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Compilation of Life Cycle Assessments of Cultivated Brown Seaweed

A recalculation of Life Cycle Inventories

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Summary in Swedish

Globalt sett minskar tillgänglig landareal för odling, samtidigt som efterfrågan för ekologisk och hållbart producerade produkter ökar. Det här har lett till att fler sektorer söker sig till det som kallas *Blue growth*. *Blue Growth* är användandet och utnyttjandet av marina miljöer för produktion, inom olika sektorer, som gynnar både det marina ekosystemet och bioekonomin. Algodling är ett exempel på en produktion som gynnar bioekonomin. Alger är en alltmer efterfrågad produkt, som redan används i flertal sektorer, så som läkemedels-, textil- och livsmedelsindustrin. Det är främst algernas egenskaper som gör att de är attraktiva att kultivera, tillsammans med strävandet av en hållbar produktion.

Den här masteruppsatsens syfte är att jämföra tidigare livscykelanalyser som har gjorts på produktionen av brunalger. Livscykelanalyser är ett verktyg inom industriell ekologi som mäter en produkts påverkan genom alla livscykler. Resultatet ges i ett numerärt värde, och är summan av produktens påverkan inom den specifika kategorin. Det denna rapport har gjort är att räkna om livscykelanalyser som tidigare har gjorts på brunalger, för att få jämförbara resultat. Syftet med rapporten är därför att granska och utvärdera publicerade livscykelanalyser av odlade brunalger. Tre delmål sattes upp vilka var:

- Bedöma skillnader och likheter i de olika livscykelinventeringarna.
- Studera och utvärdera skillnaderna mellan den beräknade livscykelanalysen av brunalger till samma parametrar.
- Utvärdera processen för att räkna om redan gjorda livscykelanalyser.

Fem rapporter valdes ut, varav sex stycken livscykelinventeringar sammanställdes, eftersom en rapport innehöll två olika livscykelanalyser. Studien började med, att sammanställa all tillgänglig data, samt att räkna om kvantiteterna i inventeringarna. Därefter räknades alla sex livscykelanalyser om, med samma förutsättningar och metod. Detta innebar att resultatet som fanns i de slutgiltiga summorna kunde jämföras och diskuteras. De tre kategorierna som livscykelanalyserna mättes mot var: potentiell global uppvärmning (kg koldioxidekvivalenter), övergödning i sötvatten (kg fosfor) och marinövergödning (kg kväve).

Det som jämförelsen visade var att alla omräknade livscykelanalyser hade olika totalbelopp i de tre kategorierna. Likväl kunde kultiveringssteget anses vara det livscykelstadie som har störst påverkan på brunalgodling, främst på grund av plastanvändningen.

På grund av de olika påverkningsgraderna som rapporterna hade, fanns det många faktorer som diskuterades kring likheterna och skillnaderna. Först och främst kan datainhämtningen ha en stor påverkan på tilliten och förtroendet på resultaten. För det andra skildrades inventeringarna på olika sätt, varav både kvantiteter och materialvalet skildes åt. Dessa skillnader kan bero på den geografiska placeringen av produktionen, men även på hur utformningen av produktionen såg ut.

Det som studien även visade var att en omberäkning på livscykelanalyser var svår att utforma utan att flertalet antaganden gjordes på grund av avsaknad av data. Processen att räkna om redan gjorda livscykelanalyser kan därför anses problematisk, vilket gör att livscykelanalys som vetenskapligt verktyg kan ifrågasättas om inte replikering av resultat kan göras med stor säkerhet.

Abstract

Seaweed production systems are necessary to fill a product demand in multiple sectors whilst contributing to the bioeconomy. The multiple seaweed qualities drive the research for sustainable seaweed production worldwide. The main studies of seaweed production consist of life cycle assessments, where cradle-to-gate analyses have been calculated. However, these assessments have had incomparable results because of the various methods used. Therefore, this thesis utilized the life cycle inventories of six previously made life cycle assessments of brown seaweed and recalculated these concerning three key environmental impact categories – Global warming potential, Freshwater Eutrophication, and Marine Eutrophication. This was done by collecting and recalculating the six different inventories to the same functional unit and then assessing the environmental impacts of the recalculated inventories. The results showed that the life cycle impact assessments of brown seaweed production varied, yet the most impacts could be seen during the cultivation stage of the life cycle, mainly due to the plastics used within the system. The variations in the results are a consequence of the various data resources used, the design and location of the production systems, and the goal and scope of the reports. This thesis also demonstrated that a replication of life cycle assessments includes several obstacles, questioning the scientific method of LCA, for example, lack of transparency and deficiency in reporting methods and data.

Keywords

Environmental impact, recalculated inventories, production system, global warming potential, freshwater eutrophication, marine eutrophication

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Ellen Ahlgren

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Abbreviations

CO_2	Carbon dioxide
eq	Equivalents
FR	France
Freshwater Eu	Freshwater Eutrophication
FU	Functional unit
GLO	Global
ha	Acres
IR	Ireland
ISO	International Organization for Standardization
kg	Kilograms
km	Kilometer
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Marine Eu	Marine Eutrophication
MJ	Megajoule
N	Nitrogen
P	Phosphorus
RER	Europe
SE	Sweden
tkm	Ton kilometer
ww	Wet weight

1 Introduction

Seaweed has been used globally throughout time, both harvested from the wild and through cultivations along coastlines. Today, most of the cultivated seaweed can be found in Asia, while the rest of the world's seaweed production mainly comes from wild biomass (FAO, 2020). Research suggests that the development and expansion of seaweed cultivation would benefit the bioeconomy and contribute to blue growth while filling a product demand (European Commission, 2012). Seaweed is used in many products, from fertilizers in the agricultural sector to pharmaceutical, textile, and cosmetic products. However, the primary purpose for seaweed remains to be for human and animal consumption (McHugh 2003; Adams et al., 2011; van Hal et al., 2014). Hence, there has been an increase in seaweed cultivation practices in the last few years, mainly to meet the product demand within multiple sectors (Alemañ et al., 2019; Thomas et al., 2020).

The numerous seaweed qualities attract and drive further research and cultivation practices, alongside sustainability aspects in ecological production. The high sugar content of seaweed makes seaweed an appropriate feedstock for bioethanol and biogas production, as shown in several pilot studies on pilot scale levels, to meet future renewable energy production demands (Langlois et al., 2012; Alvarado-Morales et al., 2012). The high protein content of seaweed makes it an alternative to soybean production (Seghetta et al., 2017). The main attraction of cultivating seaweed is the avoidance of deforestation and land competition, in addition to the absence of typical agricultural concerns like freshwater usage, fertilizers, and pesticides (Havlík et al., 2011; Aitken et al., 2014; van Oirschot et al., 2017). Seaweed can also provide ecosystem services such as carbon sequestration, bioremediation of eutrophication nutrients, and habitat provision for several species (Marinho et al., 2015; Thomas et al., 2020).

The current environmental impact assessments of seaweed production have incomparable results and are based mainly on small production sites or literature. Currently, there are no well-established large-scale seaweed productions, which means that the completed research is based on various pilot-scale productions and literature. The data are varied, and the results are mainly incomparable because of differing research questions, aims, and objectives. Additionally, even though new production sites have been added globally, research has not been increasing at the same pace. The leading research regarding seaweed cultivation has focused on life cycle assessments (LCA), in other words, calculations of seaweed production's environmental impacts. These completed calculations have been done to evaluate further development of production sites or different production methods.

Life Cycle Assessment, as an environmental assessment tool, attempts to provide an objective view of a system and the system's function and can generate different results depending on the practitioner (Freidberg, 2014). This is cited relatively frequently, primarily because of controversies around company performed LCAs, and because of the lack of system specificity in replication is known (ibid.). To achieve a fair comparison of environmental impact assessments of seaweed production will the life cycle assessments need to be recreated with the same methodology and system boundaries. Hence, this thesis will organize and harmonize the inventory data of current research of brown seaweed production for a uniform impact evaluation and make the results comparable. Comparing the environmental assessments will clarify the production's significant environmental impacts, show where data might be lacking, and present methodological differences in the production techniques. It will also highlight and illustrate replicating an already-made life cycle assessment and presenting the challenges that come with it.

1.1 Aim and objectives

The aim of the thesis is to review and evaluate published Life Cycle Assessments of cultivated brown seaweed. This will be done by compiling five LCAs input inventories and recalculating them to the same functional unit.

Three objectives were created with the intent to answer the aim.

1. Assess variations and similarities in the various Life Cycle Inventories.
2. Study and evaluate the variations between the recalculated Life Cycle Assessment of brown seaweed to the same parameters.
3. Evaluate the process of recalculating already made Life Cycle Assessments.

2 Theoretical Background

This section contains the theoretical background of the brown seaweed production system and describes the environmental assessment tool LCA with its delimitations and typical criticism of the LCA methodology.

2.1 Brown seaweed production

Seaweed production can be summed down to four steps – the nursery stage with spore preparation, offshore seaweed cultivation, harvesting, and drying (*Fig. 1*). These are the main life cycle stages included in a cradle-to-gate analysis. There are several ways to perform these steps but the analyzed reports use the so called base method; which is described below.

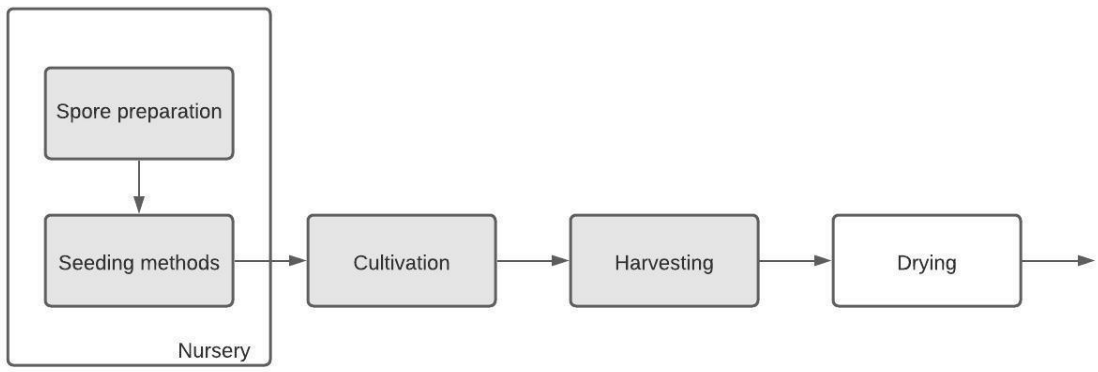

Figure 1. *The life cycle stages of seaweed production in a cradle-to-gate chain. The grey boxes are the stages included in this study.*

The first stage is the nursery stage with the spore preparation which is performed in laboratories on land. The spore preparation begins with selecting the parent specimen and then induce spore development. This then develops the fertile tissue. The next part of this first preparation stage is to prepare the lines, which means that the seaweed spores are seeded on the lines. The method mainly used here in this thesis is the submersion seeding method, which occurs in a laboratory setting with the best optimal starting growth conditions.

