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Life Cycle Assessment of pilot scale production of seaweed-based bioplastic

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ABSTRACT

The use of seaweed as a bioresource for plastic production is gaining momentum. However, the environmental impacts of the production of this novel bioplastic are still unknown. In this research, we assess the environmental impacts of the production of a bioplastic film at an experimental pilot scale using Life Cycle Assessment (LCA). The system boundaries chosen for this analysis include seaweed cultivation accounting for its carbon uptake, alginate extraction, production of bioplastic film at the pilot scale and different end-of-life pathways. The recirculation of different seaweed co-products from the alginate extraction step into the bioplastic film production is also assessed using scenario modelling and the analysis is completed with a carbon balance and an uncertainty analysis. The results show the main hotspot at the pilot scale is the last step in the production, *film fabrication*, mainly due to the glycerol in this process. The results also vary significantly depending on the end-of-life of the bioplastic, composting reduces the impacts by 30 % compared to incineration.

1. Introduction

Plastic is a widely used material due to its versatility, durability, resistance and low price [1]. However, conventional plastics are made from non-renewable sources and they threaten marine environments [2–5]. Bioplastics could potentially represent a solution to these problems but first- and second-generation bioplastics produced from biomass have been shown to exert a substantial impact in terms of direct and indirect land-use change [6–9]. Instead, seaweed is considered a third-generation feedstock for bioplastics because there is no land use involved in its cultivation [10,11]. Furthermore, seaweed cultivation delivers regulating and supporting ecosystem services and habitat provisions, such as carbon and nutrient cycling. Hence potentially contributing to the reduction of eutrophication, ocean acidification and climate change, among other benefits [12–16].

While the term bioplastic is often ambiguous as it is used to refer to either bio-based and/or biodegradable plastic [17], in this article the term bioplastic is used to describe plastic that is both bio-based and biodegradable. The production of such bioplastic from seaweed has gained interest in recent years, even though there are still doubts regarding the potential of this technology to substitute, partly, the production of plastic from fossil sources [6,18]. As an emerging technology, it is important to identify at the early stages of technological development (i.e., at a pilot scale) the environmental hotspots of

seaweed-based bioplastic production and opportunities for optimising the design of this process before it is implemented at an industrial scale [19].

Recent studies investigate and discuss the potential use of seaweed as a bioresource for bioplastics. Rimundo [20] is among the first to investigate the use of alginate as possible material for food packaging and, more recently, Carina et al. [21] expand the state of the art on seaweed polysaccharides as food packaging material using not only alginate but also other polysaccharides extracted from brown, red and green seaweed. Pacheco et al., Zhang et al. and Zanchetta et al. [17,22,23] describe the general status of seaweed polymers and their properties to produce different plastic types. Shravya et al. and Lim et al. [24,25] review the processes to extract seaweed polymers for use in bioplastic production. Some studies perform an experimental study on the production of seaweed-based plastics. Albertos et al. [26], for instance, complete an experimental production of edible films using brown and red seaweed, and Aragão et al. and Lim et al. [27,28] bioplastic using alginate in brown seaweed. While these studies review different seaweed-based plastic types, they mainly focus on the physical properties and the potential methods to produce seaweed-based plastics, some of them using experimental data, but do not assess quantitatively the environmental impacts of the production and end-of-life (EoL) of those seaweed-based plastics.

Instead, Helmes et al. [29] perform an LCA study of a seaweed-based

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plastic where they study the production of lactic acid (PLA) from the green seaweed *Ulva* spp. and show that the main impacts of producing 1 kg of purified lactic acid are the result of using electricity during land-based seaweed cultivation. There are then other studies that perform an LCA of the cultivation of the brown seaweed *Saccharina latissima* [30] and drying [31], as well as seaweed cultivation and processing of this seaweed specie to produce biofuels [32–34] and highlight that the main hotspots are seaweed processing, and fuel and drying respectively. Nonetheless, according to van den Burg et al. [35], the use of *Saccharina latissima* to produce bioplastics has not been documented yet.

Some LCA studies of algae-based bioplastic do not include the entire life cycle of the bioproduct but only consider cradle-to-gate [34,36]. It is important to account for the emission from the EoL to fully assess the impacts of the product and avoid misleading conclusions. For example, as the carbon accumulated in seaweed-based bioplastic is released in the EoL, excluding the EoL from the LCA study can erroneously display the bioproduct as a net carbon sink if only the carbon uptake is accounted for. It is moreover important to explore different EoL scenarios, as how the bioplastic is processed after use can vary substantially depending on local conditions.

In summary, while the potentials of alginate-based plastic and seaweed cultivation have been respectively addressed in the literature, the environmental impacts of seaweed-based bioplastic over its entire life cycle remain uncertain. In this context, an LCA study is conducted using primarily experimental data from a lab- and pilot-scale alginate-based plastic production using the brown seaweed *Saccharina latissima*. A carbon balance is also performed to keep track of the carbon flows and ensure a representative carbon accounting over the entire life cycle. The LCA is complemented with an uncertainty analysis.

This assessment is conducted early in the technology development and should help to identify the hot spots already present at the pilot scale. The study aims to use the consequential approach to determine impacts that arise when demanding 1 kg of bioplastic produced from brown seaweed *Saccharina latissima*.

