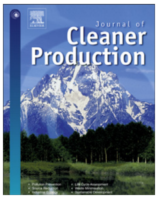
Journal of Cleaner Production 170 (2018) 1621–1627

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Life cycle impact assessment of a seaweed product obtained from *Gracilaria edulis* – A potent plant biostimulant

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ARTICLE INFO

Article history:
Received 5 April 2017
Received in revised form
20 September 2017
Accepted 26 September 2017
Available online 30 September 2017

Keywords:
Climate change
Gracilaria
Seaweed extract
Plastics
Green-house gas emissions
Carbon footprint

ABSTRACT

Increasing crop productivity for food security is a challenging task without compromising the environmental integrity. In this scenario, seaweed based plant biostimulants are one of the potential sources for sustainably improving crop productivity and mitigating climate change. However, in order to quantitatively express the environmental benefits it becomes imperative to estimate the impacts resulting from their production. Thus the present study was undertaken to determine the various impacts across nineteen environmental categories that resulted from production of 1000 L of *Gracilaria* seaweed extract-a potent plant biostimulant by using life cycle assessment methodology. The environmental impacts were apportioned between seaweed extract and downstream product (agar) on the basis of price allocation. Among the three different steps involved in production of the extract, the processing module contributed to higher proportion of impacts across different evaluated environmental impact categories and it ranged from 65 to 99% of the total impacts. Electricity requirement, shed and blow-moulding sub-processess within the processing step contributed to bulk of the evaluated environmental impact categories. Plastics used in packaging of the extract as well as those used in cultivation module contributed to more than 50% of impacts across 8 out of the 19 evaluated environmental impact categories. Thus, in order to render the product even more sustainable we would recommend the use of biodegradable products for making the raft as well as for packaging. In addition, marketing of the extract as a concentrate would further lower the environmental burden associated with the transport and packaging, thus rendering the SWE even more sustainable.

1. Introduction

Increasing crop productivity following adoption of various green revolution strategies and reducing the gap between potential and observed yield is a challenging task without compromising the environmental integrity. Yields of crops have remained stagnant in the recent years even in developed economies following continuous application of inorganic N because of the effects of diminishing returns (Tilman et al., 2002). In the impending climate change scenario, sustainably achieving food security for the human race appears to be the near term goal for the scientific communities. In this context, plant biostimulants are excellent alternatives to increase crop yields and among these, seaweeds are one of the potential sources of biostimulants for sustainably improving crop productivity (Khan et al., 2009; Calvo et al., 2014; Ghosh et al., 2015). Life cycle assessment (LCA) is an important tool to measure the basis of environmental sustainability wherein, the environmental impacts associated with all the stages of a product's life across its entire value chain starting from extraction of raw materials to its disposal or recycling are assessed. The LCA methodology was used in the present study to determine the environmental footprint of the seaweed biostimulant. With much emphasis being given to ascertain the sustainability of biofuels from algal sources (Aitken et al., 2014; Aresta et al., 2005; Brentner et al., 2011) there are very few reports that determine the environmental footprint of industrially important products such as alginates, biostimulants and essential oils (Pérez-López et al., 2014, 2016; Ghosh et al., 2015). Recently, we have shown that one of the seaweed based biostimulants obtained from *Kappaphycus alvarezii* offers great promise in enhancing the yield of many crops thereby bridging the yield gap without detrimentally affecting the environment when used in conjunction with recommended rate of fertilizers (Ghosh

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https://doi.org/10.1016/j.jclepro.2017.09.241