The second step of the life cycle is the seaweed cultivation stage, which includes the juveniles' deployment at sea. The cultivation sites are designed differently depending on the area size, sea conditions/exposure, and seaweed species. Most sites are designed quite similarly, though, with long-line culture ropes, with the spore prepared lines wrapped around structural ropes tied to the long lines. Concrete blocks are usually anchoring these cultivation systems to help stabilize, and visibility is buoys used. The growth process and cultivation stage can be varied in length depending on the geography, season, and seaweed species. During this stage, the seaweed absorbs nutrients and fixes carbon through photosynthesis.

The third stage of the life cycle stage is harvesting the seaweed, which is followed by drying and storage of the seaweed, the final step in a cradle-to-gate analysis. Depending on the cultivation site's location and size, the harvesting stage has very individual practice, and the inputs are mainly concerning transportation. The challenging part regarding harvesting is that brown seaweed has high biological productivity, and therefore high yield, and harvesting will either need a big barge or many return trips to the shore. Once the seaweed is on land, the final stage of the production is the processing, preserving, and packaging. The processing method could be drying, freezing, rinsing, or blanching, depending on the desired end-product. This study has not included any post-harvest stages.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology used for assessing the environmental impacts of a product, process, or service throughout its lifetime. A LCA is completed through a systematic inventory of energy and materials needed in the various life stages of the product, which translates to calculations of the corresponding emissions to the environment. The four steps or phases of the LCA framework are the goal and scope, the inventory analysis, the impact assessment, and lastly, the interpretation (*Fig. 2*). The framework should guide how an LCA is performed; however, the phases are interdependent and the LCA process is therefore iterative.

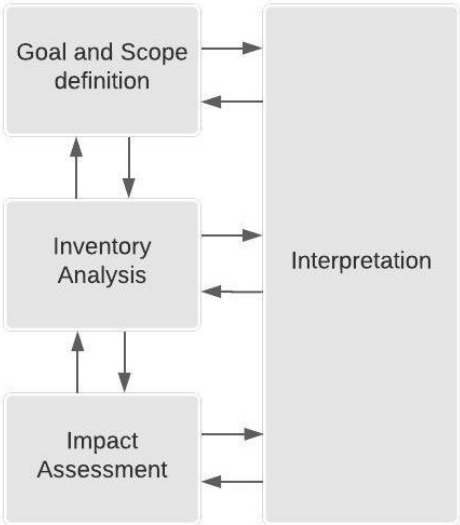

Figure 2*. The Life Cycle Assessment framework (ISO 14040:2006).*

The goal and scope will demonstrate the assessment's intent, the system boundaries, and the methods within the LCA. This part should be well-defined and transparent to invoke trust in the calculations and results and enable replicating the method in potential follow-up studies. The inventory analysis, which forms the Life Cycle Inventory (LCI), compiles the entire life cycle's inputs, energy, and material. Consequently, this part is time-consuming and should be done with preciseness since this will shape the impact assessment (LCIA) and associated results. Subsequently, is the impact assessment when the environmental inputs and outputs are translated into impacts across a predefined range of environmental impact categories. Lastly, the final stage is the interpretation, where an evaluation is made of the previous phases in relevance to the goal and scope.

2.2.1 Delimitations and critical review of LCA methodology

One of the main criticisms of life cycle assessments is that results rely on data availability. Since a significant amount of data is needed for an LCA, the absence of reliable data is common, and the results and conclusion of the assessment are thus often questionable. Because of a lack of data sources and producers' reliability, LCA practitioners often fail to collect the underlying process data because of confidentiality (Ayres, 1995). Usually, because of complications concerning data sources, or lack of specifications, many assumptions and simplifications are made, hence in the end, not reflecting the system truthfully. According to Ciroth (2006), there is a substantial absence of validation and assurance that the model represents the system. This could also be because LCA takes a steady-state approach and does not cover geographical or temporal dynamics. The used databanks could also lack unreliable scientific verification. The databanks also need constant confirmation and updates to reduce the uncertainties that could be connected to the practitioner. There also exist various levels of knowledge and consensus about the environmental impact categories used to measure the impacts of the product or process.

Another critical aspect of LCA is the practitioner's bias and subjectivity. Depending on the aim and information that the practitioner wants to focus on and recognize with life cycle assessments, the environmental impact of the same product, process, or service varies (Ayres, 1995). This bias that might produce different results might not be conscious or deliberate. To standardize an LCA performance are standards like ISO created; however, there could still be variations in results analyzing the same product.

LCA that have been performed with economic incentives, either from companies, governments, or other sources, have a more substantial bias that might affect the results of the LCA. An example where LCA has been used, is as a business factor to claim sustainability for the company and claim environmentally friendly products are adding up. One major conflict between two companies with different aims and economic drivers was the so-called diaper wars – where two manufacturers claimed that their product was more environmentally benign (Lehrburge et al., 1991; Little, 1990). The two sides were the producer of reusable diapers and the producer of reusable ones. Both companies used life cycle assessments to prove their point, and both got the results that their own product was the most environmentally friendly (Hays 1997; Portney, 2012; Freidberg, 2014). This occured because of the chosen system boundaries and factors chosen within the LCA. This unresolved LCA debate even led to creating a governmental task force to fight deceptive environmental advertising (Friedberg, 2014). The Attorney General Task Force (1991) stated that problems include comparisons of information that technically cannot be compared as well as referencing only the positive environmental aspects of one product and only the negative of the competing one. Hence, this case is a clear example where economic incentives are observed as biases in the assessment and seen as a guide in the work toward the preferred results. Additionally, the differences in results were also because of the chosen method and choices within the LCA; thus, even if an unbiased external party would perform the LCA, the results vary. This was seen when several other external parties did a comparative LCA of the same case (EDANA, 2008).

3 Method

To analyze the published reports Life Cycle Assessments of brown seaweed, a central part of the method was to assess the datasets to the same methodological structures for a fair comparison and differentiation. This was done by collecting the various Life Cycle Inventories, and every dataset was recalculated to the same functional unit (FU). The software used for the inputs is the SimaPro version (9.1.0.11), where Ecoinvent v.3 – allocation at point of substitution was used. These inputs with their corresponding environmental impacts were exported to Excel, where the LCA was done.

Life Cycle Assessments with the data and the same system boundaries were evaluated to the same environmental impact categories and the same assessment method, ReCiPe 2016 Midpoint (H). The results were then compared to their previous results within their published reports and each other. The reviewed published reports were chosen because they had similar production system methods and analyzed brown seaweed. They also had the vital aspect of well-described life cycle inventories. To summarize, this thesis consisted of a literature study at the beginning and the end of the work, while a quantitative analysis was made in between.

3.1 Reviewed published reports

The five analyzed published reports include brown seaweed LCAs throughout the last ten years (*Tab. 1*). As previously mentioned, the reports are formed with different aims and goals, and the LCAs included are also varied, mainly concerning the geographical boundaries and the data collected and used within the reports. Because of the lack of large-scale seaweed production sites, the reports are primarily based on pilot-scale production sites and verified by literature.

Table 1. *A summary of the reviewed published reports.*

Author (year)	Report	Area	Seaweed species	FU	Method	Ecoinvent
Langlois et al. (2012)	Life cycle assessment of biomethane from offshore-cultivated seaweed	Europe	*Saccharina Latissima*	1 km trip with a gas-powered car	ReCiPe	v.2.2
Aitken et al. (2014)	Life cycle assessment of macroalgae cultivation and processing for biofuel production	Chile	*Macrocystis Pyrifera*	1 MJ of energy	CML	v.2.2
Taelman et al. (2015)	Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation	Ireland & France	*Saccharina Latissima*	1 MJ exergy seaweed	CEENE	v.2.2
Seghetta et al. (2017)	Seaweed as innovative feedstock for energy and feed e Evaluating the impacts through a Life Cycle Assessment	Denmark	*Saccharina Latissima*	1 ha of sea under cultivation	ReCiPe	v.3.1
Thomas et al. (2020)	A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina Latissima	Sweden	*Saccharina Latissima*	1000 kg fresh weight biomass	CML	v.3.2

3.1.1 Langlois et al. (2012)

This report's focus and goal were to determine whether offshore-cultivated seaweeds are a more environmentally friendly feedstock for fuel production than natural gas. The data in Langlois et al. (2012) came from a semi-industrial macroalgae production site following techniques described in the literature. This assessment's geographical area was European countries, and the seaweed grown was

Saccharina Latissima (Sugar kelp). This report's system boundaries had a cradle-to-gate approach, and the method used was the ReCiPe method (H) with the data from Ecoinvent v.2.2.

3.1.2 Aitken et al. (2014)

This published report had an aim to determine the most sustainable method of cultivating and processing macroalgae to bioenergy. This was done by comparing two different macroalgae species; however, this comparative thesis only uses Macrocystis Pyrifera (Giant kelp) data because of similarities in the cultivation system. The geographical boundary in this study was Chile. The report used a cradle-to-gate approach and included hatchery, long-line cultivation, and harvesting. The data used was based on various sources, mainly from published literature and personal communication with seaweed farmers during 2012. The current studies could either be one or two hectares; however, the data were scaled to be 100 hectares, which was assumed to be a manageable size. The method used was CML 2001 with the data inputs from Ecoinvent v2.2.

3.1.3 Taelman et al. (2015)

This report aimed to compare the environmental footprint of cultivating seaweed in the Atlantic Ocean on the west coast of Ireland to the northern coast of France. The cultivated species was the brown seaweed *Saccharina Latissima;* however, two different cultivation systems were applied at the two different locations. Both locations, Ireland, and France are included in this thesis. The functional unit was the production of dried seaweed that can produce 1 MJ exergy. The report used a cradle-to-gate life cycle analysis with the LCIA method CEENE to determine the overall consumption of natural resources.

3.1.4 Seghetta et al. (2017)

This study was a comparative Life Cycle Assessment where five different scenarios were compared to provide decision support for the design of future industrial-scale production processes of macroalgae in energy and protein production. The report was based on offshore cultivation of macroalgae located on the marine water surface in Denmark. The chosen seaweed was *Saccharina Latissima* and *Laminaria Digitata* (Oarweed); however, only the data regarding *Saccharina Latissima* is used in this thesis. The cultivation area in Denmark is estimated to be 208 km^2, a short-term future estimation of large-scale seaweed production systems there. The obtained data for cultivation within the report was from a pilot cultivation site in Limfjorden, Denmark, during 2012-2013. The data of seaweed biomass was based on literature studies. The method used in this report was ReCiPe with data inputs from Ecoinvent v3.1.

