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Review article

A comparative analysis of the environmental impacts of cultivating microalgae in different production systems and climatic zones: A systematic review and meta-analysis

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ABSTRACT

Microalgae are used as alternative fuel, feed and food sources. As the production of microalgae requires energy, inorganic substances and technical equipment, life cycle assessments are necessary to evaluate the advantages of microalgae production in comparison to conventional systems. This review aims to compare different microalgae production systems that are used to produce microalgae for human nutrition in different climatic zones.

A systematic literature review according to the systematic review checklist STARR-LCA was performed using *ScienceDirect* and *Google Scholar*. The studies were included that utilized primary data, used a functional unit based on dry algal biomass and were modeled cradle-to-gate. Only the studies conducted in real pilot and experimental plants were considered. The data for the life cycle inventory were recorded and harmonized, and the environmental performance of the different microalgae species and their cultivation methods were then modeled in SimaPro according to ISO 14040/44 using the ecoinvent database v3.4.

Sixteen different production scenarios were examined with cultivation plants located in the Netherlands, Spain, the United States and Singapore. Open raceway ponds were compared to horizontal, vertical and bubble column photobioreactors. Five different microalgae species were investigated: *Nannochloropsis* sp., *Scenedesmus dimorphus*, *Heterosigma akashiwo*, *Alexandrium minutum* and *Karlodinium veneficum*.

Regardless of the cultivation system design, the hotspot processes were 'heating', 'aeration and CO_2', 'base energy for cultivation', 'cooling' and 'mixing'. Furthermore, the biomass productivity and corresponding environmental impacts were all confirmed to be highly dependent on the climatic conditions and the cultivation systems used. Open ponds and photobioreactors are each most suitable for a different climatic zone.

1. Introduction

Against the background of a growing world population, shifting diets and the burden of diet-related diseases [1], microalgae have the potential to supply humans with high-value nutrients such as proteins, polyunsaturated fatty acids, vitamins, antioxidants and minerals. Thus, they could be added to conventional foods to enhance their nutritional value and create healthier food products [2]. Microalgae have been reported to produce an adequate amount of polyunsaturated fatty acids at concentrations that are slightly higher than those found in fish oil [3]. Additionally, the oil from microalgae may be less contaminated than lipids from seafood [3]. Fish may contain toxic mercury levels or persistent organic pollutants (POPs) [4]. Currently, the nutritional demand for omega3 PUFAs (polyunsaturated fatty acids), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), cannot be met without depleting global fish stocks [5]. Microalgae are also rich in protein, of which the average quality is described as being equal or even superior to the protein from soybeans [6]. Moreover, microalgae exhibit a wide range of additional compounds that are crucial for human nutrition, for example, carotenoids, phycobilins, polysaccharides, vitamins and sterols [7], with antioxidant, antibiotic, antiviral, anticancer and anti-inflammatory effects [8].

There are two general forms of cultivation systems for microalgae: open raceway ponds (ORPs) and closed photobioreactors (PBRs). More than 90% of the microalgae biomass cultivated globally is produced in open ponds [9]. Open ponds are less expensive and easier to operate. In turn, they use light, CO_2 and water inefficiently, can easily be contaminated and cannot be used for all microalgae species [9]. The use of PBRs has been proposed to overcome the deficiencies of ORPs because they are comparatively more productive and prevent contamination

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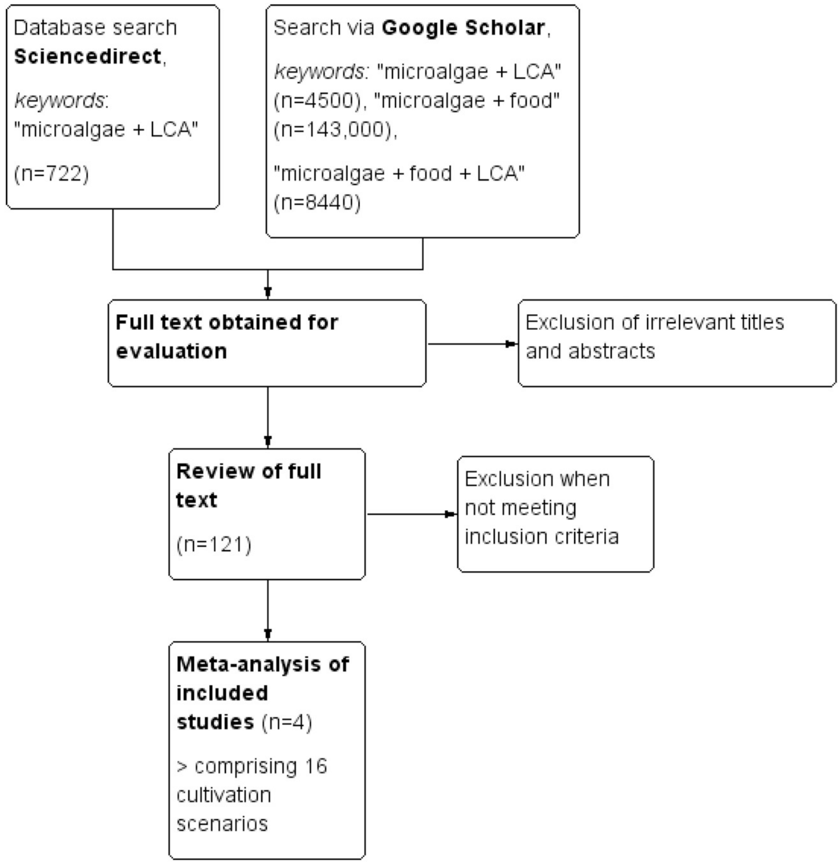


Fig. 1. Flow diagram of the systematic literature review process.

[9]. The common forms of PBRs include horizontal and vertical tubular PBRs, flat-plate panels and bubble-column PBRs. However, the technology for PBRs is still under development and expensive. Some studies have even narrowed the production of PBRs down to high-value products for human nutrition, cosmetics and pharmaceuticals because of their rather expensive cultivation prerequisites [10–12].

Thus, one of the biggest challenges in microalgae commercial production, particularly phototrophic microalgae, is their cost-intensive cultivation [8], both economically and ecologically. Hence, the determination of optimal cultivation conditions in terms of reactor design, facility location and corresponding solar radiation are crucial. However, although a higher photosynthetic efficiency accounts for higher biomass yields, the augmented costs due to the increased requirement of mixing, cooling and embodied energy may partly offset the net gains in warmer climates [9]. After all, cultivating microalgae for nutritional purposes poses higher demands on systems than the bioenergy cultivation. While the topic of bioenergy has been analyzed in multiple LCAs (life cycle assessments) on microalgae production, using microalgae for food and the challenges that arise with it have been studied relatively rarely in investigations concerning the environmental impacts of these systems.

The preceding reviews have focused predominantly on algae-based biofuel production scenarios [11,13,14], considering the economic constraints of different cultivation systems. Studies have usually suggested that microalgae cultivation may be too expensive to apply in the energy sector [11,13]. ORPs were generally found to have lower impacts on the environment but were also stated to lack productivity [11,14,15]. The risk of contamination is a further issue in ORP production [15], which is of particular importance when microalgae are cultivated for nutritional purposes. Studies have described various different processes as hotspots. One review study stressed the influence of climate on ORPs and suggested that PBRs might be able to overcome these issues [15]. A thorough discussion of recent reviews on the subject can be accessed in the Supplementary material.

In this study, recent data that – to the best of our knowledge – have not been reviewed for the underlying purpose, were analyzed in a profound meta-analysis. Whereas the preceding reviews solely compared cultivation systems, our study also included specific site characteristics to analyze the cultivation conditions extensively.