et al., 2015; Singh et al., 2016; Sharma et al., 2017; Trivedi et al., 2017). However, in the present manuscript we describe the various environmental impacts that can arise during production of another seaweed extract obtained as a co-product from the *Gracilaria edulis*, a species native to Indian waters, which is predominantly cultivated for its superior quality agar (Meena et al., 2008). This strategy of extracting the biostimulant rather than just drying the seaweeds for agar production is advantageous as it creates value addition to the entire process. The efficacy of the *Gracilaria edulis* seaweed extract (GSWE) in improving crop productivity has already been demonstrated in maize (Layek et al., 2015; Singh et al., 2016), rice (Pramanick et al., 2014a), rice-potato-green gram crop sequence (Pramanick et al., 2014b), greengram (Raverkar et al., 2016). GSWE also has the potential for partial substitution of synthetic fertilizers as well as mitigating climate change (Sharma et al., 2017). However, for quantification of the environmental benefits that can ensue from such a partial replacement of chemical fertilizers, it becomes absolutely essential to assess the impacts resulting from its production. Both *K. alvarezii* and *G. edulis* have more or less similar daily growth rates (Ashok et al., 2016; Ganesan et al., 2011). However, they differ with respect to biomass yield as well as the amount of extract that can be obtained from it. Further, as the requirement of biomass for the processing unit is different, the energy requirement in the various steps during processing for extract expulsion tends to vary. In addition, the economic value of the downstream product is also different for these two algae which would render it sensitive to allocation based on price. Thus, such variability makes it imperative to determine the impacts resulting from the cultivation, extract expulsion and various other downstream processes for any algae and hence the present work was intended to quantify the environmental impacts resulting from cradle to gate production of GSWE at an industrial scale.

2. Material and methods

2.1. System boundary and inventory

2.1.1. Goal and scope

The principal goal of the study was to determine the potential environmental footprint that can result during near-shore cultivation of *G. edulis* as well as extract expulsion and packaging by using the methodology of life cycle assessment. The study was restricted to the production of seaweed extract (SWE) at factory gate (cradle to gate). The functional unit remained the same as described in our earlier report (Ghosh et al., 2015) as the inputs required for the production of one kiloliter (1 m^3) of GSWE. GaBi software (version 6.0) along with databases from Eco-invent (version 2.2) and additional custom India specific datasets (for electricity, diesel) from GaBi (PE International, now ThinkStep) were used for modelling. All the GaBi datasets were in compliance with the ISO 14044, ISO 14064 and ISO 14025 standards. Wherever India specific datasets were not available, European datasets from Eco-invent were used. ReCiPe Midpoint indicator with hierarchist perspective was used for assessing the impacts. Price allocation (Table 1) was carried out for apportioning impacts between GSWE and agar (downstream product). The prevailing market prices of the biostimulant as well as food grade agar at factory gate were sourced from M/s. AquaAgri Pvt ltd, India and M/s. Madurai agar & alginate manufacturers welfare association, Madurai, India.

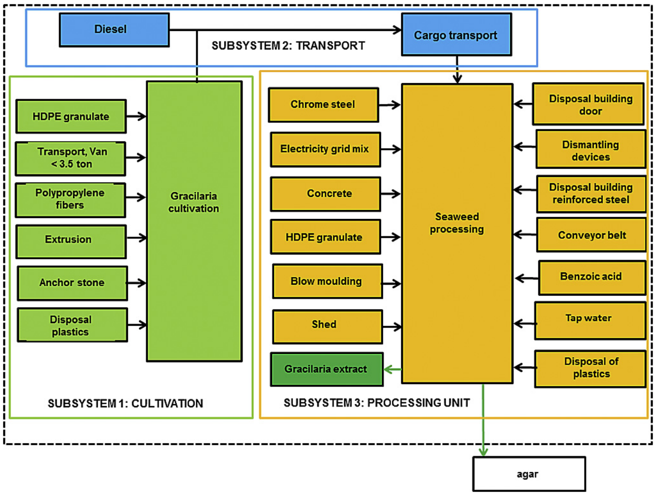

Fig. 1. Flow diagram indicating system boundaries for production of 1 kL of Gracilaria seaweed extract which happens to be the functional unit in the study.

The system boundaries are depicted in Fig. 1. The net impact of the production, use and disposal of bamboo poles was assumed as zero as it was deemed to have been collected from natural stands.