3.1.5 Thomas et al. (2020)

This report aimed to make an environmental impact-based cradle-to-gate comparison for various pathways for preserved kelp production. The data collected within this report was from a kelp farm in Sweden in the Koster archipelago, and the species studied was *Saccharina Latissima*. This report was a cradle-to-gate study and included various drying processes; however, as previously stated, this life cycle stage was not included in this thesis. The method used in the study was CML 2000, and the data used was from Ecoinvent v3.2.

3.2 Recalculation of the Life Cycle Assessments

After the reports to be compared had been chosen, the first step in the recalculation was to assess the aim and objectives, which can be found in *1.3 Aim and Objectives*. Secondly, the set methodology strategy was chosen for this LCA, including the functional unit, the system boundaries, and the impact categories to be analyzed. These choices were based on the chosen reports to be assessed and their relevance to the aim and objectives.

3.2.1 Functional unit

The functional unit chosen in this recalculated LCA was 1000 kg or 1 ton of fresh-weight seaweed. This unit was already the functional unit in one of the reports; the other had other functional units that better suited their aim and objectives. Therefore, individual factors were needed to convert the life cycle inventory to the amount that would provide 1000 kg fresh weight in the different datasets.

3.2.2 System Boundaries

The chosen system boundaries of this recalculated LCA were selected based on the reports' various system boundaries, hence how many life cycle stages could be compared in the cultivation of brown seaweed. The chosen system boundaries include the nursery stage (the spore preparation), the cultivation stage, and the harvesting; thus, this Life Cycle Assessment is a cradle-to-gate analysis. Drying, an essential part of cultivating brown seaweed for further usages, such as for biogas, was not included since not all the reports had this stage included.

3.2.3 Key Impact categories

The environmental impact categories included in an LCA depend on the methodology chosen. All five reports had different LCA methods and various impact categories assessed; however, this thesis has only the most essential categories chosen for this topic – Global Warming Potential, Freshwater Eutrophication, and Marine Eutrophication. These three impact categories are the most relevant of the existing 17 environmental impact categories within the ReCiPe 2016 midpoint method.

Global Warming Potential

The ReCiPe method impact category Global Warming Potential quantifies CO_2 or CO_2 equivalents released, where the unit is kg CO_2 emitted and the time frame is 100 years (Ministerie IenM, 2016). The gas characterization is based on the extent to which they enhance the radiative forcing in the atmosphere; 207 greenhouse gases are included (Baumann et al., 2009). This category is included because of the significant threat that excessive amounts of released carbon will affect the mean global temperature and climate change. Additionally, a seaweed production system can reduce atmospheric CO_2 through bio-extraction and provide climate change mitigation if the system becomes CO_2 neutral or negative. Therefore, this impact category shows the emissions of CO_2 from the system and the potential bio-extraction of carbon by the system.

Freshwater and Marine Eutrophication

Freshwater Eutrophication and Marine Eutrophication as impact categories refer to the excessive growth of aquatic plants or algal blooms. This excessive growth is due to the high levels of nutrient pollution of phosphorous and nitrogen (Ministerie IenM, 2016). Freshwater Eutrophication is calculated in kg phosphorus (P) released, while Marine Eutrophication is calculated in kg nitrogen (N) released. These two impact categories are included for the same reason as Global Warming Potential, both to visually see how much the system will contribute to the eutrophication levels and see the potential uptake of the same nutrients through bioremediation.

3.2.4 Sensitivity Analysis

A sensitivity analysis was included to test the results with different inputs. The analysis was included primarily because of the varying degrees of specificity in the reports' life cycle inventories. The alternative inputs were chosen for a more reliable comparison between the LCAs, primarily based on whether an input significantly contributes to the total impacts or if the input seems uncertain or distinct compared to the other reports.

4 Results

This section presents the results which exist of a compilation of the inventory data and the environmental impact assessment of the life cycle stages. The results found here are based on the recalculated results.

- The first section of the results *4.1 Recalculated inputs* presents the material and energy inputs and recalculated quantities in all the reports.

- The second section of the results *4.2 Environmental Impacts* shows the total impacts in the three chosen environmental impact categories – Global Warming, Freshwater- and Marine Eutrophication.

- The third section of the results *4.3 Hotspots in the life cycle stages* presents the recalculated life cycle assessments in the different life cycle stages in relation to the environmental impact categories. This section first presents a general picture of the percentual impacts of the stages in their reports and is later presented in relation to the three key environmental impact categories in subsections.

- Section *4.4 Material and Energy impacts* consist of a summary of the recalculated inventories divided into the most important input contributors. The reports' main contributors are then presented in relation to the various environmental impact categories and are finally summarized with a summary of the main contributors.

- The last section of the results *4.5 Sensitivity Analysis* presents the recalculated sensitivity analysis that studies the various inventories with the same electricity mix and with the same cultivation system.

4.1 Recalculated inputs

The summarized inventories presented in reports, the various chosen inputs and recalculated quantities are summarized in the following tables, which are divided between the different life cycle stages (*Tab. 2, 3 and 4*).

Table 2. *Total material and energy inputs and the recalculated quantities of each report in the nursery life cycle stage.*

Life Cycle stage	Material/Energy Input	Unit	Langlois et al.	Aitken et al.	Taelman et al. (IR)	Taelman et al. (FR)	Seghetta et al.	Thomas et al.
Nursery	Water	kg/L	4.48E+02		1.74E+00	5.46E+00		
	PET	kg					1.90E+02	
	PEHD	kg					4.00E+01	
	Polyvinyl alcohol	kg					1.07E+00	
	PVC	kg						2.75E-01
	Acrylic Perspex	kg			1.92E-03	3.64E-04		2.91E-01
	Polyethylene	kg						1.70E-02

	Polyamide	kg	6.98E01	4.30E-01				1.58E-01
	Unspecific plastic	kg		5.88E-03	8.35E-02	5.93E-01		
	Steel	kg		4.18E-02		1.60E-02		
	Concrete	m^3	1.98E-05					
	Cement	m^3	2.11E-05					
	Concrete blocks	kg	1.71E-01					
	Sand	kg					2.22E-01	
	Natural gas	kg					9.50E-02	
	Diesel	L					4.00E-01	
	F2 medium	L					2.40E-01	6.68E-01
	Ammonium nitrate	g	7.82E+00	2.13E+00	2.31E-01	6.53E-01		
	Sodium phosphate	g	3.16E+00	3.24E+00	2.10E-02	9.18E-02		
	EDTA	g	1.72E+00					
	FeCl3 (40%)	g	2.61E+01					
	Anhydrous boric acid	g	1.51E+00					
	Lightning	kg			6.69E-03	2.05E-03		
	Light-emitting diode	piece					8.98E-05	
	Aeration system	kg			5.03E-02	1.21E-02		
	Pumps	kg				8.47E-03		
	Filters	kg			6.84E-03	1.36E-02	5.18E-02	5.04E-02
	Autoclave	kg			2.74E-02	2.73E-02		
	Electricity Lamps	kWh		8.18E+00	2.22E+00	5.32E-01		1.13E+01
	Electricity Aeration system	kWh		6.86E-02	3.38E+00	7.04E+00		3.02E+00
	Electricity Pumping	kWh		5.28E-03		8.76E-03	1.84E-01	
	Electricity Filters	kWh			3.22E-01		1.87E-01	4.11E-02

	Electricity Autoclave	kWh		2.57E-02	4.92E-01	2.46E-02	1.50E+00	
	Electricity Temperature	kWh						1.09E+01
	Unspecified electricity	kWh	3.33E+01	2.91E+00				

As can be seen in *Table 2,* different studies used different specific plastic types. The way to present the electricity and the electricity compounds is also varying between the reports. The added nutrient solutions are also varying.

Table 3. *Total material and energy inputs and the recalculated quantities of each report in the cultivation life cycle stage.*

Life Cycle stage	Material/Energy Input	Unit	Langlois et al.	Aitken et al.	Taelman et al. (IR)	Taelman et al. (FR)	Seghetta et al.	Thomas et al.
Cultivation	Polyamide	kg	1.57E+00	9.46E-01			2.70E-01	
	Polyethylene	kg		4.47E-01				6.56E-01
	Polyethene	kg					4.27E+00	
	Nylon	kg					2.31E+00	
	PVC	kg						5.68E-01
	Polypropylene	kg	4.12E-01				5.17E+00	8.53E-01
	Polyester silk	kg						3.61E+00
	Polyurethane	kg	1.32E-03					
	Glass Fibers	kg	9.93E-01					
	Unspecific plastic	kg			3.87E+00	3.27E+00		
	Steel	kg	1.36E+00	3.27E-01	1.52E+01	1.45E00		2.70E+00
	Aluminum	kg		3.07E-03				
	Iron	kg					9.27E+00	
	Concrete	kg	4.87E+01	8.11E+00	9.66E-01	7.65E+00	4.15E+01	7.22E+01
	Diesel	kg		8.69E-03	6.74E+00			
	Boat transport	tkm						3.92E+00

In the cultivation stage are the chosen plastics also differing and the chosen metals (*Tab. 3*). Not all reports have included boat transportation in this stage; however, it might be combined with the harvest stage transportation.

Table 4. *Total material and energy inputs and the recalculated quantities of each report in the harvest life cycle stage.*

Life Cycle stage	Material/Energy Input	Unit	Langlois et al.	Aitken et al.	Taelman et al. (IR)	Taelman et al. (FR)	Seghetta et al.	Thomas et al.
Harvest	Polypropylene	kg					1.07E-01	4.55E-01
	Diesel	kg		7.12E-02	9.10E+00	1.16E+00		
	Boat transport	tkm	1.56E+01				6,08E+01	2.17E+01
	Barge			1.42E-06				
	Tractor transport	tkm						1.00E+00

The boat transportation is included in all reports; however, not all reports have polypropylene harvesting bags included (*Tab. 4*).

4.2 Total Environmental Impacts

The total environmental impacts of the recalculated life cycle inventories are varied, even though they are calculated to the same functional unit, which is 1000 kg fresh weight seaweed (*Tab. 5*.). The impact category Global Warming has a mean value of 47.52 kg CO_2 and with a standard deviation of 20.66 kg CO_2. The eutrophication impact categories have a mean value of 1.48E-02 kg P and 4.10E-03 kg N, while they have a standard deviation of 6.21E-03 kg P and 1.74E-03 kg N. An overview and comparison of the six systems total environmental impacts can be seen in *Figure 3*.

