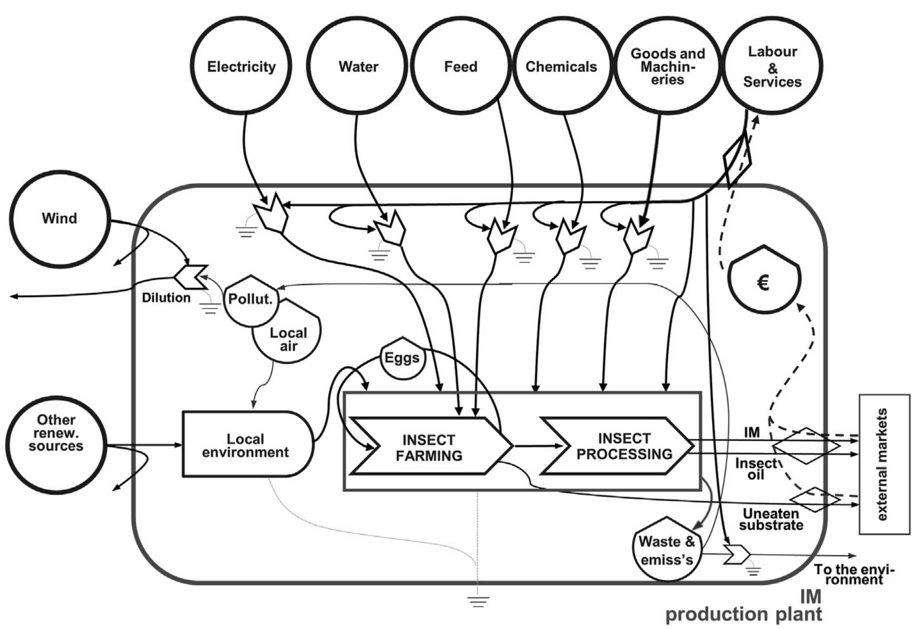

Fig. 2. System diagram of the insect meal (IM) production plant. Dashed lines represent money flows.

while the purchased inputs and the money flows (dashed lines) driving the system operation are situated at the top. All the outputs are on the right side.

2.2.1. DMB production

The two vegetal protein sources are obtained through the cultivation, harvesting, and processing of *Tetraselmis suecica*

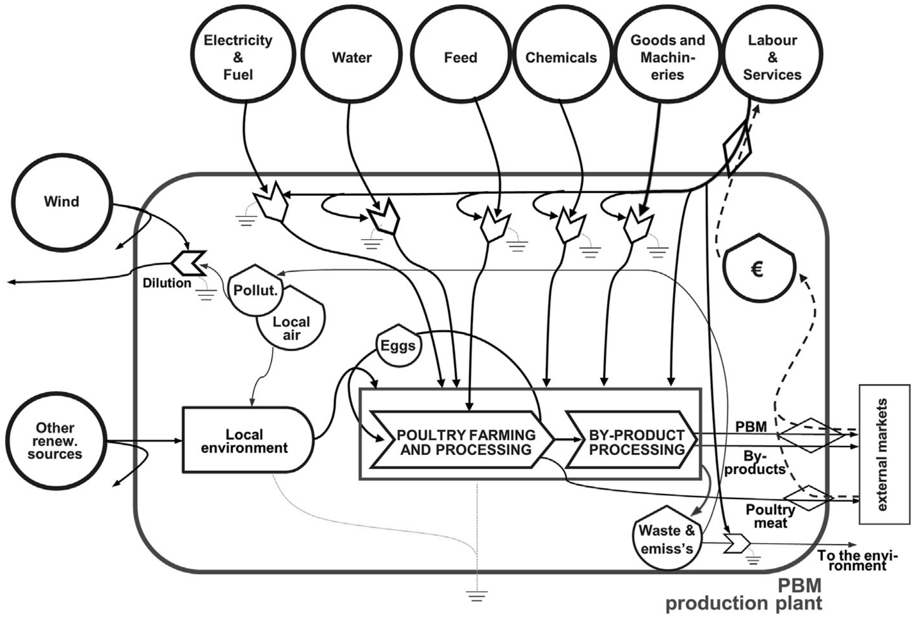

Fig. 3. System diagram of the poultry by-products (PBM) production plant. Dashed lines represent money flows.

(DMB_TETRA) and *Tisochrysis lutea* (DMB_TISO). These species are unicellular marine microalgae farmed in an outdoor closed cultivation system. The system considered is a 10,000 m^2 virtual plant composed of “Green Wall Panel” photobioreactors (GWP®) and located in Tuscany, Italy. The model of this hypothetical plant is based on an in-depth techno-economic analysis (Tredici et al., 2016) and is complemented with data gathered by interviewing experts in the field. DMB_TETRA and DMB_TISO production (Fig. 1) requires the same infrastructures and machinery but differs in terms of annual yield (36 and 25 t/y of dried meal respectively), consumable goods and energy consumption. Since the plant is located close to the coastline, the seawater filling the system is taken and then discharged into the sea. The main input injected into the photobioreactors, apart from seawater, is pure carbon dioxide stored in liquid form under pressure in cylinders. The background system leading to the production of the algal inoculum is not considered as – after preliminary calculations – it is assumed to have no significant contribution to the overall environmental demand when compared to a whole year production cycle on industrial scale like the one at issue.

At harvesting, microalgae cells are gradually separated from the exhausted culture medium (through a centrifugation and then a drying process). With regards to the mass balance, 5 t of harvested microalgal paste are needed for the production of 1 t of dry biomass in the case of DMB_TETRA, while an initial biomass of 10.34 t is needed in the case of DMB_TISO. Due to local climatic conditions, the plant operates 240 days a year (from March to October).

2.2.2. IM production

The meal is obtained from larvae of the black soldier fly (*Hermetia illucens*) and data on IM productions were gathered by interviewing the staff of the French company Innovafeed, producing 109 t/y of dried meal. Flies reproduction is not included in the analysis, since this process does not require any relevant input: only a few pre-pupae are set aside to become breeders and, once they are completely developed into adults, they do not feed and spend their very short life (less than one week) to find a mate and to reproduce. Thus, the system diagram (Fig. 2) includes: the rearing of larvae, which are voracious and can feed on very different types of substrates; the collection of the pre-pupae (at the end of their larval stage) and their slaughter and processing into meal and oil. With regards to mass balance, 9.3 t of growing substrate guarantee the production of 1.3 t of larvae (live weight), which are then converted into 1 t of IM and 0.3 t of insect oil. The 8 t of substrate residues are sold as fertiliser but, if compared with the economic value of insect meal and oil, they account for less than 3% of total net sales. The plant operates all year round.

2.2.3. PBM production

The poultry sector in Italy is grounded on well-established technologies and gross domestic production of poultry meat remained constantly above 1300 kt/y (carcass weight) over the last 5 years (Schliessnig et al., 2019).

For the emergy analysis on PBM production, data were gathered by interviewing the staff of a big Italian company producing 48 kt/y of dried meal: AIA - Agricola Italiana Alimentare S. p.A. The activities included in the system boundaries (Fig. 3) are poultry farming, poultry processing into food (which essentially includes birds slaughter, defeathering, evisceration, and cutting), poultry by-product processing into meals and fat. PBM is obtained from the processing of the biomass unsuitable for human consumption (such as heads, feet, skin, and inedible giblets): this biomass undergoes a special treatment (rendering) that separates the two animal tissue components (PBM and poultry fat) from water. However, PBM and poultry fat are produced alongside blood meal and feathers meal (within the same building) and, as such, data related to their supply chain were provided in aggregate form. With regards to the mass balance, 18.6 t of broiler (live weight) give 13.0 t of broiler meat, 1.0 t of PBM and 2.8 t of other by-products, plus 1.7 t of wastewater (removed from animal tissues). The plant operates all year round.

2.3. Emergy accounting

2.3.1. Overview

As explained in section 1, the matter and energy sources included in a LCA study represent only a part of the systems analysed through the emergy approach, since the latter also considers the resources belonging to the geo-biosphere, the services, and the money driving the processes (with physically virtual monetary flows required to detect and account for upstream geo-biophysical flows associated with indirect labour). Once quantified, all the inputs are converted into emergy units using the 'emergy evaluation table'. The conversion factors used in emergy accounting are named Unit Emergy Values (UEVs). When a UEV is expressed as the ratio of the emergy content (sej) to the energy (exergy) content (J) of a product, it can also be referred to as "transformity" (sej/J). Instead, if the emergy content (sej) is proportioned to the mass of the product (kg), it is usually named "specific emergy" (sej/kg). UEVs can be sourced from literature and from national and international databases, or calculated anew. The sum of all the emergy inputs from nature and the economy gives the total emergy of the production system, that is the solar emjoules required – annually, in general – for its ordinary management (sej/y).

2.3.2. Inputs from nature

Part of the inputs reported in the emergy evaluation table is represented by the natural resources provided for free by the environment surrounding the plant and from which the production system benefits. In this study, all the relevant inputs from nature are quantified but only the driving one is used in the final emergy assessment (Brown and Ulgiati, 2016), in order to avoid double accounting of natural resources. Formulas are reported as footnotes in Table 4.