2.1.2. Data inventory

The data for cultivation process was based on the established raft culture technique followed for commercial cultivation of the species near the coast of Thonithurai (09° 17.057″ N and 079° 10.989″ E) Tamil Nadu, India (Ganesan et al., 2011). Inventory for cultivation and processing steps in the model was based on actual mean data which was either estimated or calculated with certain assumptions made on the life span of materials used. The transport process was based on a hypothetical system with certain assumptions being made on the distances that were used as well the transport system. Packaging was assumed to be made in 5 L plastic carboys. The inputs were estimated for the functional unit on the basis of its utilization time (ratio of usage to total assumed life span). The unallocated values are presented in Table 2. As datasets for high density polyethylene (HDPE) ropes and carboys were not available, HDPE granules as well their extrusion process were considered to account for the production of ropes and packaging material. The disposal of plastics through sanitary land fill was considered as it is the most common method of disposal practiced in India.

2.1.3. Cultivation process

Near-shore cultivation of the seaweed was carried out using raft

Table 1
Financial allocation for Gracilaria seaweed extract and the hypothesis used. USD is United States Dollar.

Products	Product price		Quantity produced		Proportion of impact allocated
	Amount	Unit	Amount	Unit	
Gracilaria seaweed extract	0.46	USD $litre^{-1}$	1000	litre	27%
Agar	23.08	USD kg^{-1}	54	kg	73%

INR is Indian Rupees and the prices were obtained from the corresponding prices in Indian rupees, according to the rate 1 USD=INR 65.

Table 2
Inputs for production of biomass, its transport and processing required for one functional unit (one kilolitre of sap production at factory gate without price allocation). SWE-seaweed extract; HDPE – High density polyethylene.

Process	Material requirements	Quantity	Unit	Life span
Cultivation	Number of rafts required	185.19		
	Polypropylene ropes	4.63	kg	12 cycles
	HDPE net	12.35	kg	12 cycles
	Transport	3.32	tkm	
	Extrusion of HDPE into ropes	12.35	kg	
	Disposal of plastics to landfill	16.98	kg	
	Anchoring stone	6.67	kg	500 cycles
	Bamboo	308.64	kg	6 cycles
	Seaweed biomass	2500	kg	
Transport	Distance to processing unit	100	km	
	Cargo	2500	kg	
	Diesel	5.185	kg	
SWE extraction	Concrete platform	9.51×10^{-5}	m^3	50 years
	Shed	2.28×10^{-5}	m^2	50 years
	Electricity	146.3	MJ	
	Disposal building to final disposal	2.28×10^{-5}	m^2	
	Conveyor	3.35×10^{-5}	m	40 years
	Amount of steel in conveyor	1.68×10^{-2}	kg	
	Dismantling industrial devices manually	1.68×10^{-2}	kg	
	Chromium steel in crusher	1.43×10^{-3}	kg	30 years
	Steel in Decanter	3.81×10^{-3}	kg	30 years
	Steel tank and piping	1.84×10^{-3}	kg	100 years
	Disposal of steel to recycling	7.08×10^{-3}	kg	
	Water	625	kg	
	Benzoic acid	1	kg	
Bottling/packaging	HDPE granulate	30	kg	
	Blow moulding	30	kg	
	Disposal of plastics to sanitary landfill	30	kg	

technique. The biomass was harvested after a period of 50 days which constituted a single cycle. The average net biomass production per raft per cycle was around 13.5 kg which was used in the present study. Details of the structure of the raft have already been described by Ganesan et al. (2011) and a similar raft structure was used in the present study. Briefly, a squared frame (1.5 m × 1.5 m) was constructed by tying bamboo poles with the corners being braced with diagonally placed small bamboo in order to maintain the integrity of the structure (Fig. 2). The total bamboo requirement for building a raft was approximately 10 kg with an assumed life of 6 cycles. The seeding thalli were attached to 20 parallel running polypropylene ropes (3 mm dia) at a distance of 5 cm in between the twists of the ropes. The weight of each rope was 15 g and life was assumed as 12 cycles. The base of the raft was covered with HDPE fish net. In order to represent HDPE ropes of the fish net, HDPE granulate as well as extrusion process from eco-invent was used to substitute for the process of HDPE rope production. All the raw materials required for the cultivation purpose was assumed to be transported to the site of cultivation in van <3.5 tonnes over a distance of 10 km. During unfavourable growing conditions, the biomass was maintained in polyethylene tube-nets anchored to the same stones that anchor the rafts thereby eliminating the need for nursery which is otherwise required for maintenance of germplasm.