Table 5. *Total impacts of each report to the chosen environmental impact categories.*

	Global Warming [kg CO_2]	**Freshwater Eutrophication** [kg P]	**Marine Eutrophication** [kg N]
Langlois et al.	50.38	2.11E-02	5.80E-03
Aitken et al.	26.54	8.89E-03	3.26E-03
Taelman et al. (IR)	56.50	2.25E-02	4.23E-03
Taelman et al. (FR)	21.54	5.50E-03	2.36E-03
Seghetta et al.	84.32	1.78E-02	6.85E-03
Thomas et al.	45.85	1.30E-02	2.09E-03

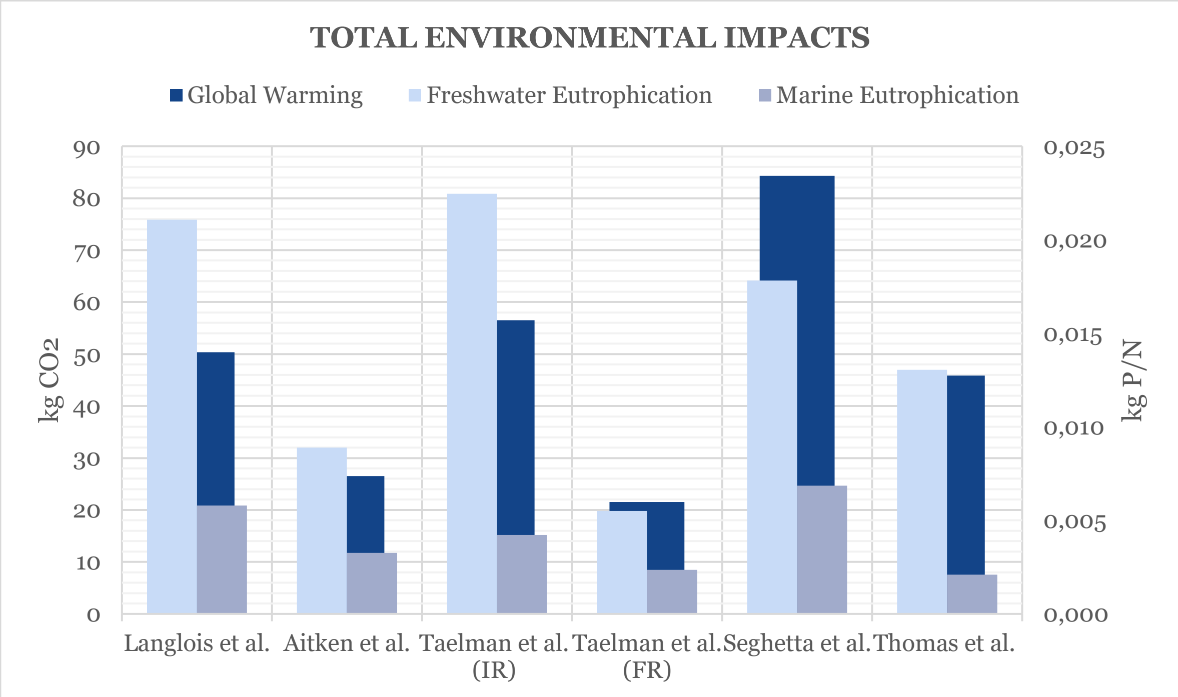

Figure 3. *Total environmental impacts of each production system. The Global Warming impact has the magnitude and unit seen on the left-hand side of the diagram, whilst the two bars in front, Freshwater Eutrophication and Marine Eutrophication, have the scale on the right side of the diagram.*

4.3 Hotspots in the life cycle stages

An overview of the impacts percentual weight of the various life cycle stages – nursery, cultivation, harvesting, as well as the impact of biomass, is presented here. This is the recalculated life cycle inventory's environmental impacts in relation to their total impacts (*Fig. 4*). This means that the six different production systems have different total environmental impacts, as was seen in *4.1 Total Environmental Impacts*. A more detailed data presentation can be found in the subsections divided into the three key environmental impact categories.

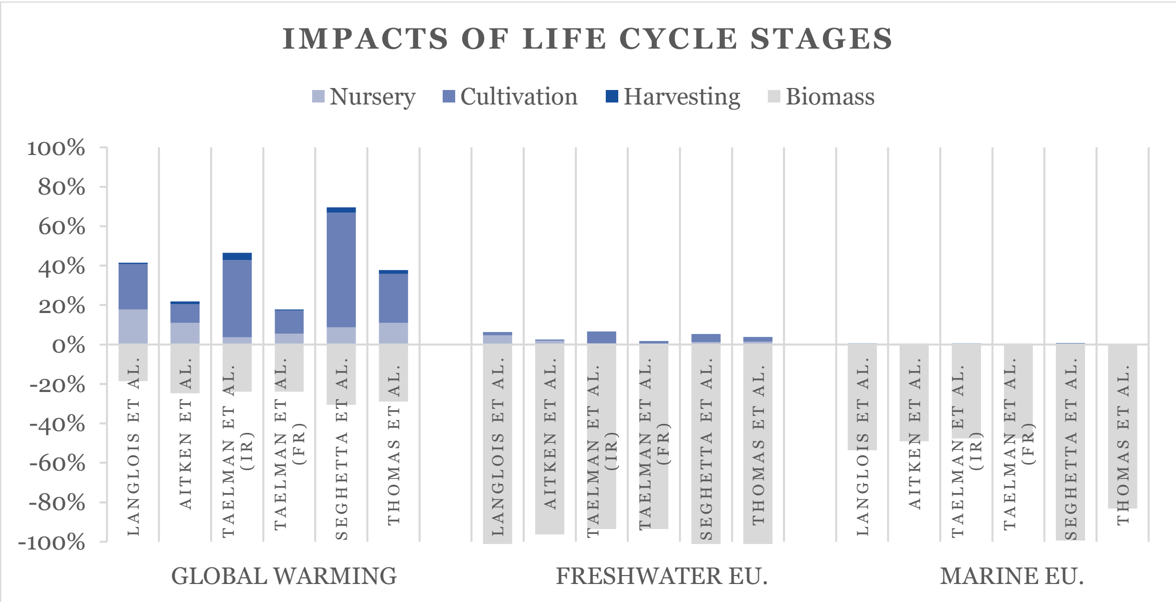

Figure 4. *A percentual overview of the life cycle stages environmental impacts in relation to the highest impacts in each environmental impact category.*

The primary assumption to be drawn regarding the recalculated results is that the life cycle stage with the highest environmental impact through all environmental impact categories could be the cultivation stage. Some differences between the report's environmental impact quantities exist and the nursery stage also shows a high percentage in relation to the total environmental impact in some cases, e.g., Langlois et al. and Aitken et al.'s global warming potential. The recalculated reports show a variation between the report's environmental impact in the three different categories, without any pattern or similarities to be noticed. This can be assumed to be because of the inventory's differences, quantities of materials, and the chosen materials.

The harvesting phase has a minor impact on the other stages; this is seen throughout all impact categories. This can be since only a couple of inputs are needed for this stage, mainly boat transportation. Still, the harvesting impact size varies between the reports, which is most likely depending on the location of the production sites in relation to the production site on land.

Another key impression from this overview is that the growth of the biomass, which is seen as a positive impact and therefore a negative emission, has a significant impact on bio-extraction and bioremediation of carbon and nutrients. This is included in this overview and thesis because bio-extraction and bioremediation are a part of the life cycle. However, an important note is that the carbon is only bound to the biomass within these system boundaries. Therefore, the carbon might be released from the biomass, depending on the life cycle stages after the harvesting.

4.3.1 Global Warming Impact

A comparison between the reports of the global warming impacts can be seen in *Figure 5,* while the specific life cycle impacts quantities on global warming and their percentual parts can be seen in *Table 6*. The total global warming impact was varied between the reports, between about 21.54 – 84.32 kg CO_2 per functional unit, the mean value being 47.52 kg CO_2, and the standard deviation of the total global warming impact 20.66 kg CO_2.

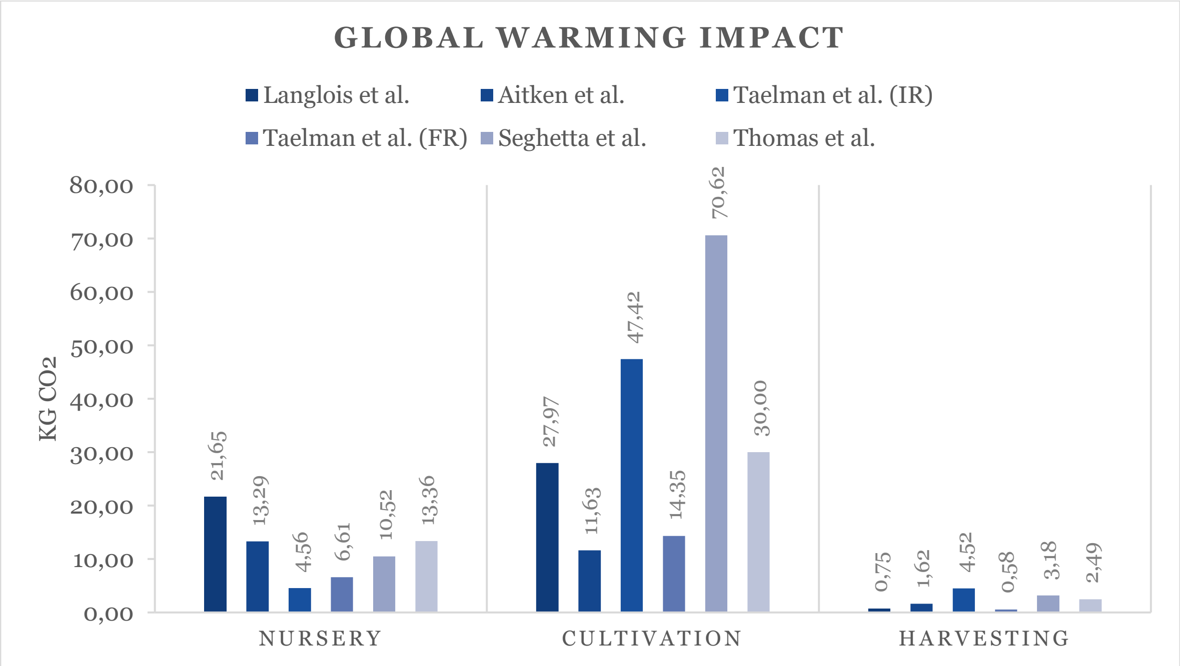

Figure 5. *The recalculated global warming impact [kg CO2] during the different life cycle stages.*

The life cycle stage with the most impact on global warming change can be assumed to be the cultivation stage with a mean percentage of 71 %, however, with some variations in quantities. The nursery will follow as the second most impactful stage with a mean percentage of 25 %, while the harvesting stage, as mentioned before, have an almost insignificant impact on this environmental impact category.