2. Methodology

2.1. Goal and scope of the LCA, system boundaries, and co-products

The consequential LCA was performed using SimaPro v9.2.0.2 and Brightway2 [37] with the ecoinvent v. 3.8 background database [38]. ReCiPe 2016 Midpoint (E) was used as the Life Cycle Impact Assessment method. SimaPro was used initially to calculate the impacts and Brightway2 to perform an uncertainty analysis. The functional unit (FU) is the production of 1 kg of bioplastic film. This bioplastic is a transparent, flexible and thin plastic film. The system under analysis (cf. Fig. 1) was modelled using a cradle-to-grave approach. The system boundaries included all the necessary processes to produce the bioplastic film, from the cultivation of the seaweed in off-shore farms, including the hatchery and CO₂ uptake of the seaweed during its growth in the sea, the seaweed biorefinery and film fabrication with plasticizers and the EoL treatment of the bioplastic. The recirculation of different co-products in the seaweed biorefinery step was assessed in five scenarios.

2.2. Life cycle inventory

The life cycle inventory (LCI) was completed using experimental data from a pilot-scale production from the PlastiSea project [39], where the project partners covered the entire supply chain: seaweed cultivation and harvesting, seaweed processing, acid wash and alkaline extraction, film fabrication at the lab- and pilot-scale.

The modelled location was Norway, where the seaweed was cultivated. It was further assumed that the bioplastic film was produced close to the seaweed farm, as there are numerous advantages to producing seaweed-based plastic in proximity to seaweed farms. The main advantage being reducing transportation costs: since the process to

produce this bioplastic uses wet seaweed, and given the high-water content of seaweed, the transportation costs of seaweed for this purpose are especially high [40]. The table with the LCI can be found in Supplementary material A.

2.2.1. Hatchery and offshore farm

Saccharina latissima is the seaweed used and its cultivation usually requires a hatchery or nursery step for seedling production. Seaweed spores are settled into ropes and incubated in tanks, which contain filtered seawater and a growing solution containing nutrients and pesticides to support their growth [41,42]. The nutrients consist of a solution called *West and McBride's Modified ES Medium*. The gametophytes grow into juvenile sporophytes for 4–6 weeks [43]. This process helps to ensure their later growth in the ocean. The result of the hatchery is small seaweeds attached to a rope that is later deployed into the ocean. With direct seeding, seeding the lines without the hatchery step, the yields are usually lower as the holdfast is often underdeveloped and they are more likely to get detached from the seeding ropes [37].

Once the seedlings are 1–2 cm long, the seeding lines are rolled around sturdy ropes and deployed into the sea in autumn [42]. The seaweed farm is organised in horizontal lines attached between buoys. The seaweeds grow for 6–7 months and are regularly monitored and checked. The length of the seaweed varies between 1 and 2 m depending on the harvesting time. At the beginning of the harvesting season, in April, seaweeds are around 1 m long and at the end of the harvesting season, in June, the seaweed can be up to 2 m long.

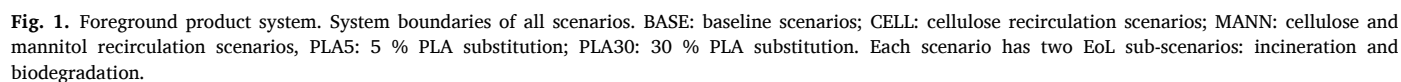
The seaweed farm is based on a mooring frame with its structural horizontal lines suspended at 3 m depth. It is a square shape of 440 m in length, divided into sectors of 110 m each, in water depths of approximately 10–30 m. The farm is located approximately 2 km east of Sistranda and Frøya Island, and 3 km from its land base. It is protected by a nearby Island in the south and partially protected on the east and northeast sites, allowing swell and wind waves to enter with estimated maximum heights of 2 m. The long lines connected to the mooring frame are stretched at a depth of 1.5–2 m, with a spacing of 15 m. The seeded substrate is connected horizontally between long lines with an average spacing of 1.5–2 m. There is annual planned maintenance of the farm structure between the harvest season and the deployments (July–August), and minor corrections are done throughout the year. Typically, aquaculture catamaran-type workboats are used for accessing the structural elements, as cranes are needed.

The LCI data from the hatchery and sea cultivation was taken from the reports of the GENIALG project [42,44] with minor modifications provided by the seaweed farmers involved in this project and updated processes from ecoinvent 3.8. This data included the materials to build and maintain the farm structure.

2.2.2. Seaweed biorefinery

This seaweed biorefinery aims to extract alginate, cellulose, mannitol, laminarin and fucoidan from *Saccharina latissima* and fresh seaweed is used for this purpose. In this research, alginate was considered the main product, and mannitol and cellulose were considered co-products. Laminarin, fucoidan and other seaweed compounds are potentially also extracted in this biorefinery process but are not used in this bioplastic film. The polysaccharide extraction is based on the method proposed by Wahlström [45], with some modifications. The insoluble fraction is sequentially treated with hydrogen peroxide (H₂O₂) and ethanol to extract high-quality cellulose. Ethanol is used to remove pigments and fatty acids [45].

The biorefinery starts with seaweed milling, followed by an acid step where hydrochloric acid (HCl, 0.2 M) is added. Laminarin, fucoidan and a mannitol-rich fraction are extracted in the acid and washing steps, which can have a high economic value and are important for economic viability [46]. The acid helps to break the cell wall structures and remove minerals such as calcium crosslinking the alginate within the biomass [47] and the washing, using tap water, helps to extract the



remaining laminarin, fucoidan and mannitol fractions. Depending on the time of harvest, mannitol can constitute up to 25 % of the seaweed's dry weight [48]. In this research, around 12 % of the dry weight was considered mannitol based on previous studies [49] and approximately 80 % of the mannitol was considered to be extracted in this biorefinery process. The process continues with an alkaline step to solubilise and extract alginate. The acid step, washing and alkaline treatment are carried out in a continuous stirred-tank reactor. The alkaline extraction starts by adding 0.2 M NaHCO₃. Centrifugation is the following step, which aims to separate the supernatant mixture and the seaweed residue [50,51], containing alginate and cellulose respectively. An alginate-rich crude extract is the main product and the seaweed residue is the co-product. The seaweed residue has a high cellulose content and two co-products could be obtained with the seaweed residue: cellulose and processed seaweed pellets. The cellulose is extracted using ethanol and H₂O₂ and the seaweed pellets are obtained by drying and milling the seaweed residue. A flow diagram illustrating the biorefinery process is presented in Supplementary material B.