Fig. 2. Raft for cultivation of *Gracilaria edulis* along the coast of Tamilnadu.

2.1.4. *Transport to processing unit*

The seaweeds at the end of the harvest cycle were assumed to be transported to a processing unit located at a distance of 100 km from the site of cultivation. A custom cargo unit which utilized diesel produced according to Indian standards was used to account for the impacts resulting during the transportation process.

2.1.5. *Seaweed expulsion and processing unit*

The processing plant (used for extract expulsion) considered in the present study is the same as described by us in Ghosh et al. (2015) for extraction of *Kappaphycus* alvarezii seaweed based biostimulant. Since the main feed stock for the processing unit which happens be *K. alvarezii* is not available throughout the year, we advocate that during the lean days the present algae may be used as a feedstock for efficient plant utilization. Furthermore, variation in the amount of biomass to be processed for extract expulsion also alters the energy requirements. The inputs for processing unit were estimated on the basis of processing capacity, life span of the material/input in hours and utilization time (hours). The processing unit has a capacity to process 30 tonnes of seaweed per shift of 8 h. The extract recovery percentage of the processing unit varies with the type of seaweeds used and in the present case it was considered at 40% which also happens to be the observed value (average of experimental values). The rest is wet granule which is used for the production of the downstream product viz., agar. Similar to that reported in Ghosh et al. (2015), the seaweed was assumed to be initially unloaded on to a concrete platform (62.5 m^3 volume). The seaweeds were subsequently loaded manually on a conveyor belt which passes through a sprinkler system that washes the seaweeds (for removal of foreign particles). The amount of water required was assumed at 1 L for every 4 kg of seaweed which is based on the water requirement of main feed stock viz., *Kappaphycus* used in the unit (Ghosh et al., 2015). The conveyor module of eco-invent was used in order to account for the impacts. The other machineries in the processing unit viz., grinder, centrifuge, storage tanks and pipes were all assumed to be made of stainless steel/chromium steel. The grinder, conveyor and centrifuge each had a processing capacity of 5 tonnes of biomass or slurry per hour with an assumed life as shown in Table 2. In order to account for the substructure, the shed module of eco-invent was used and area housing the shed was assumed to be 120 m^2. In order to account for the simple factory shed only one eights of the impacts of the original shed module of eco-invent was considered. In addition a custom module to account for the predominantly coal based Indian electricity mix was used for assessing the impacts. Benzoic acid was assumed as the preservative. Packaging of seaweed extract was assumed to be carried out in 5 L HDPE carboys. Further, two hypothetical scenarios were considered, one for estimating the impacts of re-use of plastic carboys at least once and the other for the use of biodegradable alternatives to plastics. For the first scenario, the total impacts resulting from the use and disposal of plastics required for the packaging of functional unit was estimated which was then halved to account for the one time re-use and then their relative contribution with respect to the functional unit was determined. It has to be noted that the impacts resulting from transport of the packaging materials back to the bottling plants or processing unit was not considered here. In the case of the second scenario, the relative contribution in percentage terms of the various sub-processes of plastics (raw materials, processing and disposal) required for the functional unit was determined which happens to be the maximum reduction that one can obtain by use of alternatives which would lead to the elimination of plastics assuming the alternatives to plastics have zero environmental impacts. Further, system expansion was not used to account for the uptake of nitrogen and phosphorus during the growth of the algae.