Table 6. The recalculated global warming impact [kg CO2] from the analyzed production systems and the total climate impact's percentual parts.

	Nursery		Cultivation		Harvesting		Total
Langlois et al.	21.65	43 %	27.97	56 %	0.75	1 %	50.38
Aitken et al.	13.29	50 %	11.63	44 %	1.62	6 %	26.54
Taelman et al. (IR)	4.56	8 %	47.42	84 %	4.52	8 %	56.50
Taelman et al. (FR)	6.61	31 %	14.35	67 %	0.58	2 %	21.54
Seghetta et al.	10.52	12 %	70.62	84 %	3.18	4 %	84.32
Thomas et al.	13.36	29 %	30.00	65 %	2.49	6 %	45.85
Mean	**11.67**	**25 %**	**33.67**	**71 %**	**2.19**	**5 %**	**47.52**
SD / σ	**5.52**	**-**	**20.24**	**-**	**1.38**	**-**	**20.66**

4.3.2 Freshwater Eutrophication Impact

A comparison between the six recalculated production systems' freshwater eutrophication impacts can be seen in *Figure 6*, while the life cycle impacts on freshwater eutrophication and their percentual parts can be seen in *Table 7*. The total freshwater eutrophication impact was between 5.50E-03 – 2.25E-02 kg P per functional unit, with the mean value being 1.48E-02 kg P and the standard deviation of the total freshwater eutrophication impact being 6.21E-03 kg P.

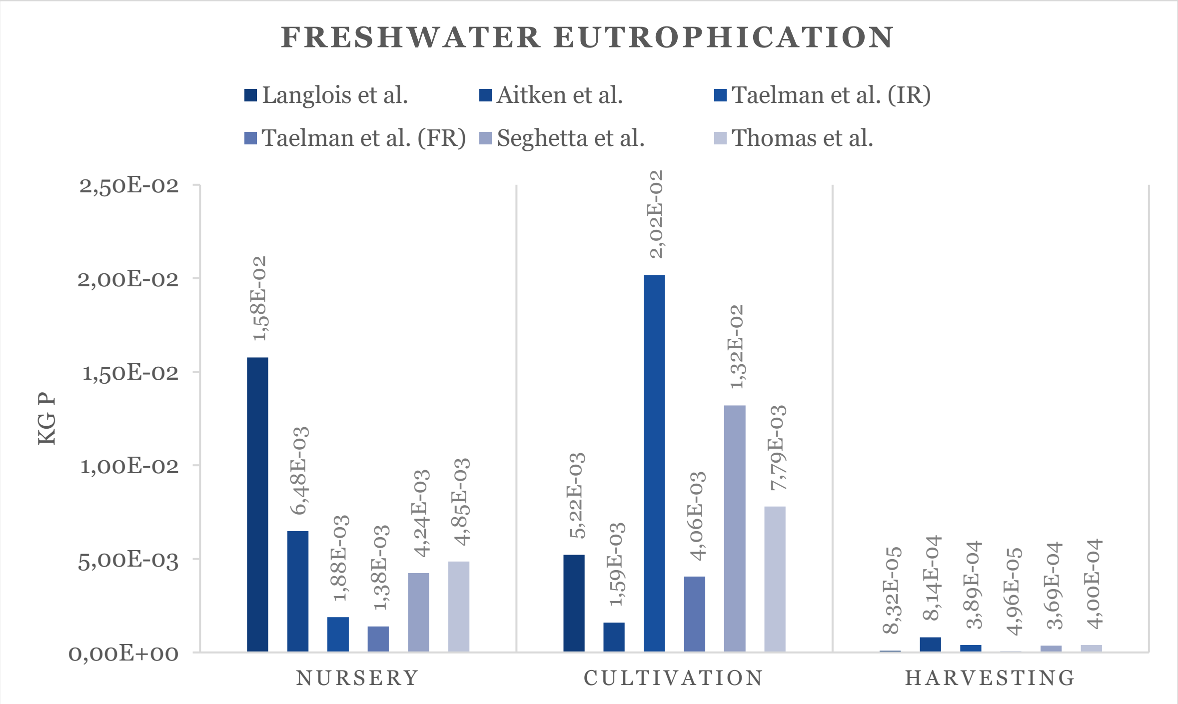

***Figure 6.** The recalculated freshwater eutrophication impact [kg P] during the different life cycle stages.*

The life cycle stage with the most impact on freshwater eutrophication in almost all the production systems can be assumed to be the cultivation stage with a mean percentage of 59 % of the total impacts, the nursery stage following with a mean percentage of 39 %. In contrast, the harvesting stage has almost no significant impact on this environmental impact category.

Table 7. The recalculated freshwater impact [kg P] from the analyzed production systems and the percentual parts of the freshwater eutrophication total impacts.

	Nursery		Cultivation		Harvesting		Total
Langlois et al.	1.58E-02	75 %	5.22E-03	25 %	8.32E-05	0 %	2.11E-02
Aitken et al.	6.48E-03	73 %	1.59E-03	18 %	8.14E-04	9 %	8.89E-03
Taelman et al. (IR)	1.88E-03	8 %	2.02E-02	90 %	3.89E-04	2 %	2.25E-02
Taelman et al. (FR)	1.38E-03	25 %	4.06E-03	74 %	4.96E-05	1 %	5.50E-03
Seghetta et al.	4.24E-03	24 %	1.32E-02	74 %	3.69E-04	2 %	1.78E-02
Thomas et al.	4.85E-03	37 %	7.79E-03	60 %	4.00E-04	3 %	1.30E-02
Mean	**5.77E-03**	**39 %**	**8.68E-03**	**59 %**	**3.51E-04**	**2 %**	**1.48E-02**
SD / σ	**4.80E-03**	**-**	**6.29E-03**	**-**	**2.52E-04**	**-**	**6.21E-03**

4.3.3 Marine Eutrophication Impact

A comparison between the impact of the system on marine eutrophication can be seen in *Figure 7*, while the life cycle impacts on marine eutrophication and their percentual parts can be seen in *Table 8*. The total marine eutrophication impact was between 2.09E-03 – 6.85E-03 kg N per functional unit, the mean value was 4.10E-03 kg N, and the standard deviation of the total impact 1.74E-03 kg N.

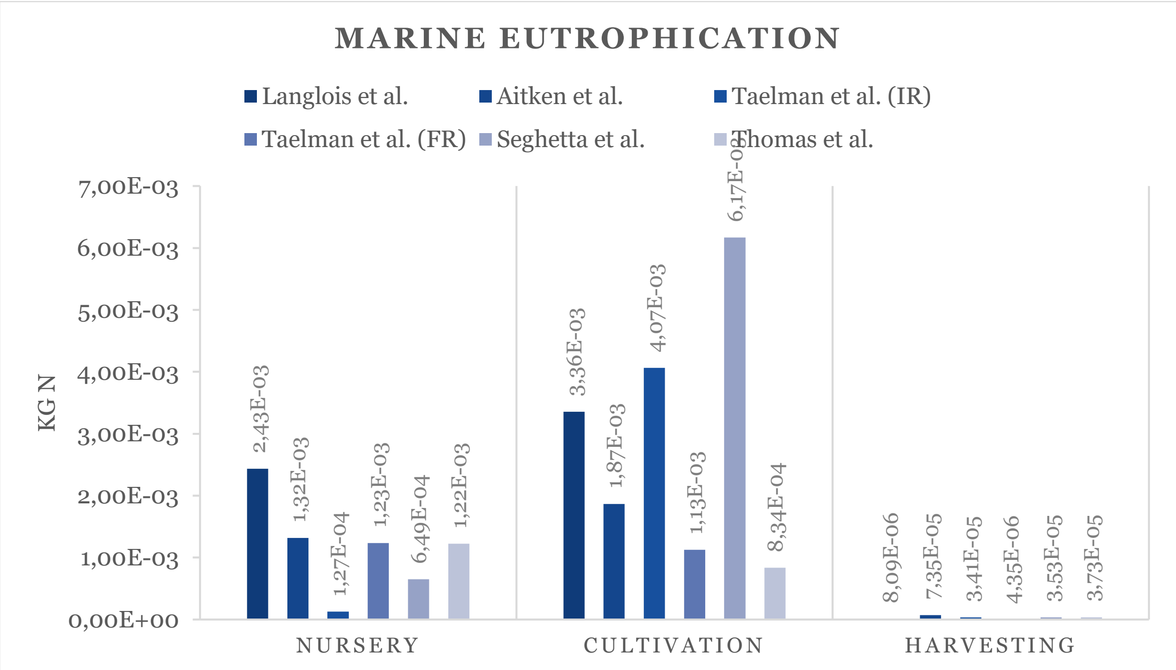

***Figure 7.** The recalculated marine eutrophication impact [kg N] during the different life cycle stages.*

The life cycle stage with the most impact on marine eutrophication can be assumed to be the cultivation stage, with a mean percentage of 71 %. The nursery stage will have a mean value of almost a third of the total impact with a mean value of 28 %, while the harvesting stage has almost no significant impact on this environmental impact category.

Table 8. The recalculated marine impact [kg N] from the analyzed reports and the percentual parts of the marine eutrophication total impact.

	Nursery		Cultivation		Harvesting		Total
Langlois et al.	2.43E-03	42 %	3.36E-03	58 %	8.09E-06	0 %	5.80E-03
Aitken et al.	1.32E-03	41 %	1.87E-03	57 %	7.35E-05	2 %	3.26E-03
Taelman et al. (IR)	1.27E-04	3 %	4.07E-03	96 %	3.41E-05	1 %	4.23E-03
Taelman et al. (FR)	1.23E-03	52 %	1.13E-03	48 %	4.35E-06	0 %	2.36E-03
Seghetta et al.	6.49E-04	9 %	6.17E-03	90 %	3.53E-05	1 %	6.85E-03
Thomas et al.	1.22E-03	58 %	8.34E-04	40 %	3.73E-05	2 %	2.09E-03
Mean	**1.16E-03**	**28 %**	**2.90E-03**	**71 %**	**3.21E-05**	**1 %**	**4.10E-03**
SD / σ	**7.05E-04**	**-**	**1.86E-03**	**-**	**2.28E-05**	**-**	**1.74E-03**

4.4 Material and Electricity impacts

The variations in the environmental impacts were anticipated, especially when reviewing and summarizing the material and energy inputs with the same functional units. The six system inventories varied in quantities and material inputs, and the significant inputs could be condensed to be electricity, plastics, concrete, metals, and transportation (*Tab. 9*).