The surface areas occupied by the production plants were provided by producers and were then cross-referenced and integrated with Google Maps measurements. Site- and time-specific data were gathered from different data sources, as better detailed in the Results and discussion section (see the emergy evaluation tables footnotes). The only local non-renewable input (land use) and the indirect renewable input (dispersion of emissions) are considered as not relevant for the emergy assessment at hand and, as such, excluded from the calculation. Concerning the former, this is due to both the uncertainty about the organic content of the original soil, often under average due to coastal sedimentary areas (de Brogniez et al., 2015) and to the values obtained in pre-calculations, with orders of magnitude significantly lower than the rest of the assessment. With regard to the discharge of liquid and gaseous substances into the environment, the emissions occurring in every system here considered are low to the point where no further dispersion service is needed than regular local renewables (Table 2). Indeed – according to the related accounting method (Ulgiati and Brown, 2002), the types and amounts of released substances at issue, and the French and Italian regulations for acceptable air quality levels – dilution and dispersion already happen abundantly through the sole wind. The approach adopted to draw this conclusion is detailed in Cristiano and Gonella (2019a). Since the driving renewables are already accounted for, any additional input would cause double counting.

2.3.3. Inputs from the economy

The other resources considered in the emergy assessment are all inputs that are not available locally and that therefore are to be imported from other systems, namely all the purchased materials (F), labour (L), and services (S). F essentially includes the matter and energy resources needed to carry out the process, including goods and machinery. The sum of F with the local renewables (R) and nonrenewables (N) yields the total emergy use of a process (U), net of labour and services; if the latter are considered too, the emergy use with labour and services is expressed as ULS. The useful lifetime of machinery and equipment was estimated by only assuming ordinary maintenance on them and is based on interviews with the company staff and consultancy with civil engineers, whose information was anyway double-checked by the authors. Storage infrastructures and logistics, administration offices, laboratories, etc. are not included in the system boundaries since they are not representative of the production processes, nor – based on pre-calculations – their order of magnitude would affect the final result. A peculiar resource involved in DMB production is represented by seawater. Seawater is imported into the system by means of pumps, and is used partly as culture medium and partly for its cooling (by flowing through a heat exchanger). Despite being a natural resource, it has to be artificially imported into the system (through the pumping system) and, as such, its contribution is accounted within F. With regard to L and S, labour cost quantification is based on the number of full-time workers involved in the processes. The quantification of the other operating costs and of the capital costs (services, or indirect labour) is based on their monetary value, since money brings the "memory" of other direct and indirect energy, material, and labour inputs.

Information gaps in the upstream processes were filled as follows. With regards to IM, the exact formulation of the feed provided to fly larvae (*i.e.* the growing substrate) was not disclosed due to IPR protection. According to the company's statement, the substrate was based on cereal by-products, thus the UEV value was taken from an emergy study on a small plant that produces black soldier fly fed with corn and wheat residues (Allegretti et al., 2018). With regards to PBM, the company could not provide information on poultry farming and slaughtering activities. Thus, the first phase was modelled according to a previous study on conventional Italian broiler farms (Castellini et al., 2006), integrated with economic data provided by a second study by the same author on the same systems (Castellini et al., 2012). These publications used meat-type

Table 2
List of substances released into the environment and reasons for ignoring them.

EMISSION TYPE	COMMENT
Liquid emissions	DMB systems – The fertilisers injected in the photobioreactors are assumed to be entirely absorbed by the microalgae (Maiolo et al., 2020), thus the organic nutrient content in microalgae wastewater is very low. After harvesting, culture medium ultrafiltration allows it to be recycled. Thus, the culture chambers are filled-up and emptied with the culture medium once a year (the first and last day of production, respectively). On the other hand, the seawater filling the cooling system is changed regularly. IM and BPM systems – Wastewaters are treated in accordance with the current legislation in both cases and lead to a low level of pollutants in the final output returned to nature. Due to its low management costs and long lifespan, the contribution of the wastewater treatment system to the total emergy assessment is negligible as well and thus excluded from calculations.
Gaseous emissions	DMB systems – 80% of the CO_2 provided to microalgae is not consumed and is eventually released into the air (259.20 t/y of CO_2 in DMB_TETRA, 181.44 t/y of CO_2 in DMB_TISO). IM and BPM systems – Green-house gases are generated by poultry and insects metabolism and by the fermentation of the insect growing substrate, but were considered as not significant (Maiolo et al., 2020). Transportation – Green-house gases are also due to the transport of consumable goods from the retailer to the facility where they are used. In this case the transportation takes place by road and from a short distance (minimum distance: 15 km; maximum distance: 80 km), thus it is pre-calculated that the yearly amount of road emissions does not exceed the local wind dilution capacity.

Table 3
Emergy assessment of ‘Dried Microalgae Biomass from *Tetraselmis suecica*‘ (DMB_TETRA) farming and processing into meal on an annual basis. UEV: Unit Emergy Values.

Note	Item	Unit	Amount	UEV ([a])	Solar emergy
			(unit/yr)	(sej/unit)	(E+14 sej/yr)
Locally available renewable inputs (R)					
1	Solar radiation	J	3.55E+13	1.00E+00	<0.5
2	Geothermal heat flow	J	7.50E+11	4.90E+03	37
3	Tidal energy	J	1.09E+12	3.09E+04	338
			Sum of tripartite		375
4	Wind, kinetic energy	J	2.17E+10	7.90E+02	<0.5
5	Wave energy	J	9.46E+12	4.20E+03	397
6	Rain, chemical potential	J	3.62E+10	7.00E+03	3
7	Rain, geopotential	J	4.01E+05	1.28E+04	≪0.5
		Largest of 2nd and 3rd sources			397
Driving renewable input[b]					*397*
Locally available non-renewable inputs (N)					
8	Land use	m^2	-	-	-
Imported inputs (F)					
9	Carbon dioxide, liquid	kg	3.24E+05	1.06E+12	3434
10	Fertilisers	kg	1.66E+04	3.89E+12	644
11	Chemicals (only chemicals in the product are considered)	kg	1.90E+02	3.58E+12	7
12	Photobioreactor - LDPE	kg	3.00E+03	8.51E+12	255
13	Photobioreactor - Wood	kg	2.40E+03	5.96E+12	143
14	Photobioreactor - Steel	kg	3.25E+03	3.13E+12	102
15	Photobioreactor - PVC	kg	3.20E+02	7.43E+12	24
16	Electricity	J	1.56E+12	2.21E+05	3457
17	Pumped seawater (medium + cooling)	m^3	7.58E+07	1.00E+11	75,802
Labour & Services (L&S)					
18	Labour				
	- Factory employees & technicians	unit	6	7.96E+16	4776
19	Services				
	- Capital costs	€	8.34E+04	1.90E+12	1585
	- Other direct and indirect operating costs	€	2.14E+05	1.90E+12	4059
Total Emergy input (U)				(sej/yr)	8.43E+18
Total Emergy input with labour and services (ULS)				(sej/yr)	9.47E+18
Output (Y)					
Dry Microalgal Biomass made of *Tetraselmis suecica* (DMB_TETRA), mass		kg	3.60E+04		
Dry Microalgal Biomass made of *Tetraselmis suecica* (DMB_TETRA), energy[c]		J	5.22E+11		
Total Emergy per DMB_TETRA unit		Specific emergy		(sej/kg)	2.34E+14
		Transformity		(sej/J)	1.61E+07
Total Emergy per DMB_TETRA unit, with labour and services		Specific emergy		(sej/kg)	2.63E+14
		Transformity		(sej/J)	1.81E+07

Footnotes
Natural resources:
Solar radiation = (plant surface area) x (annual solar radiation) x (1 − albedo) x (Carnot efficiency).
Geothermal heat flow = (plant surface area) x (heat flow).
Wind, kinetic energy = (density) x (drag coefficient) x (velocity adsorbed^3) x (plant surface area) x (time).
Rain, geopotential = (plant surface area) x (rainfall) x (% runoff) x (water density) x (average elevation) x (gravity).
Rain, chemical potential = (plant surface area) x (annual precipitation) x (average evapotranspiration) x (water density) x (Gibbs energy of rain).
Wave energy = (coast length) x (average front wave power) x (sec/y). Tidal energy = (shelf surface) x (0.5) x (tides/y) x (mean tidal range)2 x (density of seawater) x (gravity)
Area of the production plant: 10,000 m^2. **1.** Daily solar insolation along the coast of Lucca province, Tuscany region, Italy: 3.9 kWh/m^2/day, retrieved from the on-line Italian atlas of solar radiation (ENEA, 2020); albedo of green grass: 0.26 (UNI 8477−1:1983 – Solar energy. Calculation of energy gains for building applications. Evaluation of radiant received energy). **2.** Local heat flow: 75 mW/m^2 (Della Vedova et al., 2001). **3.** Average annual local surface wind speed: 1.7 m/s, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020); velocity adsorbed: geostrophic wind speed − surface wind speed = surface wind speed/0.58 − surface wind speed (Brown and Ulgiati, 2013); drag coefficient for land: 0.03 (Brown and Ulgiati, 2013); average density of air: 1.23 kg/m^3 **4.** Elevation: 5m (**Lido di Camaiore** official records); annual rainfall: 1021.4 mm, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020); runoff on built environment: 0.8 (our estimation based on previous literature). **5.** Annual rainfall: 1021.4 mm, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020). **6.** Coast length: 100.00 m; average front wave power on the Tuscany coast: 3000.00 W/m (Peviani et al., 2011). **7.** Shelf width: 10 nautical miles (our assumption based on previous literature); mean tidal range: 0.4 m (Cutroneo et al., 2017). **8.** Not considered. **9**−**17.** Maiolo et al. (2020). **18**−**19.** Adaptation of Tredici et al. (2016) to this case study.
UEV references: **1.** By definition. **2,3,4,7.** After De Vilbiss and Brown, 2015. **5**−**6.** Brown and Ulgiati (2016). **8.** Not considered. **9.** Monoethanolamine (MEA) based chemical absorption of CO_2 (Nimmanterdwong et al., 2017). **10**−**11.** Campbell et al. (2005). **12,13,15.** Buranakarn (1998). **14.** Brown and Buranakarn (2003). **16,18,19.** after Sweeney et al. (2007) (L and S in Italy). **17.** after De Vilbiss and Brown (2015).
[a] Calculated or converted from other works according to the **GEB_{2016} of 1.2E+25 seJ** (Brown et al., 2016).
[b] As per (Brown and Ulgiati, 2016), we only use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources.
[c] The gross energy content (14,5 MJ/kg) was assessed by SUSHIN-project partners: CREA (Council for Agricultural Research) and the University of Udine.

birds, concentrated feed, controlled housing (artificial light and climate control) and had a feed conversion ratio of 1.9. Poultry slaughter was modelled in terms of energy and water consumption (COM, 2005) and labour (Di Tullio et al., 2016).