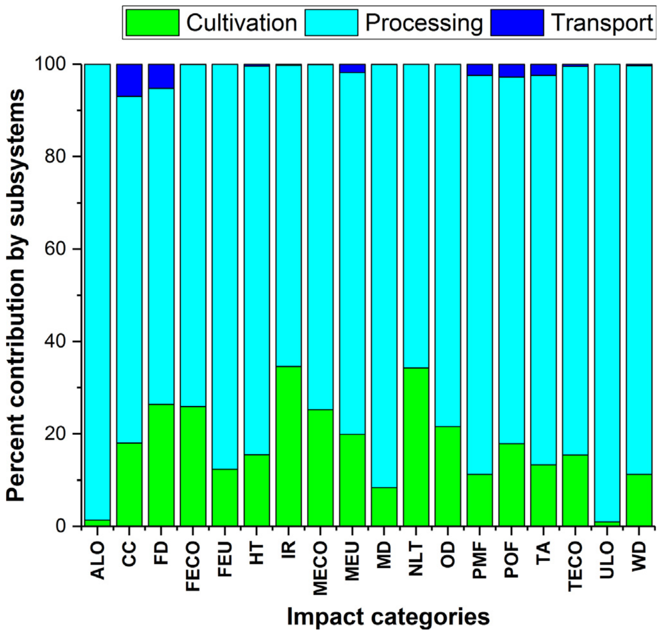

Fig. 3. Percent contribution to impact categories by various subsystems involved in the production of one kiloliter of *Gracilaria* seaweed extract factory gate. ALO - Agricultural land occupation [m^2a]; CC - Climate change [kg CO_2 eq]; FD – Fossil depletion [kg oil eq]; FECO_- Freshwater ecotoxicity [kg 1,4-DB eq]; FEU - Freshwater eutrophication [kg P eq]; HT - Human toxicity [kg 1,4-DB eq]; IR - Ionising radiation [kg U235 eq]; MECO - Marine ecotoxicity [kg 1,4-DB eq]; MEU - Marine eutrophication [kg N eq]; MD - Metal depletion [kg Fe eq]; NLT - Natural land transformation [m^2]; OD - Ozone depletion [kg CFC-11 eq]; PMF - Particulate matter formation [kg PM10 eq]; POF - Photochemical oxidant formation [kg NMVOC]; TA - Terrestrial acidification [kg SO_2 eq]; TECO - Terrestrial ecotoxicity [kg 1,4-DB eq]; Urban land occupation [m^2a]; WD - Water depletion [m^3].

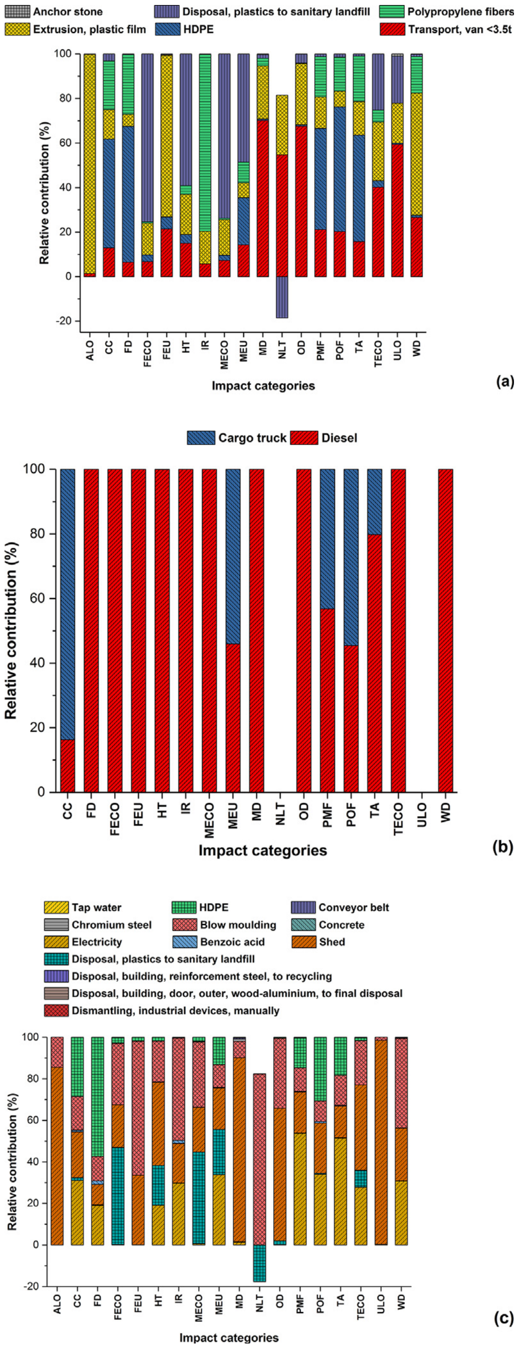

Fig. 4. Percent contribution of the various sub-processes to the environmental profile of the subsystems involved in the production of one kiloliter of seaweed biostimulant (a) cultivation subsystem (b) transport (c) processing unit. The labels in the X axis are the same as given in Fig. 3.