We thus aim to compare different cultivation scenarios for producing microalgae biomass for application in the food sector. The subprocesses of the cultivation systems will be analyzed in detail to identify environmental hotspots and gauge favorable cultivation conditions. Moreover, the climatic data (solar insolation, temperature, day length) from the cultivation sites considered will be discussed. Thus, the following research questions will be addressed in the study:

1) Is a specific microalgae cultivation system generally more favorable than others in environmental terms?
2) Where are the environmentally relevant hotspots in microalgae cultivation?
3) How do regional climatic conditions influence the environmental performance of the cultivation systems considered?

2. Materials and methods

2.1. Systematic literature research

To guarantee the accuracy of the research and minimize the risk of bias, this study was completed following the systematic review checklist STARR-LCA (standardized technique for assessing and reporting reviews of LCA) [16], which is largely based on the PRISMA statement protocol [17]. The systematic review checklist expanded the requirements of the PRISMA statement protocol and defined them for use on

Table 1
Included studies and their key characteristics.

Author and year	Country, location	Data origin	Algae species	Scale	Cultivation system	Time period	Impact assessment
Pérez-López et al. 2017 [21]	Netherlands	Pilot scale original data from AlgaePARC of Wageningen University and Research (Netherlands) Background data: ecoinvent	*Nannochloropsis* sp.	Pilot	Horizontal PBR	Summer Autumn Winter	CML 2001, CED
					Vertical PBR	Summer Autumn Winter	
					ORP	Summer Autumn	
Bennion et al. 2015 [22]	USA (Arizona)	Original data	*Scenedesmus dimorphus*	Experimental: original data from lab scale	ORP	1 year	NER, GHG emissions
Itoiz et al. 2012 [23]	Spain	Original data from Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain, under ambient Mediterranean climate conditions	*Heterosigma akashiwo*	Experimental (0.297 m^3 for each indoor and outdoor)	Indoor bubble column PBR	November to May	CML 2001
					Outdoor bubble column PBR		
			Alexandrium minutum		Indoor bubble column PBR		
					Outdoor bubble column PBR		
			Karlodinium veneficum		Indoor bubble column PBR		
					Outdoor bubble column PBR		
Khoo et al. 2011 [24]	Singapore	Original data from the Institute of Chemical and Engineering Sciences (ICES), Singapore	*Nannochloropsis* sp.	Pilot (20001 case study)	ORP → starting culture from PBR	1 year (assumed for calculation)	Energy consumption, CO_2 consumption

reviews of LCAs.

This review was conducted in December 2017 via ScienceDirect and Google Scholar. Peer-reviewed journal papers were primarily found. Other types of literature that were recorded in the research process included master's and doctoral theses, conference proceedings and gray literature. Fig. 1 provides information about the keywords used and the subsequent selection process. After an initial screening of all the articles found (based on the title and the abstracts), the relevant studies were evaluated in their entirety. Upon meeting previously established inclusion criteria, 121 studies were reviewed in detail and a meta-analysis of the four included studies was conducted. Inclusion criteria implied that the study had to contain relevant data on the environmental performance of microalgae. Studies of macroalgae were excluded from the review process. The system boundaries needed to be transparent as only data from the cultivation stage up to the dry algal biomass production were considered, and the functional unit was required to be mass-based. Furthermore, only the studies reporting primary data were considered. Most of the studies that were fully reviewed were excluded due to the latter criterion because they used secondary data. The relevant data concerning the environmental impact of microalgae biomass production included the following indicators: yield, fertilizers (nitrogen, phosphorus, and potassium), carbon dioxide use, infrastructure of the cultivation systems (steel, aluminum, and synthetic materials), water use and electricity use.

2.2. Synthesizing the results for the comparison and modeling of the datasets

The functional unit was fixed at 1 kg of dry microalgae biomass at the farm gate, and the system boundaries included the cultivation stage and the corresponding subprocesses. Detailed data on the subprocesses were recorded for energy use, water use and infrastructure. Regarding energy use, the following subprocesses were distinguished: 'cleaning', 'pumping', 'filtration', 'mixing', 'base energy of cultivation', 'aeration and CO_2', 'lighting', 'heating', 'cooling', 'microfiltration and centrifugation', and 'dewatering'. Water use was divided into the freshwater input for cleaning, the nutrient supply and cultivation, as well as the seawater input for cultivation. The infrastructure materials included steel, aluminum, polymethylmethacrylate (PMMA), polypropylene (PP) and synthetic rubber.

The datasets were then modeled according to the microalgae species and the cultivation system in SimaPro® (PRé Consultants B.V., Netherlands, Version 8.5) using ecoinvent database 3.4 to examine the environmental impacts. Due to the system boundaries and the scope of the review, an attributional modeling approach with cut-offs was applied. ReCiPe Midpoint 2016 (v1.01) was chosen as the impact assessment method because it is representative on a global scale [18] and therefore suitable for intercountry comparisons. The additional impact assessments methods applied were the cumulative energy demand (CED) and the global warming potential (GWP); see the Supplementary material. Investigations on the electricity use of subprocesses as well as the land use calculation were performed using MS Excel®. The results concerning the water use were not included in the analysis as the data availability and extent varied drastically, but the inventory data can be accessed in the Supplementary material.

2.3. Climatic data

Detailed climatic data were obtained from the NASA Power Data Access Viewer [19] for every location in the analyzed scenarios. Thus, the data from Amersfoort, NL; Phoenix, USA; Barcelona, ES and Singapore, SGP were considered. Concerning solar radiation, the parameter 'all sky insolation incident on a horizontal surface' was used which represents the monthly average amount of total solar radiation on the earth's surface. To obtain relevant data on the daytime temperature, the parameter 'maximum temperature at 2 m' was used. For