Table 9. The recalculated material inputs from the analyzed systems to the same functional units.

	Electricity [Wh]	Plastics [kg]	Concrete [kg]	Metals [kg]	Transport [tkm]
Langlois et al.	33 262.10	3.67	48.87	1.36	15.65
Aitken et al.	11 190.09	1.83	8.11	0.37	- *
Taelman et al. (IR)	6 411.48	3.96	0.97	15.21	- *
Taelman et al. (FR)	7 606.43	3.87	7.65	1.45	- *
Seghetta et al.	2 340	13.68	41.50	9.27	60.83
Thomas et al.	25 222.22	28.18	72.20	2.70	26.62

* applied a different unit for transport.

The electricity in the reports varies on the area at hand, and the specificity of the input data in the reports are differing. The various kinds of electricity mixes used in this comparison are European scale (RER) and specific country-mixes (Chilean, Irish, French, Danish, and Swedish). The electricity input quantities vary, ranging between 2 340 Wh in Seghetta et al. to 33 262.10 Wh as input in Langlois et al.

The plastic inputs include polypropylene, polyester, polyvinylchloride, and polyethylene terephthalate. The plastics can be found in various objects in all three life cycle stages, and common inventory items include ropes, buckets, and buoys. The plastics quantities range from 1.83 kg in Aitken et al. to 28.18 kg in Thomas et al. The significant material impact named concrete includes the concrete and cement found in the inventories. These are mainly anchor blocks, and the inputs range from 0.97 kg in Taelman et al. (IR) to 72.20 kg in Thomas et al. The metals used in the inputs are steel, aluminum, and iron, which are found mainly as chains or shackles in the cultivation stage. The total inputs of metals range from 0.37 kg metal in Aitken et al. to 15.21 kg in Taelman et al. in the cultivation site in Ireland. Transport is the boat usage.

Since the reports have various material and electricity input quantities and various choices of specific materials and electricity mixes, the impacts translated to the environmental impacts are also portrayed in relation to their system's total environmental impacts and the percentages. This is shown in the following subcategories and is divided into the three key environmental impact categories.

4.4.1 Global Warming Impact

The most significant contributor to the global warming impact category can be assessed as the plastics used (*Fig. 8)*. Plastics are the most significant contributor in five of the six production systems. Electricity is generally the second most significant contributor; however, it depends on the analyzed system. The higher electricity input quantities in Langlois et al., Aitken et al., and Thomas et al., as seen in Table X., are shown to have an essential contribution to their total global warming impacts. In contrast, with a lower quantity, the other production systems almost show an insignificant impact on the global warming category. Concrete and transportation are commonly the smallest percentages of the total global warming impacts, with less than 10 % in four respectively five of the six production systems.

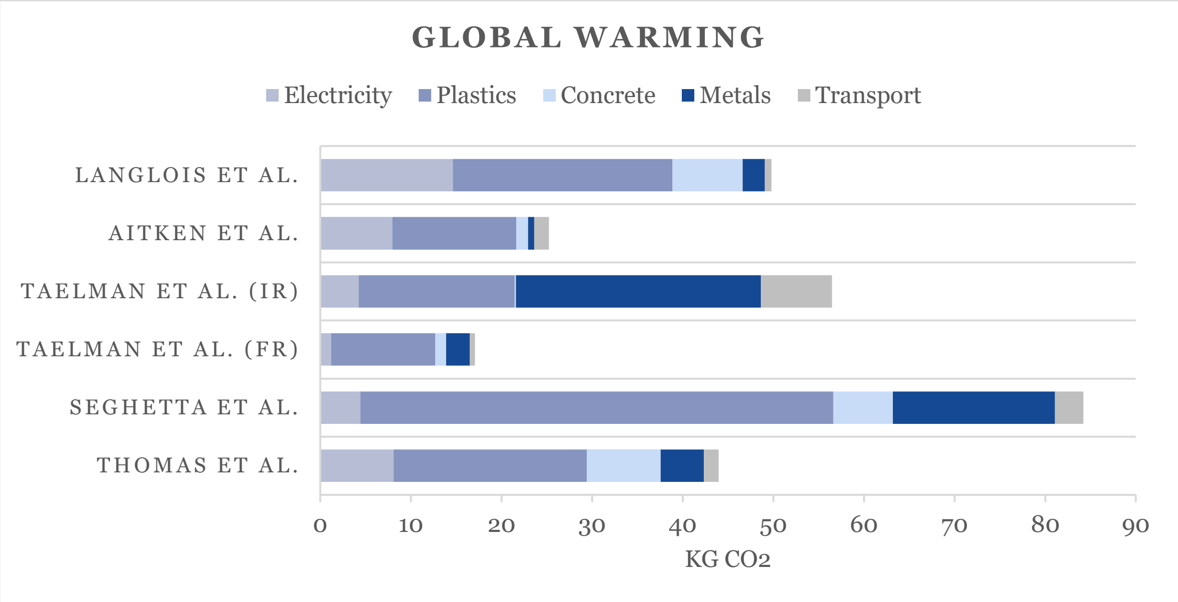

Figure 8. *The global warming impact assessment by the contributors in kg CO2 per production system.*

4.4.2 Freshwater Eutrophication Impact

The contributors to freshwater eutrophication are even more varied than the contributors to the global warming impact (*Fig. 9*). Aitken et al. and Langlois et al. both show a higher impact from the electricity inputs than the other reports, 66 % respectively 72 %. The other systems show a higher impact from the plastic inputs and the metals in both production systems from Taelman et al. The concrete and transportation inputs have less than 10 % of the total impacts in all the systems.

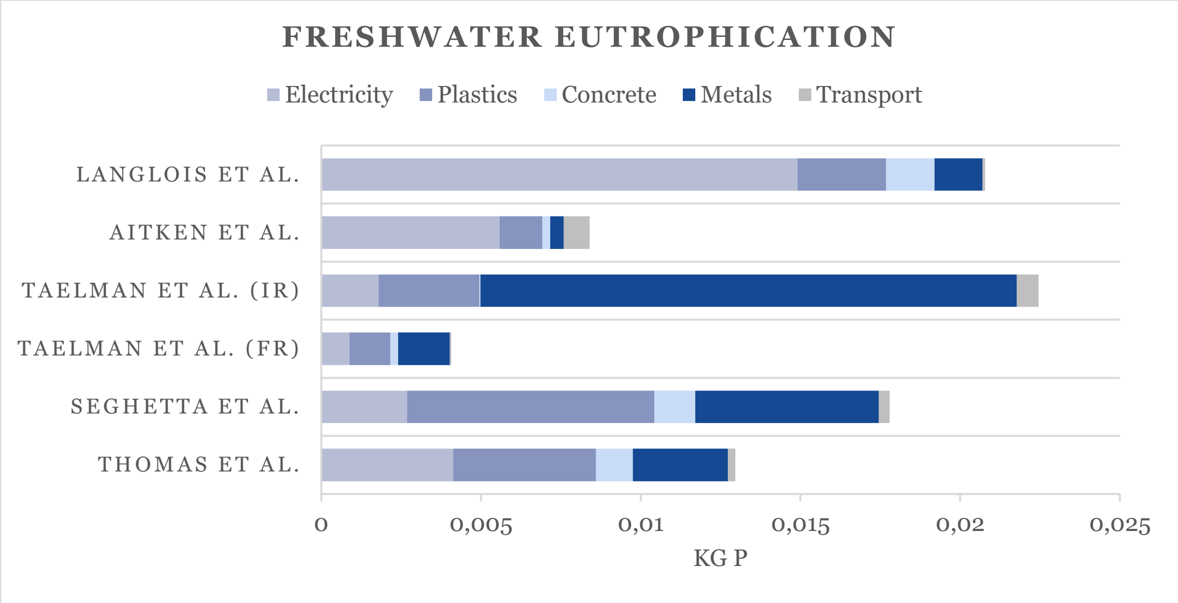

Figure 9. *The freshwater eutrophication impact assessment by the contributors in kg P per production system.*

4.4.3 Marine Eutrophication Impact

The most significant contributor to marine eutrophication is the plastics used in all six systems (*Fig. 10*). The plastics impact on marine eutrophication ranges from 47% to 85% per total impact. Thomas et al., Taelman et al. (IR), and Langlois et al. are the most varied in relation to the other reports, with electricity also having a significant impact 28 % in Thomas et al. and 19 % in Langlois et al., as well as the metals used in Taelman et al. (IR) with an impact of 40 %.

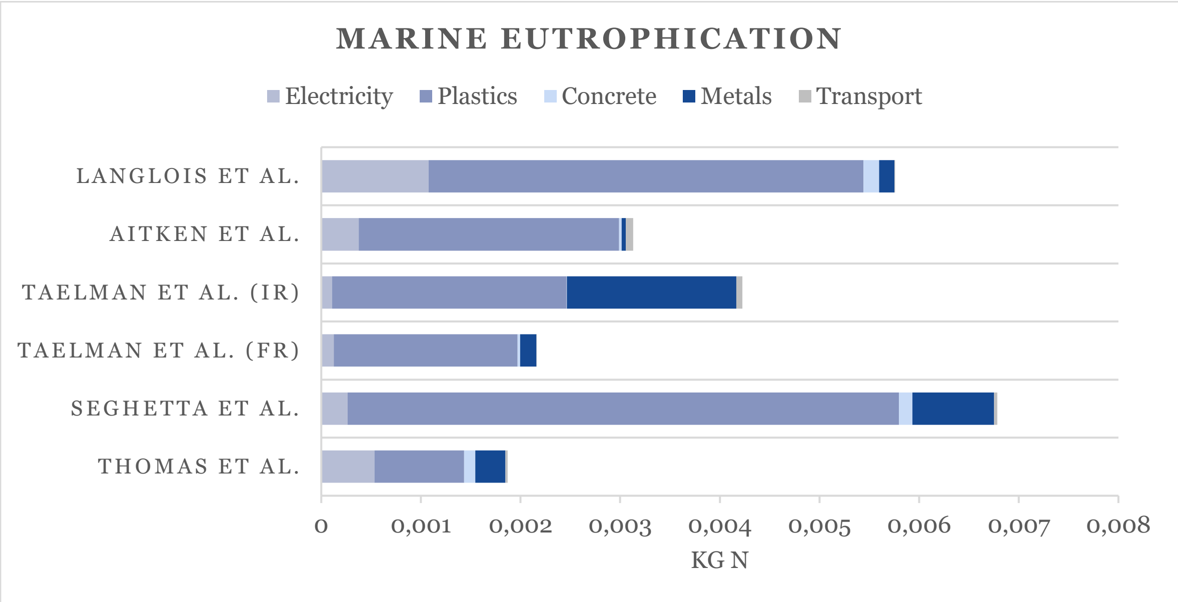

Figure 10. *The marine eutrophication impact assessment by the contributors in kg N per production system.*

4.4.4 Main input contributors

The key assumptions from the material and electricity impacts are that plastic and electricity are the main contributors to seaweed production systems. The electricity and the components using electricity are only found in the nursery stage on land; while most plastics can be found in the cultivation stage, some in the nursery stage. The third most significant contributor would be the metals used during cultivation, and these mainly have a significant contribution to the freshwater eutrophication impacts.