2.2.3. Film fabrication

Alginate is water sensitive and would have limited applications as the sole component in a bioplastic on its own. A film compounding process is, therefore, recommended to lower the final film moisture sensitivity [52]. Three steps can be distinguished in the film fabrication process where different plasticizers and polymers are used to produce this transparent and flexible bioplastic: (1) compounding and homogenization, (2) casting and (3) crosslinking.

In the compounding and homogenization step, the alginate extracted in the biorefinery step is mixed with cellulose and glycerol, which are used as functional additives within the formulation. Glycerol is a widely used plasticizer with hydrophilic biopolymers [23], improving the mechanical properties of alginate-based plastic, such as water permeability and thermal resistance [53]. Cellulose is used as a reinforcing filler. Considering the mechanical properties of cellulose, strength properties with high stiffness and tensile strength, the cellulose nanofibers (CNF) can also be used to produce bioplastic film [54] without affecting its compostability [55]. The homogenization step is accomplished by using an Ultra-Turrax for mixing and a vacuum pump for degassing.

The casting step consists of pouring the homogeneous viscous mixture onto a flat surface. Due to the properties of the mix, the method used to cast the bioplastic at the pilot scale is an adapted cast film extrusion to allow the use of aqueous mixes instead of thermoplastics. The mix is dispensed in a liquid pump, and afterwards, the material is homogeneously distributed on the roll. However, at the pilot scale, an adapted cast extrusion machine is used: the homogeneous mixture is dosed using a liquid pump and the volume to be cast is controlled by a dye.

The crosslinking step included spraying a solution of calcium chloride (CaCl₂) onto the casted solution in order to improve the mechanical properties, moisture sensitivity and visual appearance of the bioplastic, including homogeneity and thickness [52,56]. Calcium ions in combination with glycerol are claimed to be an optimum combination to enhance the mechanical properties of the alginate-based bioplastic films to increase their water resistance and flexibility [53]. Finally, the film fabrication process is concluded by a drying step, in which the water content of the film is reduced to around 20–30 %.

2.2.4. End-of-life

Since the true end-of-life of the plastic is currently unknown and might differ depending on the location where the plastic is used and collected, two different EoL pathways were modelled: incineration and composting. Incineration was chosen because it is a realistic possible pathway e.g. in Nordic countries like Denmark and Norway. Composting was chosen because this novel bioplastic is biodegradable as confirmed by both qualitative (observational — soil-burial) and quantitative (screening — closed chamber bioreactor) laboratory tests carried out

within the consortium of the research project funding this study (data not yet published). Since this bioplastic is not recyclable with conventional plastics, a mechanical recycling EoL scenario was discarded.

Both EoL scenarios were modelled using the background data from ecoinvent and modifying the background data. The background process for the composting EoL was *Biowaste {CH} | treatment of biowaste, industrial composting | Conseq, U*. The electricity mix of the background process was modified to include the electricity mix in Norway instead of Switzerland.

For incineration we used the following process: *Waste polyethylene {CH} | treatment of, municipal incineration | Conseq, U*. It was considered that polyethylene had similar properties to this seaweed-based plastic when it comes to the incineration process. This process produces electricity and heat waste. In Norway energy from the incineration process is recovered, but the dataset in ecoinvent only provides the emissions and not the recovery heat and electricity. According to the dataset documentation, 5 MJ/kg and 10.02 MJ/kg are respectively the net waste of electric and thermal energy that can be recovered for burning polyethylene in a municipal solid waste incinerator [57]. Therefore, electricity and heat were modelled as avoided products in the incineration EoL.

2.3. Carbon balance

The carbon balance accounted for the carbon uptake in the seaweed cultivation process, the carbon content from the bioplastic film components and the EoL of the bio-based plastic. The carbon content of the compounds used in all the processes to produce the bioplastic plastic was accounted for, i.e. biorefinery and film fabrication. This carbon (C) content was calculated based on the measured mass and molecular weight of polymers (alginate, cellulose and glycerol) in the produced bio-based plastic at the lab and pilot scale biorefinery. The point of departure to calculate the carbon balance was 1 kg of carbon in the bioplastic film. The carbon content of alginate, glycerol and cellulose was calculated considering their molecular weight, the number of carbon molecules and the molecular weight in each molecule, and their proportion in the bioplastic. The carbon balance was calculated using a substance flow analysis approach [58]. The carbon flows in the EoL were calculated assuming the oxidation/combustion of the polymers in 1 kg of bioplastic. The biogenic carbon was maintained separately, i.e. the carbon from the alginate, mannitol and glycerol from the seaweed, and the fossil carbon, i.e. carbon of glycerol and cellulose added in the crosslinking step not derived from the seaweed.

The carbon balance was calculated for the first three scenarios later explained (cf. [Scenario analysis](#) section). A detailed explanation of how the carbon balance was accounted for can be found in Supplementary material C.

2.4. Scenario analysis

A scenario analysis was developed to assess the circulatory of cellulose and mannitol in the seaweed biorefinery processes to be later used in the film fabrication step. Cellulose and mannitol are seaweed co-products which were originally modelled as waste diluted in the water and acid waste. Scenarios were developed with the recirculation of each co-product, mannitol and cellulose. The following figure ([Fig. 1](#)) represents the system boundaries of all the scenarios.