2.3.4. Outputs from the economy

According to PBM and IM company staff and to DMB experts, the solid waste emitted by the three systems is negligible in terms of both the quantities emitted and the services necessary for their removal from the system. Therefore, the flow of solid waste was not considered in the analysis.

3. Results and discussion

3.1. Results visualisation and discussion about emergy-based indicators

The major emergy flows of the four systems (DMB_TETRA, DMB_TISO, IM, PBM) are summarised in Tables 3–6: the inputs converted into their equivalent amount of solar joules are given on the last column on the right, as per the procedure indicated in Odum (1996). The information provided in each table and in the related footnotes is sufficient to understand the key aspects of the emergy assessment. The total emergy per unit of product (in the form of specific emergy and transformity) is summarised in Table 7.

Based on the results presented in Table 7, IM shows the highest environmental efficiency (*i.e.* less emergy needed to produce a given amount of product), followed by PBM (one order of magnitude higher in both specific emergy and transformity). On the other hand, the two microalgae production systems appear as the least efficient, with DMB_TISO scoring the worst performances: 25 times bigger than IM in terms of specific emergy and 31 times bigger in terms of transformity. Between the two algal species, *Tetraselmis suecica* has a higher growth rate, a higher annual yield and a higher gross energy content than *Tisochrysis lutea*. As a result, the total emergy needed to get one unit of DMB_TISO is around 40% higher than in DMB_TETRA when scaled on the mass (specific emergy) and 30% higher when scaled on the energy content (transformity). In any case, both algae show the worst performances per unit of product.

This result is due to their low gross energy content only in part (14.5 and 16 MJ/kg for *Tetraselmis suecica* and *Tisochrysis lutea*, respectively; 19.5 MJ/kg for the black soldier fly meal; 21.3 MJ/kg for the poultry by-product meal). Indeed, the main drivers are to be found in the low productivity of the DMB systems, combined with a high quantity of seawater imported in the system. While the energy content is species-specific and cannot be modified, a change in DMB system setting/location, technological improvements and an increase in the scale of the plant could all be valid complementary strategies to increase the annual yield and, as a consequence, to cut emergy costs per unit of output. Some words on seawater contribution is spent in section 3.3, where the inputs having the highest emergy content are discussed.

The emergy-based indicators considered here (Table 8) help to get a broader picture of systems efficiency and to detect possible areas for improvement. The chosen indicators – the Emergy Yield Ratio (EYR), the Environmental Loading Ratio (ELR), the Emergy Sustainability Index (ESI), the % Renewable Emergy (%Ren), the Areal Empower Intensity (AEI) – were calculated both with and without '*Labour*' and '*Services*', for better comparisons with other emergy studies and at the same time to determine the specific contribution of these indirect flows to the system.

The first, evident result is the lack of significant differences between the two DMB systems: the materials, energy, and services needed to carry out the two productions are similar, and no major differences are observed in any of the indicators value (all differences are below ± 0.05%).

With regard to the first index, **EYR**, the higher the relative contribution of the locally available inputs, the higher its value. Thus, a high ratio reflects a highly efficient use of local resources, irrespective of their being renewable or not. All the systems score an EYR almost equal to one, which is the minimum EYR value: 1.005 in both DMB systems; 1.001 in IM; 1.00001 in PBM. This means that they are all consumer systems, almost totally dependent on resources from the external economies (imported inputs, F): the resources taken from the natural environment surrounding the production plant (locally available inputs, R and N) exhibit much smaller amounts of energy, matter, and information "memory" and as such are negligible. In other terms, the new resources made available within the technosphere – namely DMB_TETRA, DMB_TISO, IM and PBM – contain the same amount of emergy which was contained in the resources taken from it. At a first glance, this result might suggest that the systems at issue do not depend on their local environment and thus might be located anywhere. However, this claim should be validated through a comparison with alternative systems simulating a change in those local inputs. For instance, their lack may imply higher technological inputs and related additional imported flows: this kind of assessment was carried out by Cristiano and Gonella (2019b), but is beyond the purposes of the present study. On the contrary, an increase in the availability of some local inputs may affect the results as well. According to Tredici et al. (2015), the production of the two species of microalgae could increase significantly by moving the photobioreactors in a warmer and sunnier location (*i.e.* from the Tuscanian coast in Italy to North Africa) and by integrating current technologies with solar- and other renewable-based ones, which would lead to reduce the dependence on fossil energy. Similarly, moving the black soldier fly company from Northern France to a region with a much milder climate would likely reduce the ecological and economic costs for indoor warming. Indeed, this insect, native to the warm temperate zone of America, has a growth optimum temperature of 24–29 °C and requires a high amount of energy to heat the structures and keep the microclimate conditions constant. The EYR results inclusive of labour (L) and services (S) do not markedly affect the score for the two microalgae, while it consistently increases the index of the PBM system (+43%) and almost doubles it in the IM system (+87%). In the former, this is mostly due to the indirect labour (S) contained in the production (hence the purchasing) of poultry and of fuels and electricity required for the poultry and by-product processing. In the latter, this is mainly linked to a high use of human labour (L) at the plant, followed by the costs of farming substrate and electricity.

A high **ELR** value indicates that the transformation process implies either a low fraction of renewable resources, or a high consumption of non-renewable and imported inputs (which place a high pressure on the environment), or both. For this reason, the ELR can be considered as a measure of ecosystem stress due to the production. As a reference point, the ecosystem stress is considered moderate when ELR ranges between 3 and 10, while it is low when falls below 2 (Brown and Ulgiati, 2004). All the systems analysed here show high (2.11E+02 and 7.12E+02 for the two DMB and for IM, respectively) and very high values for PBM (1.23E+05). These values are typical of systems with a high technological level and/or of systems based on inefficient processes, not sustainable in the long-term. The efficiency of microalgae cultivation is very far from the farming of traditional (*i.e.* not energy-intensive) crops, which is typically based on a high share of renewable resources. Indeed, the ELR of both DMB systems is comparable to the one of IM system which actually, being an animal farming system, was expected to be far more demanding in terms of non-renewable inputs. PBM is the

Table 4
Emergy assessment of 'Dried Microalgae Biomass from *Tisochrysis lutea*' (DMB_TISO) farming and processing into meal on an annual basis. UEV: Unit Emergy Values.

Note	Item	Unit	Amount (unit/yr)	UEV ([a]) (sej/unit)	Solar emergy (E+14 sej/yr)
Locally available renewable inputs (R)					
1	Solar radiation	J	3.55E+13	1.00E+00	<0.5
2	Geothermal heat flow	J	7.50E+11	4.90E+03	37
3	Tidal energy	J	1.09E+12	3.09E+04	338
			Sum of tripartite		375
4	Wind, kinetic energy	J	2.17E+10	7.90E+02	<0.5
5	Wave energy	J	9.46E+12	4.20E+03	397
6	Rain, chemical potential	J	3.62E+10	7.00E+03	3
7	Rain, geopotential	J	4.01E+05	1.28E+04	≪0.5
Largest of 2nd and 3rd sources					*397*
Driving renewable input[b]					*397*
Locally available non-renewable inputs (N)					
8	Land use	m^2	-	-	-
Imported inputs (F)					
9	Carbon dioxide, liquid	kg	2.27E+05	1.06E+12	2404
10	Fertilisers	kg	1.16E+04	3.89E+12	451
11	Chemicals (only chemicals in the product are considered)	kg	1.90E+02	3.58E+12	7
12	Photobioreactor - LDPE	kg	3.00E+03	8.51E+12	255
13	Photobioreactor - Wood	kg	2.40E+03	5.96E+12	143
14	Photobioreactor - Steel	kg	3.25E+03	3.13E+12	102
15	Photobioreactor - PVC	kg	3.20E+02	7.43E+12	24
16	Electricity	J	2.06E+12	2.21E+05	4543
17	Pumped seawater (medium + cooling)	m^3	7.58E+07	1.00E+11	75,802
Labour & Services (L&S)					
18	Labour				
	- Factory employees & technicians	unit	6	7.96E+16	4776
19	Services				
	- Capital costs	€	8.34E+04	1.90E+12	1585
	- Other direct and indirect operating costs	€	2.40E+05	1.90E+12	4560
Total Emergy input (U)				(sej/yr)	8.41E+18
Total Emergy input with labour and services (ULS)				(sej/yr)	9.50E+18
Output (Y)					
Dry Microalgal Biomass made of *Tisochrysis lutea* (DMB_TISO), mass		kg	2.52E+04		
Dry Microalgal Biomass made of *Tisochrysis lutea* (DMB_TISO), energy[c]		J	4.03E+11		
Total Emergy per DMB_TISO unit		Specific emergy		(sej/kg)	3.34E+14
		Transformity		(sej/J)	2.09E+07
Total Emergy per DMB_TISO unit, with labour and services		Specific emergy		(sej/kg)	3.77E+14
		Transformity		(sej/J)	2.36E+07