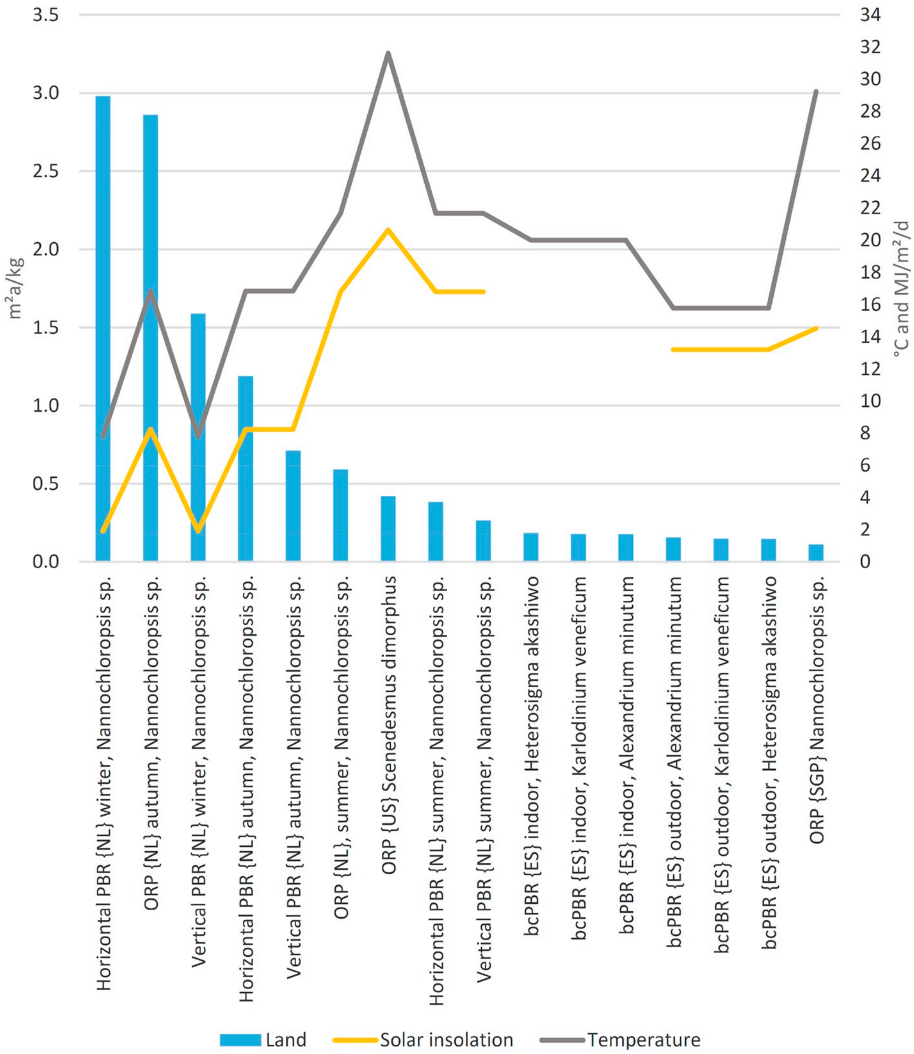


Fig. 2. Land use in m^2a/kg of the dry microalgae biomass (bars) and the corresponding solar insolation in $MJ/m^2/d$; temperature in °C (lines). The 'bcPBR {ES} indoor' scenarios were excluded from 'solar insolation' as they were not exposed to any solar insolation. The 'PBR {NL}' scenarios, in contrast, were located outdoor.

all of the parameters, the interannual data for the year 2017 were utilized. Regarding the day length, data for the same locations were obtained from the website weatherbase.com [20] where data is based on the measurements of globally present weather stations. The complete climatic data used can be accessed in the Supplementary material.

3. Results

Four studies were included in the meta-analysis (Table 1). Because two of the studies analyzed several production systems and microalgae species, a range of 16 different production scenarios was investigated. The microalgae species *Nannochloropsis* sp., *Scenedesmus dimorphus*, *Heterosigma akashiwo*, *Alexandrium minutum* and *Karlodinium veneficum* were considered in the studies. Open raceway ponds (ORP) were compared to different photobioreactor (PBR) systems: horizontal, vertical and bubble column. The latter included data on the indoor and outdoor use of bubble column PBRs.

Pérez-López et al. [21] focused on the main environmental concerns of microalgae production systems with the goal of scaling up to industrial facilities. The data resulted from a real pilot plant located at AlgaePARC in Wageningen, the Netherlands where *Nannochloropsis* sp. was cultivated. The ORP had a volume of $4.73\,m^3$ with a separation plate in the center and a paddle wheel driving the culture. CO_2 was injected at the bottom of the pond. Nutrients were pumped into the ORP and the temperature was controlled via a heat exchanger as no active cooling was needed. The horizontal tubular PBR had a volume of $0.56\,m^3$ and consisted of transparent pipes in three loops. The vertical PBR had a volume of $1.06\,m^3$ and consisted of seven loops that were arranged on top of each other. Both of the PBRs were supplied with nutrients over a distribution header. Air entered the PBRs via a sparger at the bottom. Three heat exchange spirals regulated the temperature.

Bennion et al. [22] aimed to assess the environmental impact of two different thermochemical conversion technologies for the conversion of microalgae to biofuel. Nevertheless, the technologies provided separate data on the microalgae cultivation stage. Pilot-based production data were used from an ORP located at the Arizona Center for Microalgae Technology and Innovation at Arizona State University where *Scenedesmus dimorphus* was cultivated. Mixing in the ORP was achieved by a paddle wheel.

The goal of the study conducted by Itoiz et al. [23] was to investigate the environmental and energy impacts of producing three different species of marine microalgae, namely, *Heterosigma akashiwo*, *Alexandrium minutum*, and *Karlodinium veneficum*. The data were provided from the Institute de Ciències del Mar (ICM-CSIC) in Barcelona, Spain. The polymethylmethacrylate tubes of the bubble column PBRs each had a volume of $0.033\,m^3$. Three tubes were used for each species. Filtered seawater was used to grow the microalgae, and CO_2 was injected via prefiltered air at the bottom of the PBRs. The PBRs for the indoor cultivation were placed in a temperature-controlled room.

The study by Khoo et al. [24] examined microalgae-to-biofuel production for *Nannochloropsis* sp. with data originating from the Institute of Chemical and Engineering Sciences (ICES) in Singapore. The cultivation was started in an ORP with an inoculation culture provided by a PBR. CO_2 was injected as compressed air by a gas lift, which also provided the mixing.

All of the studies included data on electricity use, nutrients, water and productivity. Only the studies by Pérez-López et al. [21] and Itoiz et al. [23] included infrastructure data. However, only the data from the first study were sufficiently precise for inclusion in the inventory. It needs to be pointed out that the systems analyzed incorporated great heterogeneity. Additionally, they were investigated under different climatic conditions. Data for both PBRs and ORPs were not available for every location.

3.1. Productivity (in terms of land use)

The productivity of the cultivation scenarios in terms of land use as well as the corresponding solar insolation and temperature are depicted in Fig. 2.

Nannochloropsis sp. cultivated in a horizontal PBR in the Netherlands in winter showed the largest land use (3.0 m^2a/kg), which was followed closely by *Nannochloropsis* sp. produced in an ORP in the Netherlands in autumn (2.9 m^2a/kg). The best performing scenario was *Nannochloropsis* sp. cultivated in an ORP in Singapore with a land use of 0.1 m^2a/kg. No trend could generally be identified in terms of the cultivation system or species cultivated. However, the facilities exposed to higher solar radiation and higher temperatures tended to have smaller land use ratios and therefore showed a higher productivity.

The five worst performing scenarios were all located in the Netherlands and run in autumn and winter with a solar insolation ranging from 1.8 to 8.2 $MJ/m^2/d$ and a maximal temperature of 7.8 to 16.8 °C. The scenarios that were also located in the Netherlands but run in summer showed a particularly better performance. Their solar insolation rate was 16.8 $MJ/m^2/d$ at a temperature of 21.7 °C. The seven best performing scenarios all had a land use ratio under 0.2 m^2a/kg and were located in Spain and Singapore. In three of the scenarios from Spain, the microalgae were cultivated indoors at a constant temperature of 20 °C. Concerning the microalgae produced outdoors in Spain and Singapore, the solar insolation ranged from 13.2 to 14.5 $MJ/m^2/d$, and the temperature was between 15.8 and 29.2 °C. The outdoor systems in Spain and Singapore performed marginally better than the indoor systems in Spain. The ORP scenario from the US depicted a slightly lower productivity than the NL summer scenarios. The US scenario was studied under an average annual solar insolation of 20.6 $MJ/m^2/d$ and an average annual temperature of 31.6 °C.

As observed in Fig. 2, microalgae cultivation productivity clearly correlates with the solar insolation and temperature of the production site. The productivity seems to rise as the solar insolation and temperature values increase. However, this productivity gain cannot be accelerated after a certain point. Thus, the US scenario showed a productivity of 0.4 m^2a/kg when the annual average solar insolation reached 20.6 $MJ/m^2/d$ and the annual average temperature was 31.6 °C. Moreover, it must be noted that the productivity in the summer scenarios in the NL was lower than that in the ES outdoor and SGP scenarios even though the latter showed a smaller solar insolation value and, concerning the ES scenarios, a lower temperature value.

In Table 2, the land use data of the different production scenarios are presented, including the mean, minimum, and maximum values and the median deviation as well as the production site, solar insolation and maximum temperature. The mean values as well as the minimum and maximum values confirm the observed slope across the five locational categories with a relatively small median deviation for all of the categories, whereas the median deviation for the production scenarios in the Netherlands in autumn and winter is moderately high. Although the values for this category are fairly dispersed, a trend can still be perceived as there is a clear difference between the minimum value of this category and the maximum value of the next category (NL, summer scenarios).

3.2. Cumulative energy demand and electricity use

The data considered for the cumulative energy demand (CED) included electricity, infrastructure, water use, fertilizers and carbon dioxide use. The results for the CED of the different production scenarios are shown in Fig. 3. The CED is provided in MJ/kg of dry microalgae biomass.