All the modelled scenarios included the seaweed hatchery, offshore cultivation farm, biorefinery, film fabrication and two end-of-life scenarios. The baseline scenario (BASE) was modelled simply considering the production of the main product, alginate-rich crude extract in the biorefinery ([Fig. 1](#)), excluding the recirculation of the co-products in the biorefinery. In the cellulose recirculation scenario (CELL), the cellulose from the seaweed was recovered in the alkaline extraction step of the biorefinery process. The recovered seaweed cellulose was recirculated to replace the commercial cellulose nanofibers (CNF) used in the film

fabrication step. Mannitol and glycerol have similar mechanical properties: both are sugar alcohols and have similar molecular structures. Mannitol can theoretically be used to substitute glycerol [59]. In the third scenario (MANN), the recirculation of mannitol from the acid wash step in the seaweed biorefinery was assumed.

Experiments conducted within the PlastiSea project [39] showed that the seaweed residues from the alkaline extraction step in the biorefinery, once dried, could be used as a filler for polylactic acid (PLA). The experiments were conducted by substituting 5 % of PLA (PLA5) and 30 % (PLA30). With a 5 % of substitution, the mechanical properties of the PLA plastic were better preserved than with a 30 % of substitution. Table 1 presents a summary of the key features for each of the modeled scenarios.

2.5. Uncertainty analysis

Since the technology under analysis was at the pilot scale, it is important to understand the uncertainties in the impact scores produced by the model. An uncertainty analysis of the following indicators was performed: *reliability*, *temporal correlation*, *geographical correlation*, *completeness* and *further technological correlation*. In this study, a stochastic approach was adopted and propagated the uncertainty in the inputs to the outputs using a Monte Carlo simulation, i.e. randomly sampling input values in their range and iterating the calculations 1000 times.

In a first-of-its-kind approach, the total uncertainty was decomposed between the uncertainty in the foreground system, i.e. the primary data about a pilot scale technology, and uncertainty in the background system, i.e. secondary database data about established technologies. While uncertainty information such as location, scale, and distribution type for each exchange in the database are available from ecoinvent, the uncertainty in the foreground system is unknown. Due to the lack of repeated measurement data, and consistency with the background database, the pedigree matrix approach was used to provide an expert-based estimate of the uncertainty in each exchange in the foreground system and assumed a lognormal distribution to avoid negative values. This is a simplified approach but pragmatic given the resources available. The Monte Carlo simulation was then performed considering the uncertainty in the foreground system only, in the background system, and the two together respectively. This allows us to appreciate the uncertainty due to this model alone and combined with the inevitable uncertainty of the database data used in the LCA.

3. Results

3.1. Carbon balance

The results in the carbon balance illustrate the carbon flow within the different scenarios (cf. Fig. 2). The first scenario (BASE) (Fig. 2, 1) assumes that alginate is the only seaweed compound used in the bioplastic and this accounts for 0.44 kg C in 1 kg of bioplastic. I.e., 44 % of the carbon is biogenic in this scenario, while cellulose and glycerol were added externally. In this scenario, 69 % of the carbon in the seaweed goes to seaweed residues. The second scenario (CELL) (Fig. 2, 2) shows the recirculation of alginate and cellulose from the seaweed to the bioplastic film. In this scenario, 12.5 % of the carbon in the cellulose nanofibers is avoided when recirculating the cellulose in the seaweed.

The third scenario (MANN) (Fig. 2, 3) displays that the mannitol in the seaweed is lower than the glycerol required for the bioplastic. The mannitol from the seaweed avoids 5 % of the carbon from the glycerol. The carbon balance in scenarios PLA5 and PLA30 (Fig. 2, 4) shows how seaweed residues in the base scenario are later used to substitute 5 % or 30 % of PLA. When using seaweed residues as PLA filler, more of the original seaweed biomass is integrated into products and less is discarded (cf. Fig. 2, 4).

Overall, the results in the carbon balance show that by recirculating cellulose and mannitol by substituting PLA in scenarios CELL, MANN, PLA5 and PLA30, more of the carbon originally absorbed by the seaweed is converted into products, and less external carbon inputs are required. In other words, the BASE scenario requires the most external carbon inputs.

3.2. Scenarios and contribution analysis

The results (Fig. 3) reflect the contribution analysis of the Global Warming (GW) impact of all the processes across all life cycle stages of 1 kg of bioplastic film. The scenarios with the highest impact are the BASE, CELL and MANN with the incineration EoL, each with an impact of 3.72 kg CO₂-eq., 3.79 kg CO₂-eq. and 3.77 kg CO₂-eq. respectively. The scenarios with the lowest impacts are the PLA substitution scenarios with the composting EoL, the lowest being PLA30 substitution with 2.3 kg CO₂-eq. and PLA5 with 2.53 kg CO₂-eq., closely followed by BASE composting, 2.56 kg CO₂-eq.

The highest impact in all cases derives from film fabrication, mainly due to the high contribution from the production of glycerol with an impact of 2.11 kg CO₂-eq. The recirculation of cellulose and mannitol in the biorefinery, both used in the film fabrication in scenarios CELL and MANN, requires the use of oxygen peroxide and ethanol in the biorefinery step. This means that the GW in biorefinery, in both CELL and MANN, is 0.11 kg CO₂-eq., which is significantly higher when compared to 0.03 kg CO₂-eq. in the BASE scenario. Moreover, a substantial amount of glycerol is needed in the film fabrication step when considering the relatively low proportion of mannitol in the seaweed with 80 % recovery in the biorefinery process. The PLA substitution scenarios (PLA5 and PLA30) have a lower impact than the BASE scenario. In the incineration sub-scenario, the impact is 3.68 kg CO₂-eq. (PLA5) and 3.46 kg CO₂-eq. (PLA30). In the composting sub-scenario, it is 2.53 kg CO₂-eq. (PLA5) and 2.3 kg CO₂-eq. (PLA30).