Footnotes
Natural resources**: s**ee the footnotes in Table 4
Area of the production plant: 10,000 m^2. **1.** Daily solar insolation along the coast of Lucca province, Tuscany region, Italy: 3.9 kWh/m^2/day, retrieved from the on-line Italian atlas of solar radiation (ENEA, 2020); albedo of green grass: 0.26 (UNI 8477−1:1983 − Solar energy. Calculation of energy gains for building applications. Evaluation of radiant received energy). **2.** Local heat flow: 75 mW/m^2 (Della Vedova et al., 2001). **3.** Average annual local surface wind speed: 1.7 m/s, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020); velocity adsorbed: geostrophic wind speed − surface wind speed = surface wind speed/0.58 − surface wind speed (Brown and Ulgiati, 2013); drag coefficient for land: 0.03 (Brown and Ulgiati, 2013); average density of air: 1.23 kg/m^3 **4.** Elevation: 5m (**Lido di Camaiore** official records); annual rainfall: 1021.4 mm, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020); runoff on built environment: 0.8 (our estimation based on previous literature). **5.** Annual rainfall: 1021.4 mm, retrieved from the on-line hydrological and geological database of the Tuscany region (SIR, 2020). **6.** Coast length: 100.00 m; average front wave power on the Tuscany coast: 3000.00 W/m (Peviani et al., 2011). **7.** Shelf width: 10 nautical miles (our assumption based on geographical location and previous literature); mean tidal range: 0.4 m (Cutroneo et al., 2017). **8.** Not considered. **9−17.** Maiolo et al. (2020). **18−19.** Adaptation of Tredici et al. (2016) to this case study.
UEV references: **1.** By definition. **2,3,4,7.** After De Vilbiss and Brown, 2015. **5−6.** Brown and Ulgiati (2016). **8.** Not considered. **9.** Monoethanolamine (MEA) based chemical absorption of CO_2 (Nimmanterdwong et al., 2017). **10−11.** Campbell et al. (2005). **12,13,15.** Buranakarn (1998). **14.** Brown and Buranakarn (2003). **16,18,19.** after Sweeney et al. (2007) (L and S in Italy). **17.** after De Vilbiss and Brown (2015).
[a] Calculated or converted from other works according to the **GEB_{2016} of 1.2E+25 seJ** (Brown et al., 2016).
[b] As per Brown and Ulgiati (2016), we only use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources.
[c] The gross energy content (16,0 MJ/kg) was assessed by SUSHIN-project partners: CREA (Council for Agricultural Research) and the University of Udine.

system with the highest yield: 1200−1700 times higher than the DMB systems and around 500 times higher than IM (Table 1). It is also the system causing the highest ecosystem stress in one year. This mean that − compared with the other systems − its scale effect does not seem to play a big role in ensuring a higher efficiency; on the contrary, with a very poor use of local renewables, higher levels of production amplify the ratio between imports from the outer economies and local renewable inputs.

ESI draws a relationship between system benefit (efficient use of local inputs) and cost (ecosystem stress), thus it reflects the ability of the systems in providing the production with a minimum environmental stress and a maximum profit. As a consequence of EYR and ELR results, the ESI turns out to be very small, always below the threshold value for a long-time sustainable process (ESI = 5): 4.8E-03 in both DMB, 1.4E-03 in IM and even 8.1E-06 in PBM. The dependence upon many external raw and processed inputs and labour plays a role in such poor sustainability.

The renewable emergy content in the product (**%Ren**) makes the reliance of all the systems on non-renewable imported inputs further explicit. The DMB system at issue is a closed photo-

Table 5
Emergy assessment of black soldier fly (*Hermetia illucens*) farming and processing into Insect Meal (IM) on an annual basis. UEV: Unit Emergy Values.

Note	Item	Unit	Amount	UEV ([a])	Solar emergy
			(unit/yr)	(sej/unit)	(E+14 sej/yr)
Locally available renewable inputs (R)					
1	Solar radiation	J	5.38E+12	1.00E+00	<0.5
2	Geothermal heat flow	J	2.25E+11	4.90E+03	11
			Sum of tripartite		11
3	Wind, kinetic energy	J	5.68E+10	7.90E+02	<0.5
4	Rain, chemical potential	J	8.12E+09	7.00E+03	<1
5	Rain, geopotential	J	2.11E+06	1.28E+04	≪0.05
Largest of 2nd and 3rd sources					<1
Driving renewable input[b]					*11*
Locally available non-renewable inputs (N)					
6	Land use	m^2	-	-	-
Imported inputs (F)					
7	Farming substrate	J	1.10E+13	4.58E+04	5035
8	Chemicals (only chemicals in the product are considered)	kg	1.90E+02	3.58E+12	7
9	Farming equipment – Boxes: PET	kg	2.97E+01	8.51E+12	3
10	Farming equipment – Frames: Steel	kg	3.96E+01	3.13E+12	1
11	Processing equipment: Steel	kg	4.40E+03	3.13E+12	138
12	Tap water	kg	6.27E+05	2.86E+09	18
13	Electricity	J	1.20E+12	2.21E+05	2652
Labour & Services (L&S)					
14	Labour				
	- Labour + Technical assistance	unit	4	9.56E+16	3824
15	Services				
	- Farming substrate	€	9.79E+04	1.85E+12	1811
	- Chemicals	€	3.32E+03	1.85E+12	61
	- Farming and processing equipment	€	1.68E+04	1.85E+12	311
	- Tap water	€	2.50E+03	1.85E+12	46
	- Electricity	€	4.00E+04	1.85E+12	740
Total Emergy input (U)				(sej/yr)	7.86E+17
Total Emergy input with labour and services (ULS)				(sej/yr)	1.47E+18
Output (Y)					
Insect Meal (IM), mass		kg	9.90E+04		
Insect Meal (IM), energy[c]		J	1.93E+12		
Fat, mass		kg	3.30E+04		
Substrate residues, mass		kg	7.92E+05		
Total Emergy per IM unit		Specific emergy		(sej/kg)	7.94E+12
		Transformity		(sej/J)	4.07E+05
Total Emergy per IM unit, with labour and services		Specific emergy		(sej/kg)	1.48E+13
		Transformity		(sej/J)	7.59E+05

Footnotes
Natural **resources: s**ee the footnotes in Table 4
Area of the production plant: 3000 m^2. **1.** Daily solar insolation in the Nord department, Hauts-de-France region, France: 2.9 kWh/m^2/day, retrieved from the French web-based software CalSol (INES, 2020); albedo of tiles and concrete: 0.27 (ASHRAE, 2001). **2.** Local heat flow: 75 mW/m^2 (Lucazeau and Vasseur, 1989). **3.** Average annual local surface wind speed: 3.5 m/s, retrieved from the French meteorological database (Météo France, 2020); velocity adsorbed: geostrophic wind speed – surface wind speed = surface wind speed/0.58 – surface wind speed (Brown and Ulgiati, 2013); drag coefficient for land: 0.03 (Brown and Ulgiati, 2013); average density of air: 1.23 kg/m^3 **4.** Elevation: 117m (**Éphey** official records); annual rainfall: 764.6 mm, retrieved from the French meteorological database (Météo France, 2020); runoff on built environment: 0.8 (our estimation based on previous literature). **5.** Annual rainfall: 764.6 mm, retrieved from the French meteorological database (Météo France, 2020) **6.** Not considered. **7.** Substrate consumption: 594 t/y (Maiolo et al., 2020); gross energy content of black soldier fly meal: 1.85E+10 J/t (Allegretti et al., 2018). **8–13.** Maiolo et al. (2020). **14.** (Allegretti et al., 2018). **15.** Farming substrate: 164.8 ± 8.3 €/t (estimate based on cereal average price on the French market, second half of 2019) (European Commission. Market observatories, 2020); chemicals: 10€/kg (average price provided by a laboratory supply company); farming and processing equipment: 18,492.80 $/y (sum of materials, facilities and equipment in Allegretti et al., 2018); tap water: 3.98 €/m^3 (Eau France, https://www.eaufrance.fr/); electricity: 0.12 €/kWh (electricity prices for non-household consumers, first half of 2019) (Eurostat: nrg_pc_205, 2020).
UEV references: 1. By definition. **2–4.** After De Vilbiss and Brown, 2015. **5.** Brown and Ulgiati (2016). **6.** Not considered. **7.** Gross energy: 1.85E+10 J/t; transformity: 4.58E+04 sej/J (Allegretti et al., 2018). **8.** Campbell et al. (2005). **9.** Buranakarn (1998). **10–11.** Brown and Buranakarn (2003). 12. Ascione et al. (2009). **13–15.** after Sweeney et al. (2007) (L and S in France).
[a] Calculated or converted from other works according to the **GEB_{2016} of 1.2E+25 seJ** (Brown et al., 2016).
[b] As per Brown and Ulgiati (2016), we only use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources.
[c] The gross energy content (19,5 MJ/kg) was assessed by SUSHIN-project partners: CREA (Council for Agricultural Research) and the University of Udine.

bioreactor, which allows one to maintain strict control over the operational variables affecting growth (*e.g.* temperature, pH) and to reduce harvesting operation costs (lower workers number) thanks to a higher volumetric productivity than open microalgae cultivation systems (Leite et al., 2013). Thus, all the inputs that are spontaneously sourced from nature in open pond cultivations are here either imported from it through pumping systems (*i.e.* seawater) or imported from other economies (*i.e.* fertilisers and liquid carbon dioxide). For everything stated above, it is not surprising to see a very low percentage of renewable emergy (0.47%) which, however, is higher than that of IM (0.14%) and PBM (8.17E-06%). A potential sustainability in the long run seems to have been traded for a higher productivity in the short run.