The worst performing scenario was the ORP located in the Netherlands that was conducted in autumn with a CED of 58,971 MJ/kg. The best performing system was also an ORP, but it was located in Singapore with a CED of 120 MJ/kg. The five worst performing scenarios in terms of their CEDs were all cultivation scenarios of *Nannochloropsis* sp., located in the Netherlands and produced in autumn or winter. The solar insolation in these scenarios was significantly lower than that in all of the other scenarios, ranging between 1.8 and 8.2 $MJ/m^2/d$. Even more pronounced than the land use, it can be stated that the CED is lower in locations where the solar insolation and temperature are higher (Fig. 3, Table 3).

However, the ES outdoor scenarios still performed better than the NL summer scenarios, even though the latter were exposed to higher solar insolation and higher temperatures.

Table 3 provides detailed information about the specific values for the CED grouped by their performance. The five scenarios with the lowest CEDs had a solar insolation rate of 13.2 to 20.6 $MJ/m^2/d$ and a temperature of 15.8 to 31.6 °C. It is notable that despite having a solar insolation of 16.8 $MJ/m^2/d$ and a temperature of 21.7, the NL summer scenarios had a mean CED value that was more than ten times as high as that of the best performing scenarios.

Again, no rating could be identified in terms of the production systems. Both the ORPs and PBRs demonstrated extremely good and bad performances. Only the bubble column PBR located in Spain displayed consistently good results, whereas the production in this system was always more efficient outdoors than indoors.

Fig. 4 shows the electricity use for the subsystems of all scenarios in MJ/kg of dry microalgae biomass, and the electricity use of every single system is itemized. The major portion of electricity in the top five worst performing scenarios was used for heating.

The values for the performances of the subprocesses of electricity use are presented in Table 4. When comparing the mean values of the subprocesses, 'heating' overwhelmingly had the highest mean value (4707 MJ/kg), which was followed by the electricity for 'aeration and CO_2', which used 273 MJ/kg on average. Additional energy intensive processes were 'mixing' (201 MJ/kg), 'base energy for cultivation' (188 MJ/kg) and 'cooling' (157 MJ/kg), whereas the electricity use for the remaining processes was negligible on average compared to that by the top processes. Upon evaluation of the maximum values for electricity use, 'lighting' had a value of 168 MJ/kg. The rather low mean value of 71 MJ/kg for 'lighting' originated from three nonvalues that were included in the calculation. All six values for 'lighting' were derived from the study by Itoiz et al. [23]; the values applied in half of the cases concerned indoor production, whereas the values for outdoor production were omitted. If only the production scenarios where 'lighting' had been applied were considered, the mean electricity use would have been 163 MJ/kg. This would make 'lighting' a passable yet considerable process regarding electricity use.

The median deviation provides information about the spread of the values for each subprocess. In particular, the processes 'mixing', 'base energy for cultivation', 'aeration and CO_2', 'heating' and 'cooling' varied widely.

Table 2
Land use of the production scenarios according to their site characteristics (location, solar insolation, and maximum temperature) in m^2a/kg of dry microalgae biomass.

Location	Amersfoort, NL, autumn/ winter	Amersfoort, NL, summer	Barcelona, ES, indoor	Barcelona, ES, outdoor; Singapore, SGP	Phoenix, USA
Land use m^2a/kg (mean)	1.87	0.41	0.18	0.14	–
Min	0.71	0.27	0.18	0.11	0.4
Max	2.98	0.59	0.19	0.16	–
Median deviation	0.84	0.12	0.00	0.01	–
n	5	3	3	4	1
Solar insolation (range) in $MJ/m^2/d$	1.8–8.2	16.8	indoor	13.2–14.5	20.6
Max temperature (range) in °C	7.8–16.8	21.7	20	15.8–29.2	31.6

n = number of measurement points.

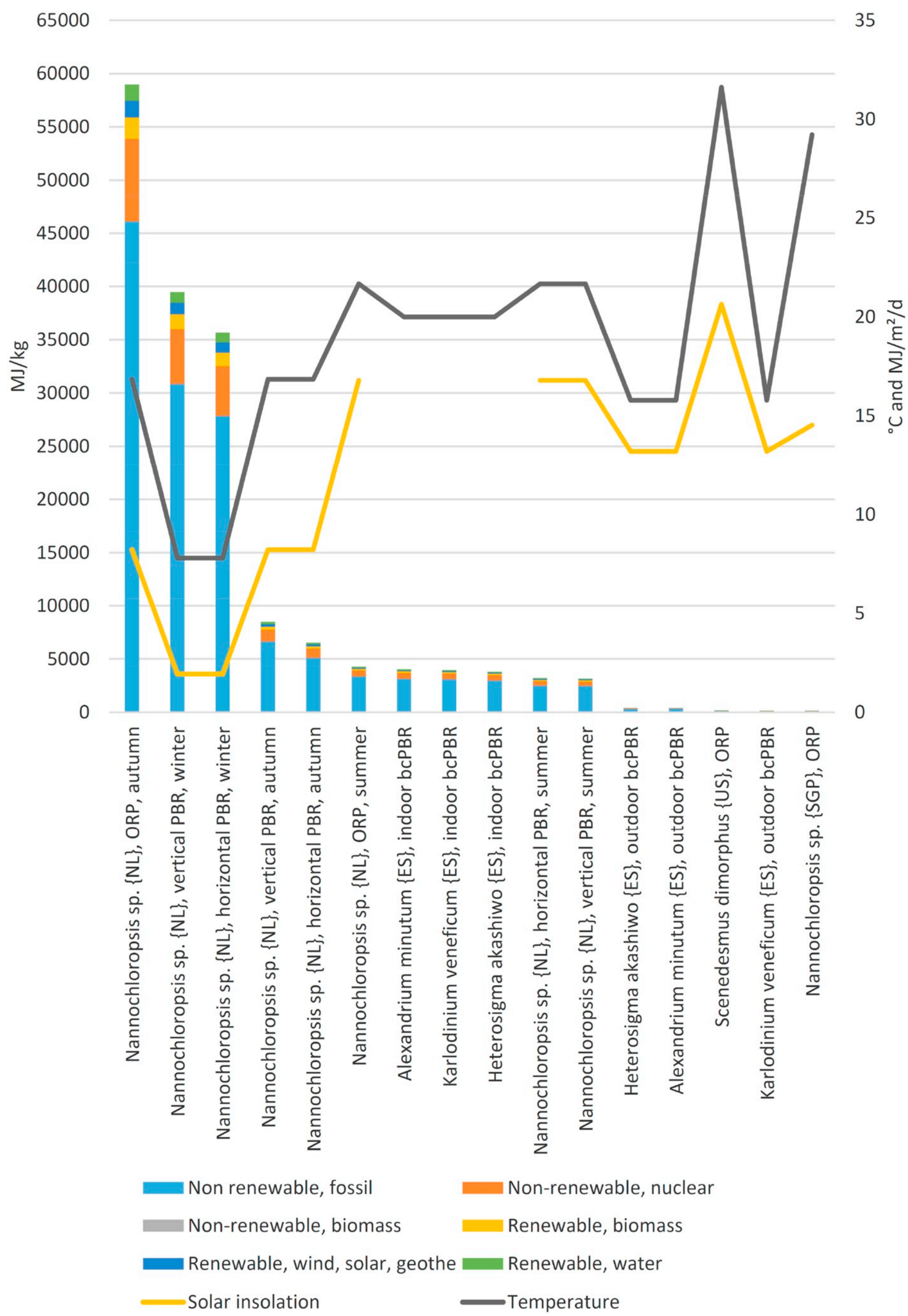


Fig. 3. The CED of microalgae biomass production in different cultivation systems in MJ/kg of dry microalgae biomass (bars) and the corresponding solar insolation in $MJ/m^2/d$; temperature in °C (lines). The 'bcPBR {ES} indoor' scenarios were excluded from 'solar insolation' as they were not exposed to any solar insolation. The 'PBR {NL}' scenarios, in contrast, were located outdoors.