In all the scenarios, the GW impacts of the offshore farm are significantly low compared to other processes, due to, for instance, the carbon uptake in seaweed cultivation. Regarding the EoL, there is a considerable difference between incineration and composting in all scenarios, with a GW impact of 1.27 kg CO₂-eq. in incineration and 0.11 kg CO₂-eq. in composting. The results from all the impact categories can be found in Supplementary material D.

3.3. Uncertainty analysis

The results of the uncertainty analysis are visualised in Fig. 4. To reproduce the results, the code used in the study is available in a GitHub repository [60]. Summary statistics for all distributions and a matrix of the differences between paired samples of all distributions are provided in Supplementary materials E and F.

These results confirm the conclusion from the static analysis that

Table 1
Summary of the scenarios modelled in the study.

Scenario acronym and name	BASE Base scenario	CELL Cellulose recirculation	MANN Mannitol and cellulose recirculation	PLA5 PLA substitution 5 %	PLA30 PLA substitution 30 %
Co-products	None	Cellulose	Cellulose and mannitol	PLA filler pellets	PLA filler pellets
End-of-life sub-scenarios	Incineration composting	Incineration composting	Incineration composting	Incineration composting	Incineration composting

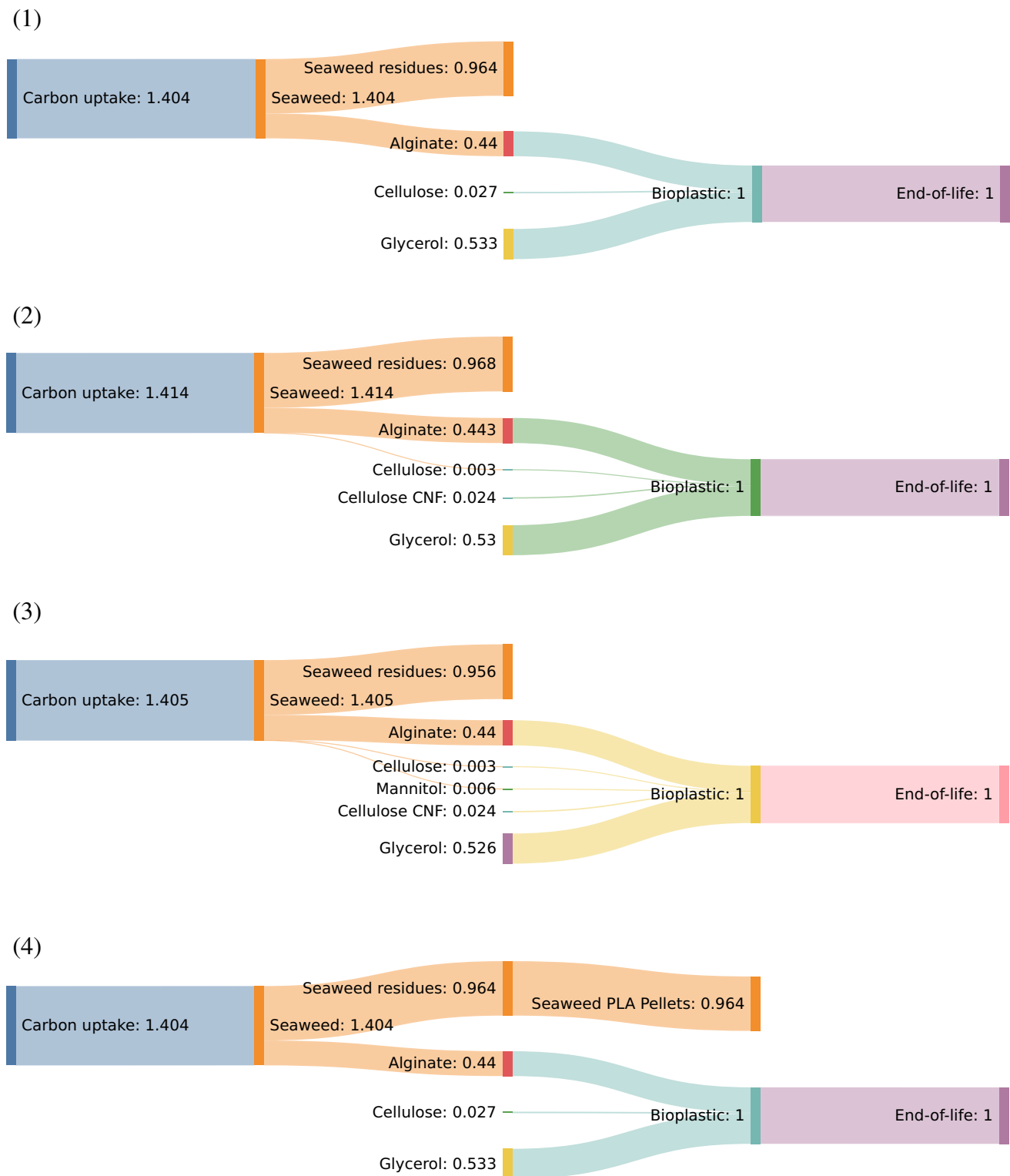


Fig. 2. Sankey diagrams of the carbon balance. Base scenario, BASE (1); cellulose recirculation scenario, CELL (2); and cellulose and mannitol recirculation scenario, MANN (3); PLA substitution 5 % and 30 %, PLA5 and PLA30 (4). Units: kg carbon.

indeed the composting alternatives (“composting”) perform better than the incineration counterparts, as more than 96 % of the time, the results in the composting scenarios are lower than those in the incineration scenarios. Visually speaking, Fig. 4 also confirms that the distributions for the composting alternatives are always shifted downwards compared to the distribution of the incineration alternatives.