To the best knowledge of the authors, no **AEI** values have been calculated before for any food production system. Indeed, these results can only be compared with those of emergy analyses in the building sector. For the first three plants (DMB_TETRA, DMB_TISO and IM), AEI values are similar to the emergy per square metre

Table 6
Emergy assessment of poultry farming and poultry by-product processing into 'Poultry By-product Meal' (PBM) on an annual basis. UEV: Unit Emergy Values.

Note	Item	Unit	Amount	UEV ([a])	Solar emergy
			(unit/yr)	(sej/unit)	(E+14 sej/yr)
Locally available renewable inputs (R)					
1	Solar radiation	J	2.77E+14	1.00E+00	3
2	Geothermal heat flow	J	8.26E+12	4.90E+03	405
			Sum of tripartite		408
3	Wind, kinetic energy	J	1.76E+11	7.90E+02	1
4	Rain, chemical potential	J	4.54E+11	7.00E+03	32
5	Rain, geopotential	J	1.45E+08	1.28E+04	<0.05
Largest of 2nd and 3rd sources					*32*
Driving renewable input[b]					*408*
Locally available non-renewable inputs (N)					
6	Land use	m^2	-	-	-
Imported inputs (F)					
7	Poultry (conventional production)	kg	8.02E+08	5.66E+12	45,330,084
8	Chemicals (only chemicals in the product are considered)	kg	5.49E+03	3.58E+12	196
9	Processing equipment: Steel	kg	2.16E+04	3.13E+12	677
10	Water	kg	2.93E+10	2.86E+09	837,176
11	Electricity	J	1.50E+15	2.21E+05	3,324,428
12	Natural gas	J	6.99E+14	5.66E+04	395,026
Labour & Services (L&S)					
13	Labour				
	- Lab. in poultry and by-product processing	unit	16	7.96E+16	12,736
14	Services				
	- Poultry (conventional production)	€	9.46E+08	1.90E+12	17,971,715
	- Chemicals	€	6.85E+04	1.90E+12	1302
	- Processing equipment	€	1.00E+04	1.90E+12	190
	- Water	€	3.96E+07	1.90E+12	751,454
	- Electricity	€	7.10E+07	1.90E+12	1,349,661
	- Natural gas	€	6.89E+07	1.90E+12	1,308,537
Total Emergy input (U)				(sej/yr)	4.99E+21
Total Emergy input with labour and services (ULS)				(sej/yr)	7.13E+21
Output (Y)					
Poultry By-product Meal (PBM), mass		kg	4.33E+07		
Poultry By-product Meal (PBM), energy[c]		J	9.22E+14		
Blood meal + Feather meal + Fat		kg	1.23E+08		
Chicken for human consumption		kg	5.61E+08		
Total Emergy per PBM unit		Specific emergy		(sej/kg)	1.15E+14
		Transformity		(sej/J)	5.41E+06
Total Emergy per PBM unit, with labour and services		Specific emergy		(sej/kg)	1.65E+14
		Transformity		(sej/J)	7.73E+06

Footnotes
Natural **resources: s**ee the footnotes in Table 4
Area of the production plants (4 slaughterhouses +2 rendering plants): 118,000 m^2. **1.** Daily solar insolation in Verona province, Veneto region, Italy: 3.8 kWh/m^2/day, retrieved from the on-line Italian atlas of solar radiation (ENEA, 2020); albedo of tiles and concrete: 0.27 (ASHRAE, 2001). **2.** Local heat flow: 70 mW/m^2 (Della Vedova et al., 2001). **3.** Average annual local surface wind speed: 1.5 m/s, retrieved from the on-line environmental database, weather report section, of the Veneto region (ARPAV, 2020); velocity adsorbed: geostrophic wind speed − surface wind speed = surface wind speed/0.58 − surface wind speed (Brown and Ulgiati, 2013); drag coefficient for land: 0.03 (Brown and Ulgiati, 2013); average density of air: 1.23 kg/m^3 **4.** Elevation: 144m (**Illasi** official records); annual rainfall: 1087.2 mm, retrieved from the on-line environmental database, weather report section, of the Veneto region (ARPAV, 2020); runoff on built environment: 0.8 (our estimation based on previous literature). **5.** Annual rainfall: 1087.2 mm, retrieved from the on-line environmental database, weather report section, of the Veneto region (ARPAV, 2020). **6.** Not considered. **7,8,9,12.** Maiolo et al. (2020). **10.** Poultry slaughter average water consumption: 36,235 L/t of poultry carcass (COM, 2005); by-product processing water consumption: 1000.0 L/t Maiolo et al. (2020). **11.** Poultry slaughter average electricity consumption: 506 kWh/t of poultry carcass (COM, 2005); by-product processing electricity consumption: 48.7 kWh/t Maiolo et al. (2020). **13.** average number of full-time workers (Di Tullio et al., 2016). **14.** Poultry, conventional production: 1.18 €/kg for the production of a chicken live weight (including labour, depreciation and interests costs) (Castellini et al., 2012); chemicals: 2,70 €/L (average price provided by a laboratory supply company); processing equipment: capital cost of 250,000 € and average lifespan of 25 years (our assumption); water: 1.35€/m^3 (Fédération des Professionnelle Entreprises de l'Eau - FP2E, 2015); electricity: 0.17 €/kWh (electricity prices for non-household consumers, first half of 2019) (Eurostat: nrg_pc_205, 2020); natural gas price: 0.0342 €/kWh (gas prices for non-household consumers, first half of 2019) (Eurostat: nrg_pc_203, 2020); natural gas energetic content: 1Nm^3 = 10.9 kWh.
UEV references: 1. By definition. **2–4.** After De Vilbiss and Brown, 2015. **5.** Brown and Ulgiati (2016). **6.** Not considered. **7.** Castellini et al. (2006). **8.** Campbell et al. (2005). **9.** Brown and Buranakarn (2003). **10.** Ascione et al. (2009). **11,13,14.** after Sweeney et al. (2007) (L and S in Italy). **12.** (Bastianoni et al., 2009).
[a] Calculated or converted from other works according to the **GEB_{2016} of 1.2E+25 seJ** (Brown et al., 2016).
[b] As per Brown and Ulgiati (2016), we only use the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources.
[c] The gross energy content (21.3 MJ/kg) was assessed by SUSHIN-project partners: CREA (Italian Council for Agricultural Research) and the University of Udine.

Table 7
Total Emergy per unit of product.

			DMB_TETRA	DMB_TISO	IM	PBM
Total Emergy per unit, without L&S	Specific emergy	(sej/kg)	2.34E+14	3.34E+14	7.94E+12	1.15E+14
	Transformity	(sej/J)	1.61E+07	2.09E+07	4.07E+05	5.41E+06
Total Emergy per unit, with L&S	Specific emergy	(sej/kg)	2.63E+14	3.77E+14	1.48E+13	1.65E+14
	Transformity	(sej/J)	1.81E+07	2.36E+07	7.59E+05	7.73E+06

Table 8
Emergy-based indicator.

	DMB_TETRA	DMB_TISO	IM	PBM
Emergy Yield Ratio (EYR)				
(U)/F	1.00	1.00	1.00	1.00
(ULS)/F	1.13	1.14	1.87	1.43
Environmental Loading Ratio (ELR)				
(N + F)/R	211	211	709	122,421
(N + F + L&S)/R	237	238	1322	174,924
Emergy Sustainability Index (ESI = EYR/ELR)				
without L&S	0.005	0.005	0.001	≪0.001
with L&S	0.005	0.005	0.001	≪0.001
% Renewable Emergy (%Ren)				
without L&S	0.5%	0.5%	0.1%	≪0.1%
with L&S	0.4%	0.4%	0.1%	≪0.1%
Areal Empower Intensity (AEI)	(sej/m^2)	(sej/m^2)	(sej/m^2)	(sej/m^2)
(U)/plant area	8.43E+14	8.41E+14	2.62E+14	4.23E+16
(ULS)/plant area	9.47E+14	9.50E+14	4.89E+14	6.04E+16

invested to deliver high quality cardiac surgical healthcare in the *Salam* hospital in Sudan (*i.e.* 4.9 E+14 sej/m^2) (Cristiano et al., 2021). The AEI of the last system, PBM production, appears to be two orders of magnitude higher, thus more similar to the AEI of Global Northern residential buildings (*ibid.*). If comparisons are hard among such different products and services annually delivered on a same surface, the novelty of this indicator for food systems represents an interesting benchmark for future studies, which will allow for further comparison about the efficiency of the processes we address in our paper.