The impacts can generally be translated to the quantities of the inputs to the system; however, depending on the specific input, the impacts vary in the chosen environmental impact category.

4.5 Sensitivity Analysis

A sensitivity analysis was performed to assess the input data's reliability, and this was made mainly regarding the electricity mixes and cultivation systems.

4.5.1 Global electricity mix

A sensitivity analysis of the electricity inputs has been performed regarding the varying electricity mixes in the inventories. The results in the nursery stage with the different electricity mixes have been tried against a common electricity input, the global electricity mix (*Fig. 11*).

With the common global electricity mix, all six reports have a higher global warming impact; the mean value of this stage impact is 54 % higher than the original mean value; however, the standard deviation is only 4 % higher. The assumption of this is that the nursery stage will have a more uniform global warming impact in relation to each other. In the other two environmental impact categories are two reports reducing their impacts, Langlois et al. and Aitken et al., which decreases the impact of freshwater and marine eutrophication. The mean value of the total freshwater eutrophication is decreased by 16 %; still, the standard deviation is 47 % higher. The mean value of marine eutrophication impact with the common electricity mix increases 9 %, but the standard deviation is decreased by 4 %.

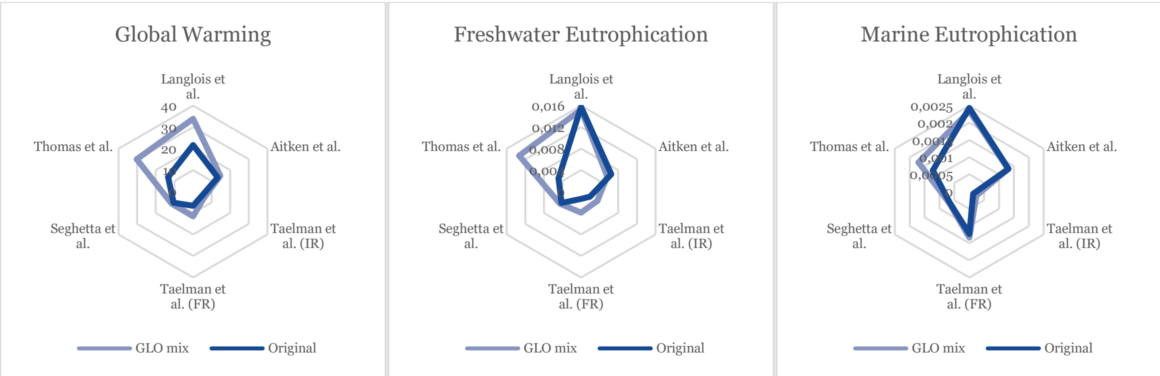

Figure 11. *The results of the nursery stage total impact in the three environmental impact categories, shown as a comparison between the original electricity mixes to the standard global electricity mix.*

4.5.2 Edited cultivation system

The impact of the cultivation systems is shown to be varied in the results and could be because of the different plastics inputs that are chosen. Therefore, a sensitivity analysis was performed with a standard cultivation system encompassing polyethylene buoys, steel chains, and polypropylene long-lines (*Fig. 12*). The quantity inputs were not changed, only the chosen plastic types.

With the edited cultivation systems is the global warming and marine eutrophication impacts lowered for all the systems. The freshwater eutrophication is reduced for all systems except for Seghetta et al. The global warming mean impact value decreases by 24 % with the edited cultivation system, while the standard deviation is decreased by 54 %. The freshwater eutrophication mean value was increased by 5 %, and the standard deviation was increased by 1 % and is therefore not assumed to be affected by the different plastics materials. However, marine eutrophication is significantly affected, and the mean impact value is lessened by 70 %, and the standard deviation is lessened by 65 %.

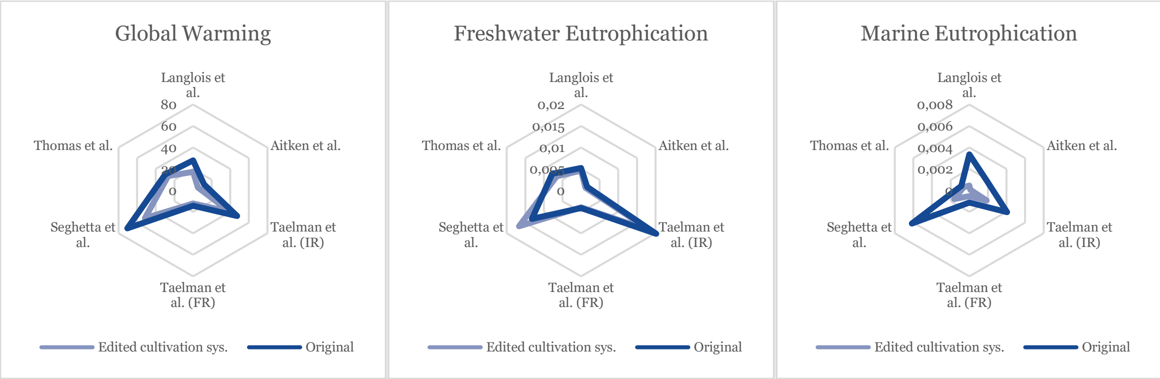

Figure 12. *The results of the cultivation stage total impact in the three environmental impact categories, shown as a comparison between the original cultivation systems to the edited common plastic choices.*

5 Discussion

This section presents the discussion, where factors that affect the results are mentioned, limitations and uncertainties are stated and deliberated, and further research is suggested.

5.1 Main environmental impacts of seaweed production

The main conclusion from the recalculated results is that the total environmental impact of seaweed production is differentiating between these six systems, even with the same functional units and with the completed sensitivity assessments. This can be explained by several factors, which are discussed in *5.2 Factors to consider*. However, some general assumptions can be drawn from the recalculated results; for example, the life cycle stage with the highest environmental impacts through all the environmental impacts categories is commonly the cultivation phase. This can be explained to the usage of plastics in long lines, ropes, buoys, and in some cases also because of the metals used. Both plastics and metals have a high impact on all three environmental impact categories, and considering the amount used in the systems, the high percentage in relation to the systems not unexpected. The nursery stage, the second most impactful life cycle stage, is primarily influenced by the electricity used and plastics. The electricity mix will significantly impact how influential the used electricity will be to the system; different countries have various sources of electricity production, hence impacting the environmental categories in different amounts.

Another important note is that the bio-extraction and bioremediation of carbon and nutrients is, as explained in *4.3 Hotspots in the life cycle stages,* seen as positive impacts from the system. The uptake of carbon and nutrients is similar between the reports, but again, varying in quantities. The bio-extraction of carbon can be seen as more than 100 % of the system's global warming impact in Aitken et al. and Taelman et al. (FR), while the rest of the systems are between 44 – 76 % of their own total global warming impact. These differences might be depended on the biomass qualities as described by the system, as well as the productivity of the system. The positive effects on freshwater and marine eutrophication are seen as over 100 % in all six systems. These differences in both carbon and nutrient content can be because the uptake can vary between different locations and between years. Also, depending on the time of harvest during the year, different months can yield various quantities in carbon and nutrient uptake.

5.2 Factors to consider

In the following sections, four factors possibly affecting the results are discussed: data collection, the content of the inventories, the production systems design, and the productivity and biomass yield.

5.2.1 Data collection and resources

The data gathering and resources used for the six different inventories will significantly influence the credibility and reliability of the results found in this thesis. The different authors have presented where and how they have collected their inventory data, and the trustworthiness of the report's inventories can depend on if they have used primary and secondary data resources (Hunt et al., 1998). The choice of resource will affect the inputs, the material choice, and the quantity, which affects the environmental impact. As mentioned in *3.1 Reviewed published reports*, the data is mainly found in pilot-study sites; however, some literature resources are also mentioned, especially when data is lacking. Literature-based inventory data can be unreliable and generate inaccurate results, but that depends significantly on the collected literature data (Hox and Boeije, 2005). The most reliable data will be collected and quantified from pilot sites by the author at hand (Heaton, 2003). Data gathering by distant communication might miss some vital information. The data collected is, in addition, not always presented as calculations, which in turn creates unreliability in the inventories. Only in Aitken et al. are the calculations presented as supplementary material.

The data collection and resources used are relevant factors to discuss in some of the studies where the reliability of the data can be seen to be lacking. Seghetta et al. has collected the cultivation data from pilot cultivation sites in Limfjorden, Denmark; however, the nursery stage data is literature-based. The high impact of the cultivation stage in relation to the nursery stage in Seghetta et al. might result from less specified data inputs in the nursery stage. The small electricity input quantity might be a consequence of this, whereas the five other systems show higher input quantities. Langlois et al. and Aitken et al. have both described that they had communicated with seaweed farmers and collected their data from them. Still, it is not clear how the data was collected, which might influence the results. As previously stated, some information might get missed in distant communication.

5.2.2 Inventory content

All reports differ significantly regarding their inventories and the content within these. The structure of the inventories also varies, either being very thorough and transparent with all the input and quantities, or they are more unspecific and not mentioning, e.g., the choice of material in Ecoinvent. The content within the inventories is also varied, where inventory items might be included in one inventory but not in another one. Examples of this are the use of autoclaves, buckets, and harvesting bags. Such differences in inventory items might suggest that the production systems are different and placed in different locations; however, it can also create a doubt that the inventory might be missing an item since the other inventories are more thorough and detailed.

Choice of Material

Variations in the choice of materials, mainly in terms of choice of plastic, are found in all the compared inventories. Many types of plastic are used, e.g., polypropylene, polyester, polyvinylchloride, polyethylene terephthalate, and the environmental impacts of these differ entirely. The choice of plastic will consequently create massive differences in the environmental impacts for the different systems even though they might have similar input quantities, as e.g., Langlois et al. and Taelman et al. (both IR and FR) have. The choice of material for the authors and this thesis recalculations depended on the availability of the correct material in Ecoinvent. It might also have been dependent on the author's knowledge, e.g., about the different kinds of plastics or the production system.