Given the uncertainty, the ranking across the various scenario can,

however, not be confirmed with confidence. Results for the MANN, CELL and PLA5 scenarios are lower than the BASE scenario in less than 50 % of the samples, and less than 60 % for the PLA30 substitution scenario. Given the uncertainties, these scenarios are not clearly distinguishable from the BASE scenario. This result reflects two aspects: first, the technology is still at the pilot scale and uncertainties are expected to be high; second, the pedigree approach used for estimating these uncertainties

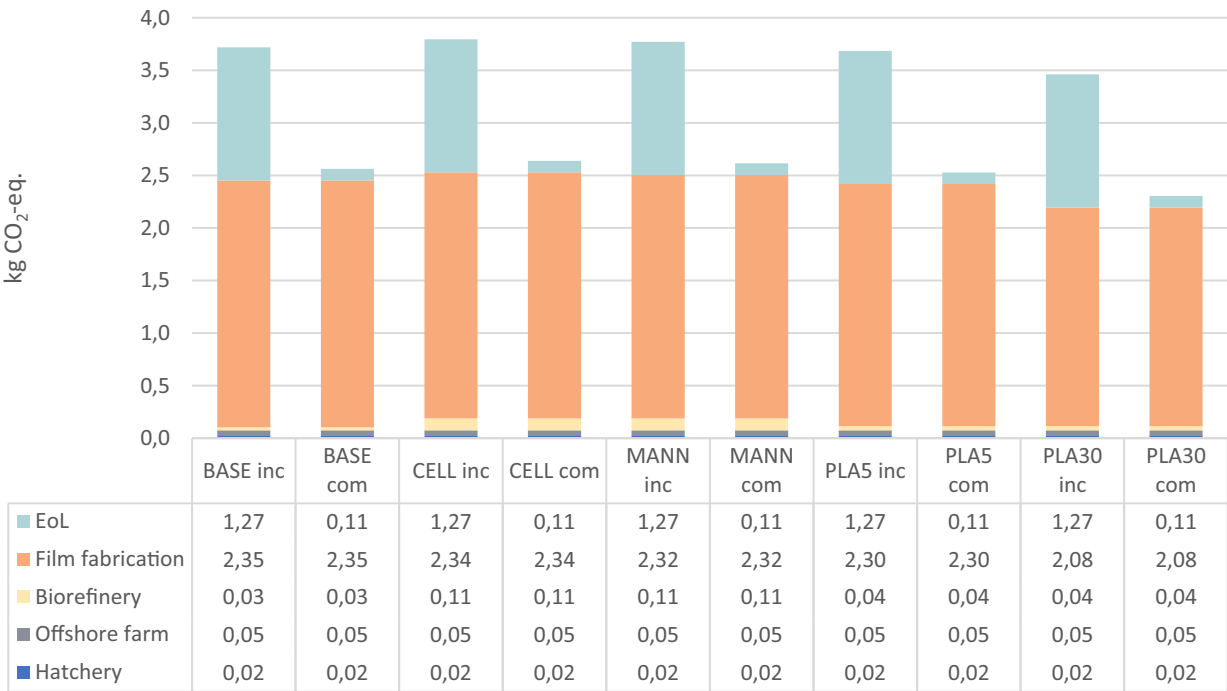


Fig. 3. Contribution analysis in the impact category Global Warming (GW) impact of all the scenarios and sub-scenarios: BASE, CELL, MANN, PLA5, PLA30, incineration (Inc.) and composting (Com.).