3. Results and discussion

Among the three different subsystems involved in the production of GSWE viz., cultivation, processing (extract expulsion) and transport modules, the processing module contributed to higher proportion of environmental impacts across different categories and it ranged from 65 to 99% of the total environmental impacts (Fig. 3). The relative contribution of the processing subsystem to the environmental profile of functional unit was the highest (>98.6%) for agricultural (ALO) and urban land transformation (ULO) categories while it was the least (65%) for ionising radiation (IR) and natural land transformation (NLT) environmental impact categories (Fig. 3). The cultivation process on the other hand contributed to less than 20% of environmental impacts among the 14 out of 19 impact categories that were evaluated (Fig. 3). The internal transport sub-process contributed most to metal depletion (MD), NLT and ozone depletion categories (OD) within the cultivation subsystem (Fig. 4a). Use of plastics and their disposal accounted for 94% of environmental impacts under IR in cultivation process (Fig. 4a) while it was 32.6% with respect to the total impacts for 1 kL of GSWE production which happens to be functional unit. In the transport subsystem, diesel requirement was the major contributor the environmental profile (Fig. 4b). Within the processing module, shed and blow moulding and electricity requirement were the subprocesses that were responsible for the major proportion of impacts within this subsystem (Fig. 4c). For instance, these subprocesses accounted for at least 99.6% impacts under ALO and ULO categories within the subsystem while their relative contribution to the functional unit was 98.7%. In addition, the subprocesses also contributed at least 97.5% of the total impacts with respect to OD and MD environmental impact categories within the processing subsystem (Fig. 4c) while their relative contribution to the functional unit was 76.5% and 89.5%, respectively. Furthermore, the processing module accounted for the greater proportion of environmental impacts (>79%) in the category of particulate matter formation, photochemical oxidant formation as well as terrestrial acidification (Fig. 3) with electricity, shed and blow moulding processes in the value chain contributing to the bulk of these impacts (Fig. 4c).

Among the three different steps involved in GSWE production, the processing module was responsible for 75% of the impacts under climate change (CC), while cultivation and transport were responsible for 18 and 7%, respectively (Table 3). Plastics used in the packaging of the extract as well as those used in cultivation subsystem together with their processing modules (blow moulding and extrusion) contributed to the bulk of the impacts (48.6%) under CC and 64.7% under IR environmental impact category (Fig. 4 a, c). On the other hand, electricity accounted for 23.31% in CC during GSWE production. Pérez-López et al. (2014, 2016) have also reported that the major contributor to the environmental burden during the production of products from macro-algae was electricity used in the process. In addition, use of plastic products during GSWE production contributed to higher proportion of impacts in fossil depletion (71.8%) as well as freshwater eutrophication (67.8%) categories. Further, the disposal route of plastics by land filling which is supposedly one of the most common practices followed in India contributed to 51.5 and 54.1% of impacts, respectively, in marine ecotoxicity (MECO) and freshwater ecotoxicity (FECO). Further, it also accounted for 25% of impacts under the human toxicity environmental category (HT). Water depletion (WD) was higher in processing subsystem This was not account of water that was used for washing of the seaweeds but was mainly due to three sub processes viz., electricity, blow moulding and shed which together contributed to 99% of environmental impact within the subsystem and an overall impact of 87.7% to the functional unit. Attention is brought to the fact that we have used only one eighth portion of original usage time for shed in order to account for a simple substructure.