The most striking inventory differences are regarding Seghetta et al., and Taelman et al. Seghetta et al. is the only inventory including iron, which is noteworthy. The iron in this inventory is used as iron bars and as screw anchors in the cultivation phase, which most likely is deployed in the water. This might not be the ideal material for submersion because of its high vulnerability to oxidation, causing rust, decreasing the material's lifespan. In Taelman et al. (both IR and FR), all material inputs are missing entirely from the inventory, only mentioning the inventory item used, which creates uncertainty in the results presented in this thesis. These two inventories' materials were therefore presumed based on the materials that the other systems used.

Lifespan and quantities

Another critical aspect of the inventories is that the quantities of the input materials are affected by the evaluated and assessed lifespan. Again, the reports vary in specificity when describing the chosen lifetime assessments of the materials, both in the reports and supplementary material. For example, neither Langlois et al. nor Taelman et al. has specified whether the lifespan assessment has been included in the input quantities; however, an assumption was made that it was included and might result from these two systems being untruthful. The different lifespan assessments can generate vast differences in the environmental impacts of said material. Additionally, the same material in different locations or with different functions might not have the same lifetime. The material, or systems, various surroundings might create different strains to the material, and even though it is the same material, the setting might make a lifespan difference.

An important note regarding the quantities in the production systems is that the compared reports have been extrapolated to match the functional unit. This means that the input quantities in the production systems have been multiplied to create the yield of 1000 kg wet weight of seaweed. Therefore, an assumption is made that the seaweed production is linear, which might not be the case. The extrapolation of data from pilot-scale to more extensive production systems can create unavoidable inaccuracies and should be handled sensibly (Aitken et al., 2014). Seghetta et al., which was calculating an area of 208 km^2, might be a victim of extrapolation inaccuracies because of the great total environmental impact compared to the other reports.

5.2.3 Production systems

Even though all the compared systems have been recalculated with the same system boundaries and methods, variations and differences in the production system design and location are most likely to affect the results. A point worth mentioning is that all reports have cultivated *Saccharina Latissima*, except the report by Aitken et al., which focused on *Macrocystis Pyrifera,* which might explain some differences between Aitken et al. and the other reports. The different designs of the production systems can be a consequence of the location selected for the cultivation stage. Depending on if the cultivation occurs in the open ocean, with strong currents and storms often occurring, or in a more sheltered area, various systems might be designed to provide different degrees of the system's robustness. However, not all systems have specified the location of the cultivation system. Seghetta et al. are one report with specified locations, and these locations are unprotected from currents and storms. The high impact of the cultivation stage in Seghetta et al. could therefore be explained by the chosen material inputs as seen in *Table 3.*, which might be chosen for a sturdier cultivation system and provide higher environmental impacts.

Considerable differences in the various production systems can be found in the nursery stage. For instance, the plantlet production in Langlois et al. is found in cement ponds, while the more common method is in culture tanks, as described in the other reports. The high environmental impact in Langlois et al. might be explained by this great amount of concrete needed for the ponds. The seeding methods of juveniles onto seeding lines might differ; not all the reports have specified the method used.

The cultivation stage at sea also differs between the systems – with the length in long-lines varying between 50 – 280 m, at a depth of between 0.5 – 2 m. The number of buoys and anchors to stabilize the system also varies. Even though these inputs have been modified through the recalculations to the same functional units, the cultivation systems have different layouts to begin with, which affects the system's environmental impact. Taelman et al. (FR) have a similar cultivation system as the other, but it exists as a raft system instead of a long-line system because of the many currents at the site. This could explain the considerable differences in the total environmental impact of this system compared to the other reports. As seen in *Figure 3*. in *4.2 Total Environmental Impacts* are Taelman et al. (FR) and Aitken et al., the two systems with the most varied total impacts, which might be because of the production systems and species cultivated.

5.2.4 Productivity and biomass yield

The functional unit within the report relies on the cultivation system's productivity, which is an essential factor of this recalculation that needs to be considered. The productivity, in this case, is measured in kg biomass collected per meter long-line. The system's productivity is a factor in how big the scale of the system needs to be, hence affecting all the input quantities. The productivity in these systems is usually an average value, recognizing the differences in production volume depending on the season and year. Also, factors as storms, general weather, disease, and variations in the nursery stage will create variability in the cultivation yield.

The systems that have studied long-line production of *Saccharina Latissima* have based their inventories on a similar productivity value ranging from 8.95 to 10 kg ww/m long-line. Only Taelman et al. (IR) have a higher estimate, 25 kg ww/m. Taelman et al. (FR) studied the same species, but used a raft system, used a productivity value of 5 kg ww/m because of the created friction of culture ropes with buoys and tubes. Aitken et al. studied Macrocystis Pyrifera, which used a maximum yield of 25 kg ww/m long-line and a minimum yield of 22 kg ww/m. These high amounts can be both because of Chile's location and the species analyzed. Harvesting locations will be a factor here, including being, for example, lengths of the days, temperatures, currents, and nutrient levels. Ranges in yields and production values can also be due to the different harvest times. The chosen months for cultivation, growth, and harvest will factor in the final yield and productivity value. This is mentioned in some of the analyzed reports, but not all reports have stated the months for the production.

These varying productivity and biomass yields are relevant and affect the recalculation. Some aspects to mention can therefore be important. Firstly, the resource of the productivity value is vital since the productivity of the system is connected to the environmental impacts. Therefore, if the systems yield is based on the same case study or pilot study, some verification confirms the results. However, if the biomass yields are based on literature, will the productivity not be connected to the inventory, creating a lack of certainty in the results. In addition, in this case, literature resources are lacking because of the limited numbers of existing pilot-scale production sites, and consequently, not much data exists for confirmation of productivity amounts. Secondly, the biomass yields are worth reviewing because the results connected to the yields can be twofold. Either can the system's environmental impact be lessened because of the calculations of high biomass productivity in the system, impacting the functional unit. A seaweed production system with a higher yield will need less input quantity. Alternatively, because of the system's sturdiness at hand, both materials and quantities, the higher yield might occur and result in a higher environmental impact.

5.3 Limitations and uncertainties

As discussed in *5.2 Factors to consider*, recalculation of the inventories for a fair comparison has many factors that will affect the results in various ways. Additionally, there are generally limitations and uncertainties to recalculating that should be noted and discussed.

One main limitation in this thesis has been the lack of reports available for comparison. The choice of system boundaries, the production system, and species choice were the main factors when finding reports to compare. Among the reports that could be recalculated, many reports lacked a clear inventory for recalculation. Possibly due to the size restriction of published reports, the inventories have been excluded in the final versions, making a recreation of an LCA impossible without many assumptions and speculations. Additionally, the compared reports often had a different aim than calculating the environmental impact of the seaweed production system, primarily regarding biofuel production. This can suggest that the explanation of the seaweed production systems and the input calculations was not the focus of the reports; hence, the lack of specificity in the six LCIs and their methods might have impacted the results in this recalculation.

As mentioned in *5.2.2 The Inventories content* was the inventories varying in specificity and clarity, which was a significant limitation for recreating the LCAs. Also, some of the inputs were limitations in themselves, particularly the electrical components and the transportation by boat. Because this was a recreation of their LCA, relying on the specificity and details in the five reports was an essential part of what inputs got chosen in this thesis. If no explanation or Ecoinvent input data existed in the report, assumptions had to be made. This was, as mentioned, mainly regarding the electrical components such as lamps, aquarium filters, autoclaves, and the boat used for transportation.

5.4 LCA as a reproducible research method

As assessed in this discussion, many obstacles and limitations to recreating LCAs exist and essential factors in analyzing recalculated results. As stated in the theoretical background, LCAs of the same product and different authors create different outcomes as in the diaper wars. This thesis showed that a recalculation with the same method and functional unit created different environmental impact results.

Science, by definition, should be able to be replicated, and if obtaining the same results is the end goal of replication, then the study should be reproducible (Ioannidis, 2005). LCA is a method that, if replicated, should generate the same results hence a reproducible research method should be performed. The most crucial part of achieving reproducibility in research is fully transparent data and methods (Kühne and Liehr, 2009). The lack of transparency and completeness in reporting of methods, data, and analysis is part of the reproducibility crisis debated through the last decades (Fidler and Wilcox, 2018). As mentioned in the theoretical background, LCA is a tool that can easily be portrayed as the truth, especially for companies and government assessments, even though it is modified to suit the aim of the LCA practitioner or the financier. LCA is supposed to give environmental impacts on the entire life cycle chain and can therefore be used to measure and improve the production of a product and communicate said results (Friedberg, 2013). However, because of lacking to capture the complexity of a product’s life and transparency, even the same products might get different outcomes.

During the analysis of these five reports in this thesis, many assumptions had to be made because of the lack of data in the original studies, which naturally affects the results of this study and the comparison between the six systems. LCA can hence be questioned as a well-established method for calculating environmental impacts, mainly depending on the practitioners’ bias and thoroughness. Transparency and trust in the LCA are gained through the inventories by clearly stating the inventory input, the material choice, and the calculations of the input quantity. If one of these is lacking, a replication and recreation of LCI will be more challenging to do, especially since additional assumptions must be made.

5.5 Further research and suggestion

For a more detailed picture of brown seaweed cultivation, could additional life cycle assessments be analyzed. More reports might enhance the results and illustrate more clearly why the results vary. The discussion points indicate that many factors could be the source of the differences, and additional reports could reveal that some factors are more important than others. Further research should, if possible, also include more life cycle stages. The drying stage was not included in this thesis because of lack of data; however, if there are life cycle assessments with, for example, more details regarding the drying stage, then that would be interesting to compare as well.

A general suggestion for all life cycle assessments being made is to be clear and transparent with the inventories and methods used. The replication and reproducibility of a project are essential to invoke trust and for gaining scientific validation. The reports analyzed in this thesis lacked data in several parts, making a recalculation without assumptions difficult.

Conclusion

This thesis concludes that the recalculation of the brown seaweed life cycle inventories has various total environmental impacts in the chosen impact categories – Global Warming Potential, Freshwater Eutrophication, and Marine Eutrophication. However, the recalculated results also showed that the life cycle stage with the most impact could be assumed to be the cultivation stage, and the major material impact within this stage is the plastics used. The six inventories do not present the same quantities of the life cycle stages or material impacts, and they vary in terms of the percentage of total impact to the system. Several factors might explain the differences between the analyzed reports. One major factor is the system design, which might depend on the type of brown seaweed species and the location for cultivation. Another factor is the resources used for the inventories and the specificity of the inventories and data used. Overall, the transparency and detailedness of the life cycle assessments inventories lack and the method descriptions. Recalculations, or replications, are necessary for scientific validation, which this thesis found to be difficult without numerous assumptions.

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