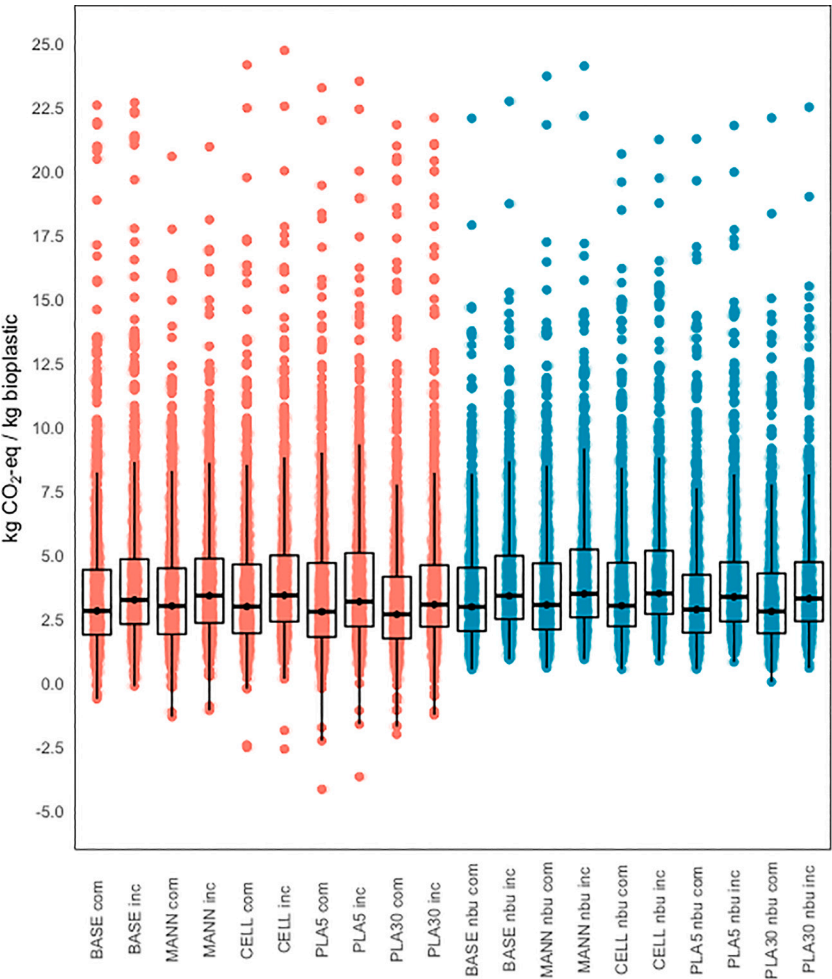


Fig. 4. Uncertainty analysis in all scenarios. The figure shows the result of the Monte Carlo simulation (1000 paired samples) across scenarios both by including foreground and background uncertainty (left side, red colour) and by excluding the background uncertainty (right side, light blue colour, label “nbu” — no background uncertainty) respectively. Boxplot: box bottom = 25 % quantile, box top = 75 % quantile, bold line = 50 % quantile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

has low precision and is likely to overestimate the uncertainty.

The comparison between the uncertainty generated when considering both the foreground and background uncertainty, and the foreground uncertainty only also provides interesting insights. Fig. 4, shows no substantial difference in the spread of the distributions with or without background uncertainty. Interestingly, without background uncertainty, the distributions tend to remain more positive while removing negative outliers — a sign that the uncertainty in specific background activities in the database might skew the results. When comparing the summary statistics, it can be seen more clearly that the uncertainty in the distributions obtained without background uncertainty is reduced as the standard deviations of all distributions decrease. A more accurate comparison between the summary statistics of the distributions obtained with and without background uncertainty is not possible, as the sampling is not paired across the two versions of the background database (with and without uncertainty) used in the simulation.

4. Discussion and conclusion

This study explores the environmental impacts of a novel seaweed-based plastic using *Saccharina latissima* and the potential of recirculating some co-products in the biorefinery step, to reuse in the later film fabrication step. This potential is assessed via carbon balance and LCA.

Previous studies stress the importance of using the entire seaweed biomass to increase its value [46]. That is not only relevant from an environmental perspective but also from an economic perspective. Seaweed biomass has a high demand in the food and feed sector, where a high economic value is given to biomass. The price of the seaweed biomass for plastic production is significantly lower, thus the utilization of all the seaweed biomass and co-products from the biocrude extraction increases its value [35]. The results of this study, however, show that the scenarios where mannitol and cellulose are recirculated have a slightly higher impact at the pilot scale than the base scenario, although due to the substantial uncertainties involved this difference can only be confirmed with low confidence. It needs to be considered that we assumed that 12 % of the dry matter of the seaweed is mannitol and 5 % cellulose and the mass of mannitol and cellulose obtained from the biomass is insufficient to produce this bioplastic film. Nevertheless, other studies show the influence of using whole seaweed biomass versus extracting a single component when the biorefinery processes are optimised [46,61].

In the different scenarios, we see that the end-of-life scenario reduces the carbon footprint by approximately 30 % via composting compared to incineration. These results show the importance of having an EoL aligned with the properties of the bioplastic. In this case, the bioplastic is 100 % compostable and is, therefore, important to compost this bioplastic film to reduce its impacts and increase its circularity.

It needs to be acknowledged that the carbon release is postponed in time with composting. In the composting scenario, 42 % of the carbon is stored but this carbon will eventually be released in the long term. A time-dependent analysis would be needed to appreciate this delay in emissions [62] but it was beyond the scope of this study. The contribution to the GW impact from the electricity consumption is not substantial due to the high percentage of hydropower and wind power in the Norwegian consequential electricity mix. Patel et al. [63] confirm the benefits of using renewable energy to develop algal products.

The base scenario has a carbon footprint of 3.7 kg CO₂-eq. in the incineration sub-scenario and 2.6 kg CO₂-eq. in the composting scenario. For comparison, the carbon footprint of 1 kg of polypropylene and polypropylene is 1.71 and 2.4 kg CO₂-eq. respectively using ReCiPe 2016 Midpoint (E) and default datasets from the ecoinvent database [38]. Looking at other bioplastics, we can see that the carbon footprint of bio-based PLA is higher than fossil-based plastics, 4.21 kg CO₂-eq. [38]. For contextualisation, it needs to be considered that conventional fossil-based plastics are well-stabilised industries and the impacts are

analysed at an industrial scale while the bioplastic production technology modelled in this study is at a pilot scale.

It is also worth mentioning the importance of including the entire life cycle of bio-based products [17]. If the carbon uptake is accounted for in seaweed cultivation, the stage where the carbon is released, the EoL should also be considered. Otherwise, an excessive benefit is given to the system. In this regard, performing a carbon balance is recommended to ensure how the carbon is distributed within and released from the system.

In this study, the carbon emissions for 1 kg of wet-weight (WW) seaweed is 0.082 kg CO₂-eq. This value is within the range of estimates from other studies assessing the carbon footprint of seaweed cultivation or harvest. Thomas et al. [30] report 55.2 kg CO₂-eq./tonne WW (0.0522 kg CO₂-eq./kg WW) in cultivation and Zhang et al. [61] 5187.6 kg CO₂-eq/tonne dry weight (approximately 0.5 CO₂-eq/kg WW) in harvesting.