Table 3
CED for the different location characteristics (location, solar insolation, and maximum temperature) in MJ/kg of dry microalgae biomass.

Location	Amersfoort, NL, autumn/winter	Amersfoort, NL, summer	Southern Locations indoor: Barcelona, ES	Southern Locations outdoor: Barcelona, ES; Phoenix, USA; Singapore, SGP
CED in MJ/kg (mean)	29,827	3545	3930	244
Min	6535	3154	3805	120
Max	58,971	4281	4026	406
Median deviation	17,857	490	84	122
n	5	3	3	5
Solar insolation (range) in MJ/m^2/d	1.8–8.2	16.8	indoor	13.2–20.6
Max temperature (range) in °C	7.8–16.8	21.7	20	15.8–31.6

n = number of measurement points.

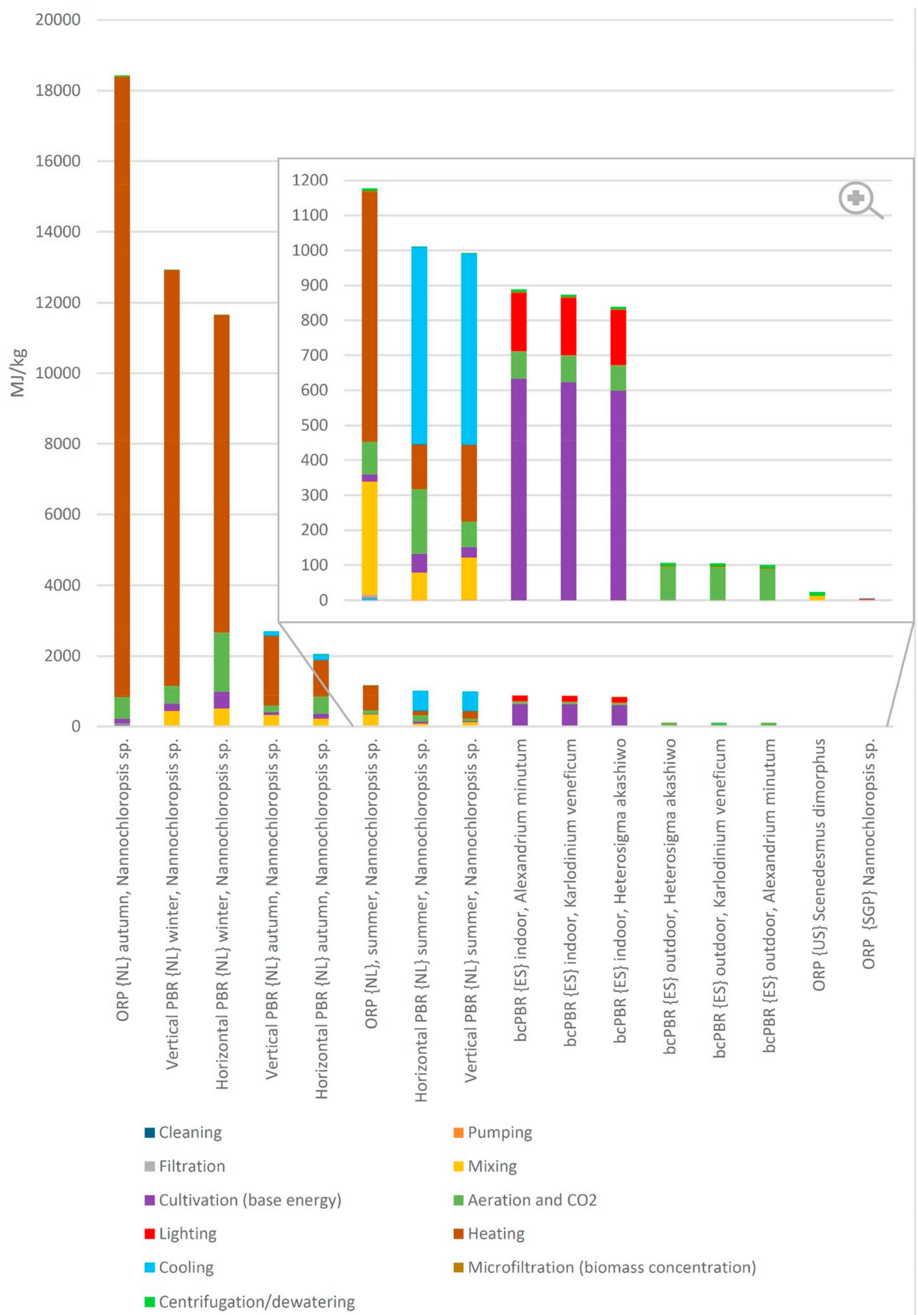


Fig. 4. Electricity use of the subprocesses in the cultivation of microalgae biomass in MJ/kg of dry microalgae biomass.

Table 4
Electricity use of the subprocesses in MJ/kg of dry microalgae biomass.

	Cleaning	Pumping	Filtration	Mixing	Cultivation (base energy)	Aeration and CO_2	Lighting	Heating	Cooling	Microfiltration (biomass concentration)	Centrifugation/dewatering	Total
Electricity use in MJ/kg mean	6.9	2.6	4.1	201.4	188.1	273.0	70.9	4706.9	156.7	4.5	6.6	3170.3
Min	0.1	0.1	0.5	0.8	0.0	0.1	0.0	127.8	0.0	0.0	0.4	4.9
Max	45.3	15.5	18.4	500.9	633.9	1677.6	167.5	17,542.8	565.2	23.1	26.1	18,429.8
Median deviation	12.9	2.1	3.7	152.4	205.4	285.8	81.7	5601.5	190.3	2.7	3.8	4113.4
n	6.0	13.0	6.0	7.0	13.0	13.0	6.0	6.0	6.0	13.0	14.0	14.0

n = number of measurement points.

3.3. Environmental impacts – ReCiPe midpoint 2016

Fig. 5 displays the environmental impacts of all production scenarios modeled with ReCiPe Midpoint 2016 in %. It shows the relative distribution of the impacts for each scenario, which are subdivided into the input categories 'carbon dioxide', 'electricity', 'fertilizer', 'infrastructure', 'transformation, from grassland, natural (non-use)' and 'water'. The figure confirms the insights gained from modeling the CED and the subprocesses of electricity use. Energy clearly dominates almost all the impact categories, especially in the NL scenarios and the ES indoor scenarios. The NL PBR scenarios and the ES indoor scenarios usually had more than 70 to nearly 100% of the environmental impacts resulting from energy use in almost all of the impact categories. The contribution to the environmental impacts from energy use in the NL ORP scenarios was approximately 50 to 80%.

Only for the NL scenarios was data on infrastructure available. Interestingly, infrastructure seems to have a noticeable impact on the environment, especially regarding cultivation in the PBRs (see Fig. 5). The impacts caused by infrastructure might be even greater when it is assumed that the scenarios considered here showed a high energy use and the values were portrayed in % in relation to each other. In the ORPs, water use was very relevant.

Even though all of the scenarios applied an autotrophic cultivation, the use of fertilizers still had a visible impact, particularly in the NL scenarios. The ORP in Singapore also showed a relatively high impact due to fertilizer, which was caused by the rather small impacts of the other processes. A detailed overview of all the input subprocesses contributing to the global warming potential can be accessed in the Supplementary material.