3.2. Literature comparison

To the best of the authors' knowledge, no previous publications applied the emergy approach to algae cultivation in photobioreactors before. The only studies that are somewhat comparable with ours are a paper on biofuel production from microalgae farmed in a large scale plant located in Texas (da Cruz and Nascimento, 2012) and a paper exploring the sustainability of a theoretical cold climate microalgae wastewater treatment plant, designed to operate in Sweden for 10,000 person equivalents (Grönlund et al., 2004). Both papers include three main consecutive steps: algae farming in ponds; harvesting; either processing into biofuel or landfilling. And both papers show an EYR close to 1, an ELR above the moderate ecosystem stress threshold (*i.e.* 10) and a small renewable emergy content in the product (%Ren), although not as small as the one assessed here for DMB_TETRA and DMB_TISO (Table 9).

With regard to insect meal, our IM system can only be compared with one study on a Brazilian pilot plant which rears black soldier fly larvae (Allegretti et al., 2018). At first glance, the two systems may look quite similar, both in terms of the final product (with an insect meal gross energy content of 19,5 MJ/kg in our study and of 28.9 MJ/kg in the Brazilian one) and in terms of rearing and processing steps (*e.g.* in both cases, insects are fed with cereal by-products). EYR looks similar as well, meaning that also the Brazilian system merely transforms resources that were already available from other external economic processes, without making an efficient use of local resources. Still, our total emergy appears one order of magnitude bigger and, consequently, the transformity is also bigger (0.76E+06 sej/j with L&S, against 0.078E+06 sej/j in the other study). Moreover, the choice made in Allegretti et al. (2018) of including, within the calculation of the renewable flow, a share of the imported inputs, L and S and the 100% of negative externalities leaded to an ELR over 1200 times smaller (1 against 1322) and a % Ren 600 times bigger (48.6% against 0.08%).

The emergy-based indicators provided by the four papers on poultry systems (Castellini et al., 2006; Hu et al., 2012; Park et al., 2016; Zhang et al., 2013) look more in line with ours, although the present research includes two further processing steps (*i.e.*

Table 9
Literature comparison.

	Paper	Case study	Transformity (E+06 sej/j)	EYR	ELR	ESI	% Renew
ALGAE	Our study	Microalgae farmed in a photobioreactor and harvested to produce dry microalgae biomass (used as feed ingredient)	Tetra = 18.1 Tiso = 23.6	Tetra = 1.13 Tiso = 1.14	Tetra = 237 Tiso = 238	Tetra = 0.005 Tiso = 0.005	Tetra = 0.4% Tiso = 0.4%
	Grönlund et al. (2004)	Theoretical microalgae wastewater treatment plant.	//	1.054	186	57 × 10^{-3}	5.1%
	da Cruz and Nascimento (2012)	Microalgae farmed in raceway ponds and harvested to produce oil to generate biofuel. Results are provided in form of joint transformity (JT) in order to include both oil and dry biomass (co-products).	JT = 0.10; JT with services = 0.13	1.09	11.10	0.10	8.3%
INSECT	Our study	Small company rearing black soldier fly with cereal by-products in France.	0.76	1.87	1322	0.001	0.1%
	Allegretti et al. (2018)	Pilot plant rearing black soldier fly with grain residues (corn and wheat) in Brazil.	0.078	1.00	1.04	0.96	48.6%
POULTRY	Our study	Conventional poultry production system in Italy.	7.73	1.43	174,924	≪0.001	≪0.1%
	Castellini et al. (2006)	Conventional poultry production system in Italy.	0.61	1.19	5.21	//	//
	Hu et al. (2012)	Family-operated Organic rearing system in China (FO) Orchard-based Field rearing system in China (OrF)	//	FO = 1.10 OrF = 1.11	FO = 3.10 OrF = 3.44	FO = 0.36 OrF = 0.32	//
	Zhang et al. (2013)	Backyard rearing system in China (BY) Orchard rearing system in China (OR)	BY = 2.17 OR = 1.58	BY = 1.43 OR = 1.48	BY = 2.34 OR = 2.28	BY = 0.61 OR = 0.65	BY = 0.30 OR = 0.30

poultry and by-product processing). These similarities were expected since, despite some differences, poultry farming is an already optimised production system, based on consolidated techniques all over the world. The only remarkable difference is in term of ELR. In Castellini et al. (2006) it might be due to the inclusion, within the calculation of the renewable sources, of a high share of poultry feed ingredients and labour. In the two papers on Chinese poultry farming, the analysed systems are far smaller than the Italian one considered in this paper: only 200 and 4000 birds farmed in one year (two life cycles) in the family-operated organic and in the orchard-based field systems respectively (Hu et al., 2012); 100 and 2000 birds in two years (one life cycle) in the backyard and orchard egg-production systems respectively (Zhang et al., 2013). As a consequence, the imported inputs, labour and services needed by our Italian systems (which processes more than 620,000 birds each day) are vastly larger and not counterbalanced by an adequate contribution from the renewable local resources, which remains low.

3.3. Comparison with LCA results and actions for improvement

As said in the introduction section, a recent study (Maiolo et al., 2020) applied the LCA methodology on the same protein sources and quantified the extent of the global warming, acidification, eutrophication, cumulative energy demand, and water use impacts. The cross-check of LCA results with those provided by this emergy assessment gives a broader picture of products sustainability, helping to point out possible strategies to undertake for their improvement.

As concerns the two **DMB** systems, the main contribution in terms of emergy flow comes from the pumped seawater used as culture medium (2.19E+03 m^3/y) and, above all, for the system cooling (7.58E+07 m^3/y) (F), accounting together for 80% of ULS (*i.e.* of the total emergy of the system). Electricity (5%), L (5%) and S (6%) follow at a great distance. Seawater emergy content is high despite the plant is located on the coast. This is because the water is not part of the system and needs to be brought by means of energy, machinery, and other technology. The high contribution of seawater to the total emergy of the DMB_TETRA and DMB_TISO systems flattens the differences between the two algal species, making their environmental performance fully comparable. The emergy result is completely in contrast with LCA findings, which indicate the fertilisers, the carbon supply and electricity as the main impact drivers (accounting together for at least 76% in all the impact categories considered). In brief, despite the inclusion of the water use within LCA, this impact category simply quantified the potential human and ecosystem water deprivation along the whole DMB_TETRA and DMB_TISO life cycle, disregarding any form of temporary water loan imported into the photobioreactors from the local natural environment. Thus, from a LCA perspective, the total absence of impacts deriving from the temporary seawater loan accentuates the distinct performances of the two species, performances related to differences in consumable goods and energy consumption.

Going back to the emergy perspective, a decreased in the **water used for the system cooling** is not considered a viable way. Even if its use was halved, the total contribution of seawater to the emergy of the system would continue to be very high (from the current 80%–67%), against a slight increase in the contribution of the other main inputs: electricity (from 5 to 6%), L (from 5 to 8%), S (from 6 to 10%). Overall, the total emergy of the system and the various indicators would not undergo major changes as well. ULS would remain higher than that of IM system (from 9.47E+18 to 5.68E+18 sej/yr), while EYR and %Ren would hardly change at all. The ecosystem stress, although reduced by 40%, would remain high (ELR = 142) and comparable to the one caused by IM system, ESI would continue to be far below the threshold value for a long-time sustainable process (from 0.005 to 0.009) and the emergy per square metre would remains comparable to the one of IM system and of the Salam hospital (AEI = 5.68E+14). As such, in the authors' opinion, two options to increase DMB sustainability remain on the table: (i) the development of a new system setup which naturally brings such water into the system (hence making it a locally available input); (ii) the development of new, more emergy-efficient ways to cool down the photobioreactors, without resorting to seawater at all. The first option would cause all the emergy indicators to dramatically change, with higher ratios of renewability and sustainability, while also reducing the UEVs in the light of a decreased need for external energy, machinery, and technologies. Still, the authors don't have the expertise to propose new setup solutions to achieve this goal. With regards to the second option, improvements could be attained by improving the thermal properties of the materials that make up the photobioreactor, in order to increase insulation without worsening its optical characteristics (*i.e.* LDPE culture chamber transparency, that guarantees microalgae photosynthesis).

In terms of LCA, the environmental performances of **IM** and **PBM** (the two animal protein sources) look very similar, with the feed provided to insect and poultry accounting alone for more than 50% of the total impact (and often up to 70 or even 90%). The remaining contribution is mainly due to energy consumption. These results are more in line with the emergy accounting findings, which address the insect substrate contribution to ULS as the key input of the IM system (34% of ULS as imported input and 12% as service), followed at a short distance by labour (26%) and purchased electricity (18%). Emergy results on PBM system are in line as well: the imported input 'Poultry, conventional production' (F) appears as the main hotspot, accounting alone for 64% of ULS (three quarters of which are due to poultry feed, according to Castellini et al., 2006). The related service 'Poultry, conventional production' (S) accounts for most of the rest (25% of ULS), with an emergy content mainly due to the economic cost of the feed (Castellini et al., 2012). Still, unlike in LCAs, an increase in annual yield while keeping the input quantities constant would lead to no performance improvement, since emergy-based indicators are not dependent on the yield. Moreover, again unlike LCAs, the PBM system is already operating on a very large scale, but its performances are not rewarded by the expected effects of an economy of scale and are always worse than those of the small IM system.