The cultivation technique employed in the present study was also found to be carbon friendly with 13.2 kg CO_2 equivalents (eq) for the production of 2.5 tonnes of fresh biomass (Table 3). This would translate to 40.5 kg CO_2 eq for tonne of dry biomass (assuming 87% water content) which is lower than 176 kg CO_2 eq for the production of one tonne dry biomass of *Laminaria* (Alvarado-Morales et al., 2013). Another advantage of this cultivation strategy is that there is no nursery requirement for maintenance of the germplasm which also contributes to significantly to the environmental profile of the algal product as reported by Langlois et al. (2012). It is evident from the results that the impact under CC was a mere 73.1 kg CO_2 eq for 1000 L GSWE production following price allocation (Table 3). This value was found to be lower than that estimated for *Kappaphycus* SWE which was 118.6 kg CO_2 eq (Ghosh et al., 2015). Considering the fact that the SWEs are applied at a much lower dilutions, it follows that the environmental

Table 3
Allocated ReCiPe Midpoint (H) impacts for one functional unit involving various processes during the production of one kilolitre of Gracilaria seaweed extract at factory gate.

Impact categories	Steps in production of seaweed extract			Total
	Cultivation	Transport	Processing (Extract expulsion)	
Agricultural land occupation [m^2a]	0.554	0	40.7	41.2
Climate change [kg CO_2 eq]	13.2	5.08	54.9	73.1
Fossil depletion [kg oil eq]	9.31	1.84	24.1	35.2
Freshwater ecotoxicity [kg 1,4-DB eq]	0.106	7.22×10^{-5}	0.303	0.410
Freshwater eutrophication [kg P eq]	1.67×10^{-3}	1×10^{-6}	0.01184	0.0135
Human toxicity [kg 1,4-DB eq]	1.42	0.0345	7.71	9.16
Ionising radiation [kg U235 eq]	2.24	0.0128	4.22	6.47
Marine ecotoxicity [kg 1,4-DB eq]	0.0907	2.956×10^{-4}	0.268	0.359
Marine eutrophication [kg N eq]	0.01995	1.79×10^{-3}	0.07847	0.100
Metal depletion [kg Fe eq]	0.2241	8.9×10^{-4}	2.44	2.67
Natural land transformation [m^2]	6.82	0	13.0	19.9
Ozone depletion [kg CFC-11 eq]	3.588×10^{-7}	1.86×10^{-11}	1.302×10^{-6}	1.661×10^{-6}
Particulate matter formation [kg PM10 eq]	0.0145	3.09×10^{-3}	0.111	0.128
Photochemical oxidant formation [kg NMVOC]	0.0513	7.90×10^{-3}	0.228	0.287
Terrestrial acidification [kg SO_2 eq]	0.0412	7.43×10^{-3}	0.261	0.310
Terrestrial ecotoxicity [kg 1,4-DB eq]	7.4×10^{-4}	2×10^{-5}	4.03×10^{-3}	4.79×10^{-3}
Urban land occupation [m^2a]	0.0812	0	8.48	8.56
Water depletion [m^3]	17.2	0.41833	135	153
Agricultural land occupation [m^2a]	0.554	0	40.7	41.2