4. Discussion

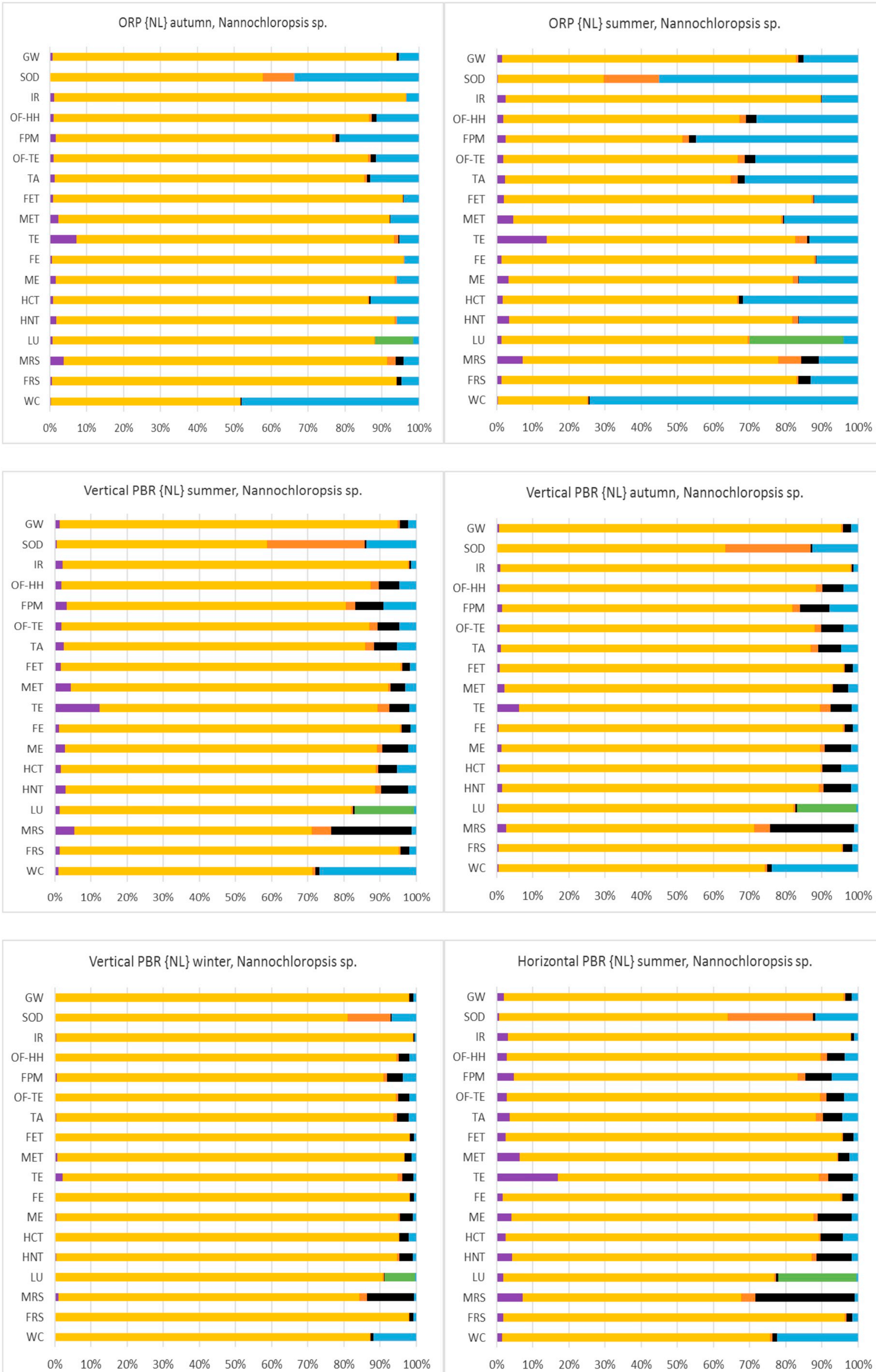
Based on primary data and a functional unit of 1 kg of dry mass, in this systematic review and meta-analysis, we showed for the first time, to the best of our knowledge, that the environmental performance of microalgae cultivation strongly depends on the cultivation system, location, season, scale and the algae species considered.

Even though the importance of the geographic location for microalgae cultivation had been addressed in the literature for various reasons [15,25], its impact had not been previously analyzed in the context of different cultivation system scenarios. The strength of our study was that an extensive meta-analysis was conducted that only used primary data in which not only the cultivation systems but also detailed locational characteristics (solar insolation, temperature, and day length) were considered. Furthermore, our study reviewed recent data that have not previously been analyzed for this purpose.

It was surprising that no cultivation system was found to be generally favorable in terms of productivity, CED, or environmental impacts. Based on our findings, this might be due to climatic characteristics that influence microalgae cultivation to such an extent that not every system is suitable for every specific climatic prerequisite and thus no system is favorable in general. It is crucial to validate these assumptions by further studies on the subject.

In terms of productivity, an ORP system was found to have required the least amount of land, even though in the literature ORPs are often described as lacking productivity. From what we observed in our results, this might be due to the fact that in this scenario, the optimal cultivation system had been chosen for the specific climatic conditions. Here, the ORP was located in Singapore, where a constant solar radiation of 14.5 MJ/m^2/d correlates with an almost ideal maximum temperature for microalgae cultivation[1] of 29.2 °C on average annually. This temperature exceeds the ideal temperature for the cultivation of

[1] The optimal temperature for the cultivation of *Nannochloropsis* sp. is 25 °C [30].



(caption on next page)

Fig. 5. ReCiPe Midpoint 2016 characterization for microalgae cultivation under different systems, in %; 100% corresponds to the environmental impacts for each scenario.
GW global warming, SOD stratospheric ozone depletion, IR ionizing radiation, OF-HH ozone formation human health, FPM fine particulate matter formation, OZ-TE ozone formation terrestrial ecosystems, TA terrestrial acidification, FET freshwater eutrophication, MET marine eutrophication, TE terrestrial ecotoxicity, FE freshwater ecotoxicity, ME marine ecotoxicity, HCT human carciogenic toxicity, HNT human non-carciogenic toxicity, LU land use, MRS mineral resource scarcity, FRS fossil resource scarcity, WC water consumption.

Nannochloropsis sp., but cooling is passively provided in ORPs through evaporation.

Concerning the CED and electricity use, single processes were found to be significant. The critical processes were 'heating', 'aeration and CO_2', 'base energy for cultivation', 'cooling' and 'mixing'. These processes also exhibited a high mean deviation in their results. They were highly dependent on either external factors, particularly temperature for heating and cooling, or the system design which might have influenced 'aeration and CO_2', 'base energy' and 'mixing' greatly. Cooling can also be dependent on the applied system and might be dispensable in ORPs due to evaporation. In particular, the CED displayed very high values, with a total energy use of almost 59,000 MJ/kg of dry microalgae biomass for the worst performing scenario, which was the NL ORP scenario run in autumn. Even the five scenarios with the lowest CEDs still showed values between 120 and 406 MJ/kg of dry microalgae biomass. In the literature, the energy content of dry microalgae biomass is indicated to range between 18 and 30 MJ/kg [26–28]. Hence, an average value of 24 MJ/kg microalgae dry mass energy content is assumed in our study, which makes the energy ratio of microalgae cultivation in these scenarios highly unfavorable. However, it should be kept in mind that the scenarios investigated here are derived from experimental/pilot scale production; thus, there is much room for amelioration. Concerning the CED, it is moreover noticeable that the NL PBR summer scenarios displayed higher values than the ES outdoor scenarios even though the temperature and solar insolation were higher in the NL scenarios. This could generally be due to the system design, and in the ES scenarios, infrastructure data was not available, which could have influenced the CED.

'Lighting' was characterized by relatively small yet considerable energy consumption and could possibly be an option for indoor microalgae production or vitamin D generation. In such applications, UVB radiation would need to be applied. Brennan and Owende [15] indicate that lighting might not be applied exclusively for microalgae cultivation at the pilot scale due to having a significantly higher energy input. However, for the generation of high-value products, the application might be justified.