For everything stated above, the only possible way to improve both IM and PBM systems from an emergy perspective is a change in the type and/or quantity of inputs used. With regards to the **feed** provided to insect and poultry, a reduction in the amount consumed may be attained by improving the nutrient characteristics (in order to keep production constant while reducing the amount of inputs) and by choosing ingredients with a reduced emergy content. For instance, improvements may be achieved by integrating the feed with food supplements with the function of growth enhancers and/or immunostimulants and having at the same time a reduced emergy content. On the contrary, the use of crop by-products (like maize bran or oat hulls) as feed ingredients won't help decreasing the total emergy of the system. This is because when a process produces different types of outputs (like maize and oat processing), the emergy flow is entirely assigned to each of them regardless of their economic or nutritional value (second rule of the emergy-algebra, as described in Odum, 1996). This approach is distinctly different from the allocation used in the LCA and is explained by the fact that each product cannot be produced without producing the other, and thus it requires the total emergy input to be produced. Speaking of the **energy**

consumption, three alternative options have already been proposed about DBM system (sections 3.1 and 3.3) and are considered efficient also in this case. First, a shift to renewable energy sources would surely improve IM performances. Secondly, benefits would certainly be obtained by moving the IM company to a region with a milder climate, as this change would allow to reduce energy needs linked to the heating. A third option is the use of building materials with increased insulation properties. With regard to the high contribution of **hand labour** to the total emergy of IM system, regrettably knowledge on how to improve production efficiency in terms of management and mechanization is still scarce (Dossey et al., 2016). This is due both to the development of intensive insect farming on an industrial scale only in recent times, and to specific growth needs of fly larvae (*i.e.* reduced substrate thickness), which binds a possible increase in the production scale to an increase in the number of rearing boxes and to a consequent increase in the labour (Čičková et al., 2015).

Finally, a few words should be said on further research to supplement this study.

On the one hand, it should be noted that each of the four protein sources analysed was produced to be used as an ingredient in aquafeed formulations. In other words, the ultimate function of each ingredient is to contribute to the production of fish for human consumption: thus, its environmental performance should eventually be weighed with that of the other ingredients included in the feed and according to the growth efficiency of the farmed fish. This analysis was not carried out as it is outside the scope of this study.

On the other hand, the share of each protein source within an aquafeed will be obviously dependent on its protein content, which is in turn linked to the energy content. Indeed, according to Maiolo et al. (2020) and Tables 3–6 of this study, the minimum crude protein content (on a dry basis) and the gross energy content are, respectively: 0.40 kg/kg and 14,5 MJ/kg (DMB_TETRA); 0.41 kg/kg and 16,0 MJ/kg (DMB_TISO); 0.50 kg/kg and 19,5 MJ/kg (IM); 0.66 kg/kg and 21.3 MJ/kg (PBM). In brief, the nutritional properties of each protein source are somehow already considered in the study, but the present results do not explicitly consider the ultimate function of the four ingredients (*i.e.* the contribution to the increase in the fish body weight) and future additional studies are certainly desirable.

4. Conclusion

To sum up the results, all the systems turned out to be intensive industrial processes, with a non-significant exploitation of local resources and a high level of ecosystem stress (imported inputs from the economy represent 99% of total emergy flow). Among them, IM appears to have the highest environmental efficiency (lowest environmental support per unit produced), followed by PBM and finally by the two DMB systems. Several differences emerged with the few publications available, partly due to the systems setup, partly due to methodological choices (*e.g.* the choice, made in several papers, to include in the calculations the renewable share of economy inputs).

The coupling of the two resource accounting methods applied to DMB system revealed different criticalities: the high carbon dioxide and energy needs in LCA, the high consumption of seawater in emergy accounting. In respect to IM and PBM systems, LCA and emergy approaches highlighted the same main hotspot, that is the feed provided to insect and poultry. Still, if on the one hand the emergy accounting emphasized the striking importance of the feed in the PBM system (in which it represents almost 90% of the total emergy), on the other hand it showed the relevance of other two inputs in the IM system: human labour and energy. Despite the authors are unable to indicate any technical improvement about IM human labour, an increase in the environmental performances can be attained by finding more nutritional feed formulations for chicken and insects. Moreover, a better insulation of the facility is expected to reduce IM system energy needs, while more emergy-efficient ways to cool down the photobioreactors (by making sure that only the seawater necessary as cultivation medium is imported into the system) should benefit the two DMB systems.

In conclusion, the use of complementary resource accounting tools shows that some inputs are critical in both analyses and should undoubtedly be targeted for improvement actions. However, it also revealed hidden aspects of the system sustainability that were not detected by the use of LCA tool alone. In other terms, the comparison between emergy accounting and LCA results provided a more complete picture of the situation. In fact, it demonstrated how complex and intricate the network of flows and related environmental effects can be even within production systems which, according to common opinion, are considered as already eco-friendly. And, due to this complexity, attention should be paid while making changes to these systems, since the improvement of one aspect could possibly lead to the worsening of others.

Author contributions

All authors conceived the analysis, provided critical feedback, and helped shape the research, analysis, and manuscript. F.G. and R.P. established and supervised the inter-group cooperation and activities, with R.P. also acquiring the funds. S.M. collected the raw data and most information about the case studies, supervised by R.P., and cured the literature review, supervised by S.C.; S.C. set up and supervised the analytical method, processes, and layout. S.M. performed the analytical calculations. S.C. contributed to the analytical calculations and verified the results. S.M., S.C. and F.G. jointly designed the systems diagrams. All authors contributed to the first interpretation of the results and to the manuscript review. Original drafts, most writing, and editing by S.M., with contributions by S.C.

Declaration of competing interest

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

Acknowledgments

The authors would like to express sincere thanks to Dr. Sofia Spagnolo for the guidance in the first approach to the EMA. The research leading to these results - mostly based on the dataset and results of a peer-reviewed LCA study (Maiolo et al., 2020) - has received funding from SUSHIN (SUstainable fiSH feeds INnovative ingredients), a project funded by Ager AGER2-SUSHIN, Cod 2016-0112, and from the European Union's HORIZON 2020 Framework Programme under GRANT AGREEMENT NO. 773330.

References

Allegretti, G., Talamini, E., Schmidt, V., Bogorni, P.C., Ortega, E., 2018. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. J. Clean. Prod. 171, 403–412. https://doi.org/10.1016/J.JCLEPRO.2017.09.244.

ARPAV - Agency for environmental protection and prevention of the Veneto region, 2020. Dati ambientali. Section "Bollettini > Dati storici > Meteo-Idro ultimi anni". Online database. Retrieved March 25,. https://www.arpa.veneto.it/dati-ambientali.

Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. Environmental driving forces of urban growth and development. Landsc. Urban Plann. 93, 238–249. https://doi.org/10.1016/j.landurbplan.2009.07.011.

ASHRAE, 2001. Chapter 3. Heat transfer. In: Handbook Fundamentals. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, Georgia.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. The solar transformity of petroleum fuels. Ecol. Model. 220, 40–50. https://doi.org/10.1016/j.ecolmodel.2008.09.003.

Brown, M., Ulgiati, Sergio, 2013. A geobiosphere baseline for LCA-emergy evaluations. In: Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S., Kang, D., Rydberg, T., Tilley, D., Ulgiati, S. (Eds.), Emergy Synthesis 7: Theory and Applications of the Emergy Methodology. Book of Proceedings from the Seventh Biennial Emergy Research Conference, Gainesville, Florida, January, 2012. Center for Environmental Policy, University of Florida, Gainesville, FL, pp. 481–492.

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38, 1–22. https://doi.org/10.1016/S0921-3449(02)00093-9.

Brown, M.T., Campbell, D.E., De Vilbiss, C., Ulgiati, S., 2016. The geobiosphere emergy baseline: a synthesis. Ecol. Model. 339, 92–95. https://doi.org/10.1016/j.ecolmodel.2016.03.018.

Brown, M.T., Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Model. 339, 148–156. https://doi.org/10.1016/j.ecolmodel.2016.03.010.

Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. In: Encyclopedia of Energy. Elsevier, pp. 329–354. https://doi.org/10.1016/B0-12-176480-X/00242-4.

Buranakarn, V., 1998. Evaluation of Recycling and Reuse of Building Materials Using the Emergy Analysis Method. Department of Architecture, University of Florida, Gainesville, p. 257. Ph.D dissertation, Department of Architecture, University of Florida, Gainesville, FL.

Campbell, D., Brandt-Williams, S., Meisch, M., 2005. Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. Report N. AED-03-104, Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. Narragansett, RI.

Castellini, C., Bastianoni, S., Granai, C., Bosco, A.D., Brunetti, M., 2006. Sustainability of poultry production using the emergy approach: comparison of conventional and organic rearing systems. Agric. Ecosyst. Environ. 114, 343–350. https://doi.org/10.1016/J.AGEE.2005.11.014.