Helmes et al. [29] is the closest previous assessment study of a seaweed-based plastic. They assess the environmental impacts of producing lactic acid from *Ulva* spp., a type of green seaweed with different properties than brown seaweed. The polylactic acid under assessment is a precursor of polylactic acid (PLA), but this is excluded from their system boundaries because the system only includes seaweed cultivation and processing. *Ulva* spp. has a different cultivation technique compared to brown seaweed, as it is cultivated in both land-based and off-shore systems. Due to the onshore cultivation needed for cultivating *Ulva* spp., electricity consumption is a hotspot in Helmes et al. [29] with a GW impact of 1.47 kg CO₂-eq./kg of purified lactic acid. The offshore cultivation of *Ulva* spp. is currently in progress and that would decrease the impacts of land-based [64]. Beckstrom et al. [36] assess the production of bioplastic feedstock from microalgae, with a worst-performing scenario showing a carbon footprint of 0.66 kg CO₂-eq./kg of bioplastic. Nilsson et al. [34] analyse a seaweed-based biorefinery where the GW impact is 2.73 kg CO₂-eq./kg of sodium alginate. In their case, drying the seaweed is a hotspot, but this processing step is not needed in the current research. Those studies do not include the entire lifecycle of the product as the EoL is excluded from their system boundaries. Even if the EoL only contributes to 5 % of emission composting and 30 % of incinerating, partially explains why their reported carbon footprints are lower than those reported in the current study. Another remarkable aspect is the fact that the current study shows pilot scale impacts and the processes are not optimised. That is noticeable in the case of the film fabrication stage. On that account, an LCA should be repeated in the future on an upscaled version of the product system.

There are some uncertainties given that the data for the LCI is done at a pilot scale. Following the uncertainty factors for the pedigree matrix [65], we consider a low uncertainty in *reliability*, *temporal correlation* and *geographical correlation* as the data is real experimental pilot-scale data, in a specific time and location. The *completeness* indicator has a higher uncertainty because the data is only at the pilot scale. Regarding the *further technological correlation* indicator, some processes were modelled with lower uncertainty and some with higher. Performing an uncertainty analysis also quantifies the confidence of the model. The processes at the lab- and pilot scale are not optimised. Therefore, and according to previous studies on the upscaling of emerging technologies [66–68], it could be reasonable to think that a reduction in the impacts would be possible when the system is upscaled to an industrial scale as the processes will be optimised, including the recirculation of co-products, and, consequently, fewer resources, energy and waste will be needed per FU.

The validity of the results of the uncertainty analysis needs to be discussed critically. Although 50 % of the data are contained approximately within a factor two range, several samples differ by a factor three from the median and outliers up to a factor ten are obtained in the simulation. The stochastic procedure is somehow artificial as it generates a large number (1000) of virtual instances of the system under analysis, and it is expectable to obtain a few very high and very low values in the sampling, leading to a large range overall, that needs to be

contextualised for better interpretation. On the one hand, the uncertainty range in the foreground system obtained with the pedigree matrix, and thus with a substantial degree of subjectivity in the assessment, might lead to overestimation. On the other hand, being some of the processes such as film fabrication are still at the pilot scale, it makes sense to obtain a large uncertainty on the results. The use of pedigree matrices and Monte Carlo simulation has been criticised in the LCA literature [69–71] and it is, hence, recommended to consider the results of the uncertainty analysis only in a comparative context to explore the degree of confidence with which we can say one alternative is better than the other given the uncertainty. Furthermore, we stress that the approach here used is a rough estimation of the uncertainty related to the assessment of technology at the pilot scale, and that more fine-tuned approaches to modelling upscaling should be applied to reduce model uncertainty, such as performing process simulations to upscale the biorefinery and processes and should be the topic of further research.

Another point of discussion is the limitation of using LCA for the overall environmental analysis of seaweed bioplastics compared to fossil plastics. For instance, current impact categories do not reflect the impacts of microplastics coming from fossil plastics, and thus, do not benefit bioplastics compared to fossil plastics.

While other studies assess the potential of using seaweed to produce bioplastics, this is one of the first studies to quantify its impacts. It can be concluded that seaweed-based plastic is a promising alternative to conventional land-based. The identified hotspots at the pilot scale are glycerol and cellulose in the film compounding step in the film fabrication.

Regarding the overall properties of this bioplastic film and its applicability, alginate is partially diluted in water. Thus, this bioplastic could be used as food packaging for greasy or dry food, until water barrier properties are improved by novel formulations and manufacturing methods. This bioplastic has also been proven to be suitable for fresh fruits and vegetables. It could likewise potentially be used as packaging for the fashion industry, cosmetics or other dry goods. Jabeen et al. [72] describe that storage tests, including oxygenation and water solubility, are necessary before upscaling and commercializing new bioplastics.

Although seaweed-based bioplastics are not the main climate solution, they help to reduce dependency on fossils and, hence, slightly contribute to reducing carbon emissions. Overall, it can be argued that one of the main environmental advantages of these seaweed-based plastics compared to first- and second-generation bioplastics are the low impact on land use in seaweed production. However, seaweed-based plastics are still in the early R&D stage and further research is needed to upscale and commercialise this novel bioplastic. Future work on upscaled industrial-scale impacts and upscaling scenarios using different techniques will be carried out.

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CRedit authorship contribution statement

Maddalen Ayala: Conceptualization, Data curation, Formal analysis, Software, Visualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Marianne Thomsen:** Conceptualization, Supervision, Validation, Investigation, Methodology, Writing – review & editing. **Massimo Pizzol:** Funding acquisition, Conceptualization, Supervision, Formal analysis, Software, Visualization, Investigation, Methodology, Validation, Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data is shared in the supplementary material

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