'Heating' was the process that created the highest environmental impact when it was applied. A clear trend was noticed concerning the corresponding climatic data, namely, the solar insolation and temperature. The scenarios in the Netherlands in autumn and winter, with a solar insolation of 1.2 to 8.2 $MJ/m^2/d$ and a maximum temperature of 7.8 to 16.8 °C, exhibited rather poor results compared to all of the other scenarios where solar radiation was higher than 13 $MJ/m^2/d$ (up to 20.6 $MJ/m^2/d$ on an annual average) and the temperature was between 15.8 and 31.6 °C. If another microalgae species had been used, the autumn/winter scenarios might have performed tremendously better. Some microalgae species prefer cooler temperatures than *Nannochloropsis* sp. which was cultivated in this scenario. This could vastly reduce cost for heating. If heating is of concern in optimized scenarios, the use of renewable energies (e.g., photovoltaics) could be considered as well as the possible use of the waste heat from industries. These options should be evaluated in further studies. In contrast, concerning the NL summer scenarios with a solar insolation of 16.8 $MJ/m^2/d$ and a temperature of 21.7 °C, cooling needed more than 500 MJ/kg of dry biomass and thus had a larger influence on the environmental impacts. It hence might be a critical factor regarding the selection of a location with a solar insolation and temperature that is equal or higher than here. An option might be to use ORPs, if applicable, for the production of microalgae species because ORPs typically do not need to be actively cooled because of evaporation.

Other studies have mostly given general recommendations regarding the climate of the facility site without providing detailed specifications. Light has been addressed as a limiting factor with the suggestion of selecting production sites with a high solar radiation [9,12,15]. This can also partly be confirmed by our results. However, in the USA ORP [22] scenario, the productivity was smaller than that in the other scenarios with a higher solar insolation. This might be due to the extremely high temperatures in this scenario. Thus, from what we observed, light in correlation with temperature can be assumed to be the most limiting factor. However, places with a relatively high solar insolation commonly also exhibit elevated temperatures, which in turn would increase the cooling costs in PBRs substantially. Hence, recommendations about microalgae cultivation should always be specified in detail concerning the climatic characteristics of the location, the cultivation system that should be applied, and the microalgae species.

There was a slight trend visible concerning which cultivation system is more suitable in certain climatic conditions. The ORPs thus tended to perform better in regions with a solar insolation of approximately 20 $MJ/m^2/d$ and a temperature of approximately 25 °C or slightly higher. ORPs have the advantage of not needing active cooling because it is usually provided through evaporation which makes them the optimal system for warm regions. For locations with lower solar radiation and temperatures, PBRs might be more suitable and economical because the light reaches the entire biomass without 'dark zones' as they can exist in ORPs. Furthermore, production will probably be limited to certain months of the year depending on the climatic circumstances. As is already practiced today and from what we found in our analysis, systems should not be run when the solar radiation is much lower than 13 $MJ/m^2/d$ and the temperatures fall below 15 °C. These conditions would make the production highly ineffective and expensive. Our analysis of the productivity of the scenarios pointed at a possible upper limit for microalgae cultivation concerning solar insolation and temperature. Thus, the productivity in the USA ORP scenario was even lower than that in the NL PBR summer scenarios though the solar radiation was higher than 20 $MJ/m^2/d$ and the temperature exceeded 31 °C. It would be very interesting to provide further proof of these assumptions with a larger dataset.

This finding is especially interesting in terms of microalgae for nutritional purposes. Concerning edible microalgae cultivation, the contamination issue of ORPs plays an important role. Open systems can possibly be contaminated very easily. Although the majority of microalgae biomass for nutrition today is produced in ORPs, PBRs might be more suitable for this purpose. Specific nutritional requirements could be applied more easily in PBRs (e.g., the adjustment of parameters to meet the demands of certain microalgae strains, the evaluation of charges with a higher share of certain nutrients or vitamins, the realization of control purposes etc.). Since PBRs require active heating and cooling when the external temperatures get too high or too low, it would be crucial to install them at a location where the solar insolation is sufficient without the temperatures becoming too high. Upon the analysis of the four locations from our study, Barcelona, ES and Amersfoort, NL would be most suitable. Moreover, a regional production could be favorable for the food industry because consumers are becoming more aware of the origin of food. The solar insolation in Barcelona reaches its maximum in June with a value of 25.86 $MJ/m^2/d$ while the maximum temperature reaches 27.5 °C in August. Production

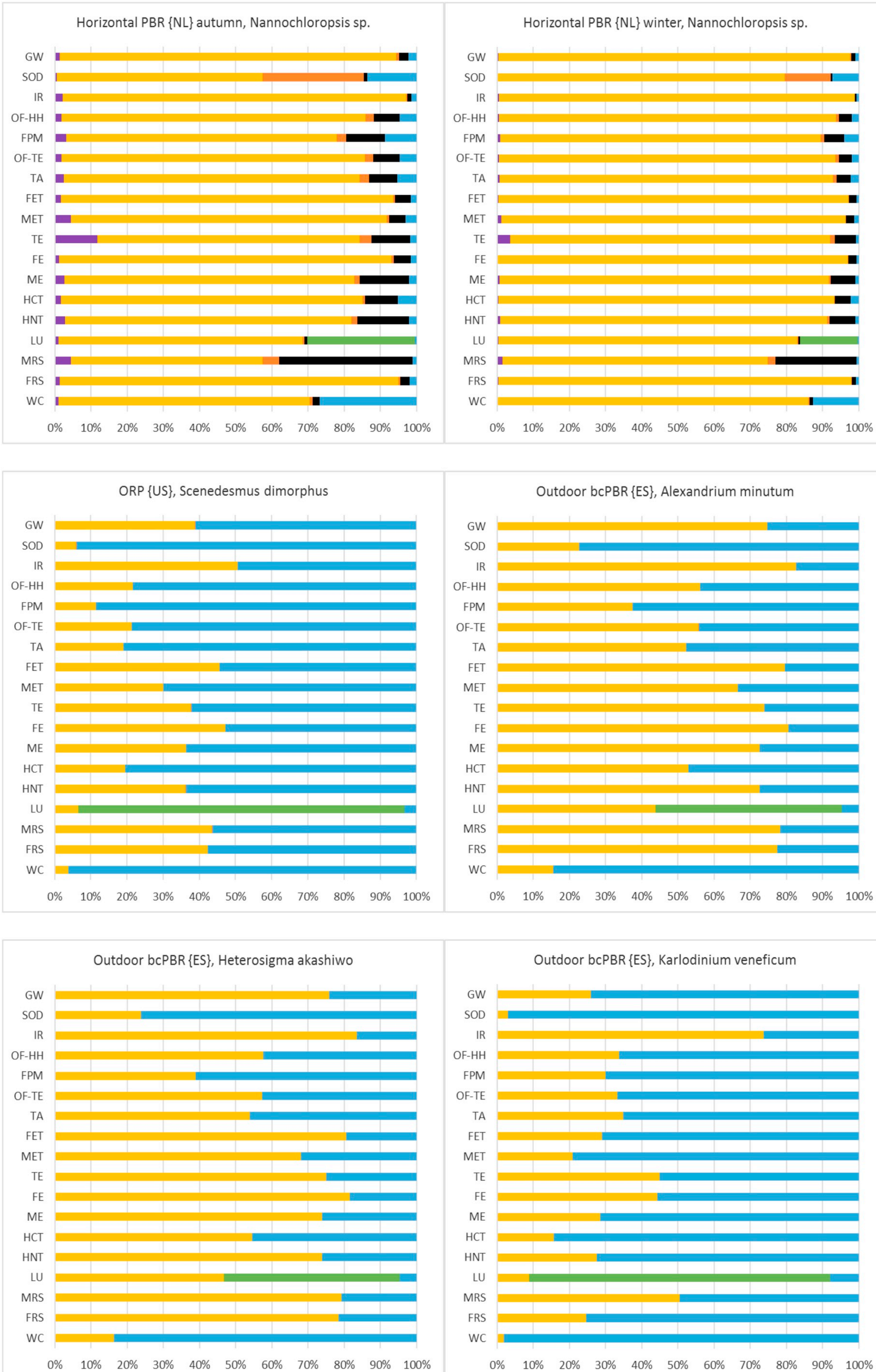


Fig. 5. (*continued*)