Castellini, C., Boggia, A., Cortina, C., Dal Bosco, A., Paolotti, L., Novelli, E., Mugnai, C., 2012. A multicriteria approach for measuring the sustainability of different poultry production systems. J. Clean. Prod. 37, 192–201. https://doi.org/10.1016/j.jclepro.2012.07.006.

Chen, W., Liu, W., Geng, Y., Brown, M.T., Gao, C., Wu, R., 2017. Recent progress on emergy research: a bibliometric analysis. Renew. Sustain. Energy Rev. 73, 1051–1060. https://doi.org/10.1016/j.rser.2017.02.041.

Čičková, H., Newton, G.L., Lacy, R.C., Kozánek, M., 2015. The use of fly larvae for organic waste treatment. Waste Manag. 35, 68–80. https://doi.org/10.1016/j.wasman.2014.09.026.

COM, 2005. Reference Document on Best Available Techniques (BAT) in the Slaughterhouses and Animal By-Products Industries. SA BREF).

Cristiano, S., Gonella, F., 2019a. To build or not to build? Megaprojects, resources, and environment: an emergy synthesis for a systemic evaluation of a major highway expansion. J. Clean. Prod. 223, 772–789. https://doi.org/10.1016/j.jclepro.2019.03.129.

Cristiano, S., Gonella, F., 2019b. Learning from hybrid innovative-vernacular solutions in building design: emergy analysis of Sudanese energy-saving technologies. J. Environ. Account. Manag. 7, 213–227. https://doi.org/10.5890/JEAM.2019.06.007.

Cristiano, S., Ulgiati, S., Gonella, F., 2021. Systemic sustainability and resilience assessment of health systems, addressing global societal priorities: learnings from a top nonprofit hospital in a bioclimatic building in Africa. Renew. Sustain. Energy Rev. 141, 110765. https://doi.org/10.1016/j.rser.2021.110765. In press.

Cutroneo, L., Ferretti, G., Scafidi, D., Ardizzone, G.D., Vagge, G., Capello, M., 2017. Current observations from a looking down vertical V-ADCP: interaction with winds and tide? The case of Giglio Island (Tyrrhenian Sea, Italy). Oceanologia 59, 139–152. https://doi.org/10.1016/j.oceano.2016.11.001.

da Cruz, R.V.A., Nascimento, C.A.O. do, 2012. Emergy analysis of oil production from microalgae. Biomass Bioenergy 47, 418–425. https://doi.org/10.1016/j.biombioe.2012.09.016.

de Brogniez, D., Ballabio, C., Stevens, A., Jones, R.J.A., Montanarella, L., van Wesemael, B., 2015. A map of the topsoil organic carbon content of Europe generated by a generalized additive model. Eur. J. Soil Sci. 66, 121–134. https://doi.org/10.1111/ejss.12193.

De Vilbiss, C.D., Brown, M.T., 2015. New method to compute the emergy of crustal minerals. Ecol. Model. 315, 108–115. https://doi.org/10.1016/j.ecolmodel.2015.04.007.

Della Vedova, B., Bellani, S., Pellis, G., Squarci, P., 2001. Deep temperatures and surface heat flow distribution. Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins. Springer Netherlands, Dordrecht, pp. 65–76. https://doi.org/10.1007/978-94-015-9829-3_7.

Di Tullio, E., Di Faustino, E., Basile, M., 2016. L'avicoltura italiana: un modello sostenibile e di integrazione di filiera nel settore delle carni. Report NOMISMA, 40 pages.

Dossey, A.T., Morales-Ramos, J.A., Guadalupe Rojas, M. (Eds.), 2016. Insects as Sustainable Food Ingredients: Production, Processing and Food Applications. Elsevier. https://doi.org/10.1016/C2014-0-03534-4.

ENEA - Italian agency for new energy technologies and sustainable economic development, 2020. Atlante italiano della radiazione solare. Online database. http://www.solaritaly.enea.it/index.php.

European Commission. Market observatories. Cereal statistics: EU weekly cereals prices. Online database. Retrieved March 25, 2020, from: https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/overviews/market-observatories/crops/cereals-statistics_en.

Eurostat. nrg_pc_203., "Statistics Explained" official website. Gas prices for non-household consumers. Retrieved March 25, 2020, from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics.

Eurostat, 2020. nrg_pc_205., "Statistics Explained" official website. Electricity prices for non-household consumers. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics.

FAO, 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome, Italy.

FAO, 2018. The State of World Fisheries and Aquaculture 2018. Meeting the sustainable development goals, Rome, Italy.

Fédération des Professionnelle Entreprises de l'Eau - FP2E, 2015. 10ème baromètre des prix des services d'eau en europe. Published online 10 June 2015 on the web page: https://www.fp2e.org/10eme-barometre-des-prix-des-services-deau-en-europe/.

Grönlund, E., Klang, A., Falk, S., Hanæus, J., 2004. Sustainability of wastewater treatment with microalgae in cold climate, evaluated with emergy and socio-ecological principles. Ecol. Eng. 22, 155–174. https://doi.org/10.1016/j.ecoleng.2004.03.002.

Heuzé, V., Tran, G., Kaushik, S., 2015. Fish meal. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. https://www.feedipedia.org/node/208. Last updated on May 11, 2015.

Hu, Q.H., Zhang, L.X., Wang, C.B., 2012. Emergy-based analysis of two chicken farming systems: a perception of organic production model in China. Procedia Environ. Sci. 13, 445–454. https://doi.org/10.1016/j.proenv.2012.01.038.

INES - French Institute of Solar Energy. CalSol. Web-based software. Retrieved March 25, 2020, from: http://ines.solaire.free.fr/index.php.

ISO, 2006a. ISO 14044: Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment. Geneva, Switzerland.

ISO, 2006b. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. Paris, France.

Leite, G.B., Abdelaziz, A.E.M., Hallenbeck, P.C., 2013. Algal biofuels: challenges and opportunities. Bioresour. Technol. 145, 134–141. https://doi.org/10.1016/j.biortech.2013.02.007.

Lucazeau, F., Vasseur, G., 1989. Heat flow density data from France and surrounding margins. Tectonophysics 164, 251–258. https://doi.org/10.1016/0040-1951(89)90018-8.

Maiolo, S., Parisi, G., Biondi, N., Lunelli, F., Tibaldi, E., Pastres, R., 2020. Fishmeal partial substitution within aquafeed formulations: life cycle assessment of four alternative protein sources. Int. J. Life Cycle Assess. 25, 1455–1471. https://doi.org/10.1007/s11367-020-01759-z.

Météo France - French national meteorological service. Fiche climatologique. Données publiques. Section "Catalogue > Climatologie > Normales et records > Fiche climatologique > Sélection et téléchargement". Online database. Retrieved March 25, 2020, from: https://donneespubliques.meteofrance.fr/.

Nimmanterdwong, P., Chalermsinsuwan, B., Piumsomboon, P., 2017. Emergy analysis of three alternative carbon dioxide capture processes. Energy 128, 101–108. https://doi.org/10.1016/j.energy.2017.03.154.

Odum, H.T., 1996. Environmental Accounting: Emergy and Decision Making. Wiley, New York.

Park, Y.S., Egilmez, G., Kucukvar, M., 2016. Emergy and end-point impact assessment of agricultural and food production in the United States: a supply chain-linked Ecologically-based Life Cycle Assessment. Ecol. Indicat. 62, 117–137. https://doi.org/10.1016/j.ecolind.2015.11.045.

Peviani, M., Carli, F., Bonamano, S., 2011. Wave energy potential map along the Italian coast available for marine power generation. In: HYDRO2011. Prague, Czech Republic.

Schliessnig, H., Griffiths, R., Lapasin, C., Larsen, M., Oyj, HKScan, 2019. Avec - annual report 2019. Brussels, Belgium.

SIR. Hydrological and geological division of the Tuscany region. Archivio storico dei dati meteo-idrologici. Online database. Retrieved March 25, 2020, from: http://www.sir.toscana.it/ricerca-dati.

Sweeney, S., Cohen, M.J., King, D.M., Brown, M.T., 2007. Creation of a global emergy database for standardized national emergy synthesis. In: Brown, M.T. (Ed.), Proceedings of the 4th Biennial Emergy Research Conference. Center for Environmental Policy, Gainesville, FL. Center for Environmental Policy, Gainesville, FL.

Tredici, M.R., Bassi, N., Prussi, M., Biondi, N., Rodolfi, L., Chini Zittelli, G., Sampietro, G., 2015. Energy balance of algal biomass production in a 1-ha "Green Wall Panel" plant: how to produce algal biomass in a closed reactor achieving a high Net Energy Ratio. Appl. Energy 154, 1103–1111. https://doi.org/10.1016/J.APENERGY.2015.01.086.

Tredici, M.R., Rodolfi, L., Biondi, N., Bassi, N., Sampietro, G., 2016. Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP®) plant. Algal Res 19, 253–263. https://doi.org/10.1016/J.ALGAL.2016.09.005.

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions. J. Clean. Prod. 10, 335–348. https://doi.org/10.1016/S0959-6526(01)00044-0.

United Nations, 1987. A/42/427. Report of the World Commission on Environment and Development: Our Common Future. New York, NY.

Zhang, L.-X., Hu, Q.-H., Wang, C.-B., 2013. Emergy evaluation of environmental sustainability of poultry farming that produces products with organic claims on the outskirts of mega-cities in China. Ecol. Eng. 54, 128–135. https://doi.org/10.1016/j.ecoleng.2013.01.030.