Fig. 5. (*continued*)

could be feasible from March (16.64 MJ/m^2/d, 16.2 °C) until the beginning of October (12.1 MJ/m^2/d, 22.1 °C). In Amersfoort, the solar insolation also reaches a peak in June at 19.4 MJ/m^2/d at a temperature of 21.6 °C. It would be most productive to cultivate microalgae here from May (18.0 MJ/m^2/d, 18.7 °C) until September (10.8 MJ/m^2/d, 17.8 °C). The PBR cultivation in Phoenix, USA would be most effective from November to March because the temperatures get too high the rest of the year and active cooling would be needed. However, the solar insolation during these months is lower (on average 14.0 MJ/m^2/d with a peak in March at 21.3 MJ/m^2/d) than that in Amersfoort and Barcelona at optimal times. The temperatures in Singapore are fairly constant year round 29.2 °C on average, as is the solar radiation which only reaches 14.5 MJ/m^2/d on average. Thus, active cooling might be needed here whereas the solar insolation is lower than that in Barcelona and Amersfoort at optimal times.

However, compared to conventional foods such as fish, meat, crops, and legumes that supply people with important micronutrients, the algae cultivation facilities considered in this study had a higher environmental impact on average in terms of their CED, ReCiPe points and GWP (exception: land use). Still, in the background of depleting resources, microalgae could become one alternative to supply people with essential nutrients.

The insights gained from conversations with various experts also suggest that the infrastructure of production plants might be important regarding environmental and economic concerns, which is why the materials for production systems should be selected with caution. This issue also became visible in our results of the environmental impacts where the relative contribution of infrastructure in the NL PBR scenarios ranged between 2.66 and 7.85% on average across the impact categories. In the NL ORP scenarios, the infrastructure contribution amounted to 0.56 and 1.26%. These relative contributions do not seem considerable but they have been put into relation with the environmental impacts caused by energy use. Unfortunately, data on infrastructure were not available for the remaining scenarios. In terms of the PBRs, glass tubes were preferred by experts over synthetic materials because the former were more easily cleaned, more economically friendly, cheaper and had a higher translucence. Data from future studies are needed to formulate more decisive conclusions regarding the impact of infrastructure and different materials. Moreover, glass as a material for the PBRs was not considered in the analyzed studies. Thus, cultivation system materials should be focused upon in future analyses.

4.1. Limitations

The following limitations of our study must be mentioned. The selection of studies to be included in the meta-analysis was relatively small. Finally, only four articles covering 16 different production scenarios were included, of which especially the winter scenarios in the Netherlands supposed highly unfavorable climatic prerequisites. However, since algae production in cooler climates is technically and economically feasible, we decided not to exclude the corresponding data in advance. Data on both PBRs and ORPs were not available for every location, which made it difficult to draw consistent conclusions. Although the data provided by the selected studies were harmonized, an interstudy comparison was not possible for every parameter considered. The system-boundaries and the technological setup (experimental/pilot scale) varied greatly, as did the goal products and the primary focus of all the studies. The systems studied here were all applied at pilot/experimental scale, which is why it should nevertheless be stressed that extensive improvements to system processes can be expected. The values obtained from our analysis for microalgae cultivation inputs were fairly high and they should decrease in an optimized setting. Even though all of the systems were at pilot/experimental scale, the size of the cultivation systems still varied. The study by Pérez-López et al. [21] used an ORP with a size of $4.73\,m^3$, and the mixing was provided by a paddle wheel. The ORP in the study by Bennion et al. [22] also used a paddle wheel, but the size of the ORP was not indicated. Khoo et al. [24] investigated a $2\,m^3$ ORP where the mixing was provided by a gas lift. The horizontal tubular PBR considered by Pérez-López et al. had a volume of $0.56\,m^3$ consisting of three loops, while the vertical tubular PBR in the same study had a volume of $1.06\,m^3$ consisting of seven loops. The bubble column PBR in the study by Itoiz et al. [23] comprised 3 columns, each with a size of $0.033\,m^3$.

It should additionally be noted that concerning PBRs in particular, a wide range of system designs exists that could not be covered by our review due to a lack of data. It would be relevant to analyze the environmental impacts of Christmas tree PBRs, flat-plate PBRs and porous substrate PBRs.

Moreover, the heterotrophic production of microalgae was not analyzed because no relevant data could be allocated. However, according to expert insights, heterotrophic cultivation could be a promising option, especially for edible microalgae production, because there is a very low risk of contamination. Nonetheless, heterotrophic production might not be applicable for all microalgae species and goal products, particularly if specific nutrients are to be produced. Thus, heterotrophic production should be investigated thoroughly, and it would be interesting and very relevant to conduct a comparison between heterotrophic and autotrophic production systems based on the nutrients in the microalgae biomass obtained and the environmental impacts of the systems.

Furthermore, our conclusions might have been more consistent if only one microalgae species had been analyzed across the different production systems. However, as noted in the Materials and methods section, data, and particularly primary data, on the cultivation of microalgae is rare; therefore, the further selection of studies, in terms of the microalgae species would have been a dispensable restriction. Nonetheless, the difference in the results generated by microalgae species was supposed to be negligible at this point in the analysis. Moreover, it will be crucial in further studies to test a greater variety of microalgae species in one system. A vast number of microalgae species exists, many of which have not yet been classified. Thus, certain species have been shown to grow, e.g., at a lower temperature (15–18 °C water temperature) [29] than the species observed in our study.

The geographical location, including solar radiation and temperature, was shown to be the most crucial factor influencing microalgae cultivation. The consideration of more climatic parameters would be of interest for further studies. For example, wind could be interesting for cooling purposes, but could also be obstructive in open systems due to contamination. Moreover, rainfall is an aspect that should be studied because it could influence productivity due to cooling effects.

Generally, it would be helpful if studies included their full life cycle data to enable further research. An analysis of secondary data on microalgae cultivation could be considered but should be discussed thoroughly as studies using secondary data tend to apply idealistic settings, and they occasionally trace back to the same source.

5. Conclusions

The biomass productivity, CED and electricity use and total environmental impacts were all highly dependent on the production site, its climatic characteristics (solar insolation and temperature) and seasonal variations. In contrast, no uniform trend was identified in terms of the cultivation systems. The performances of the ORPs and the different types of PBRs were rather mixed. Similarly, there was no recognizable scheme concerning the microalgae species. All of the species exhibited varying results. This implies that it cannot be generally stated that one system type performs better than the other. The best option needs to be verified in every single case based on site characteristics (solar radiation, temperature, and day length, as well as other parameters such as wind and rainfall), the microalgae species and the target products.

However, as different cultivation technologies are forthcoming from pilot to the industrial scale (Christmas tree PBRs, flat-plate PBRs, porous substrate PBRs, etc.) further improvements in system design could perhaps compensate for climatic disadvantages, as microalgae cultivation is still an emerging field and many considerations for system enhancement still need to be evaluated.

Conflict of interest

The authors declare no conflict of interests.

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Author contribution

TM initiated and designed the study. SS conceptualized the structure of the manuscript, conducted the acquisition of data and the analysis, and wrote the manuscript. SS and TM performed the interpretation of data, revised and finalised the manuscript. All authors agree to authorship and approve the final manuscript for submission.

Statement of informed consent, human or animal rights

No conflicts, informed consent, human or animal rights applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2019.101485.

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