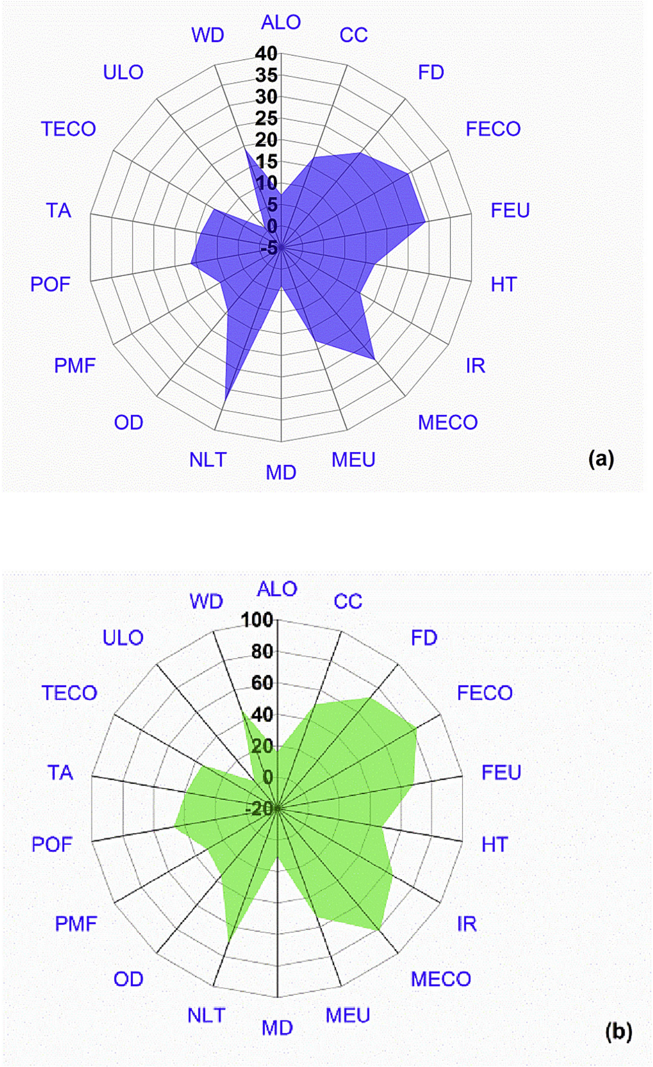

Fig. 5. Percent reduction in the evaluated environmental impact categories (a) owing to reuse or recycling of plastics used in packaging (b) replacement of plastics by biodegradable alternatives. ALO - Agricultural land occupation [m^2a]; CC - Climate change [kg CO_2 eq]; FD – Fossil depletion [kg oil eq]; FECO_- Freshwater ecotoxicity [kg 1,4-DB eq]; FEU - Freshwater eutrophication [kg P eq]; HT - Human toxicity [kg 1,4-DB eq]; IR - Ionising radiation [kg U235 eq]; MECO - Marine ecotoxicity [kg 1,4-DB eq]; MEU - Marine eutrophication [kg N eq]; MD - Metal depletion [kg Fe eq]; NLT - Natural land transformation [m^2]; OD - Ozone depletion [kg CFC-11 eq]; PMF - Particulate matter formation [kg PM10 eq]; POF - Photochemical oxidant formation [kg NMVOC]; TA - Terrestrial acidification [kg SO_2 eq]; TECO - Terrestrial ecotoxicity [kg 1,4-DB eq]; Urban land occupation [m^2a]; WD - Water depletion [m^3].

impacts of its use would be very less. GSWE has the potential to improve productivity when used in conjunction with recommended rate of fertilizers and the improvement is sustainable as it comes at the cost of minimal carbon footprint. Thus, the results of the present investigation was used for deducing the environmental footprint per unit of rice production when seaweed extracts were used in combination with recommended rate of fertilizers (RRF) at 100% or 50% (Sharma et al., 2017). Further, it was shown that in combination with 100% RRF, GSWE when applied at a concentration of 15% was able to increase the grain yield of rice by 28% while being at par with control when used in combination with 50% RRF thus resulting in savings of 10.8 and 35 kg CO_2 eq, respectively.

It is apparent that the use of plastic products during GSWE production has resulted in an increase in evaluated environmental impact categories. In order to mitigate the problem and make the product more sustainable, we recommend the use of environmentally friendly biodegradable products such as jute, coir fibres for maintaining the raft substructure as well as for packaging. This is evident from the results of the hypothetic scenario involving one time reuse of the plastic carboys used for packaging that would reduce the footprint of product in the climate change environmental impact category by 17%. Further, the reductions in FECO, MECO and freshwater eutrophication impact categories were around 29% (Fig. 5a). Maximum reduction of environmental impact due to recycling was observed in NLT (32.8%) category while the least was observed in ULO environmental impact category (0.9%). Further, a 19% reduction in WD could be observed on account of recycling of packaging product which could amount to savings of nearly 30 cubic meters of water for every kiloliter of GSWE production. For the scenario 2, maximum benefits could be obtained in FECO and MECO categories which amounted to 82 and 81% percent, respectively, for every kiloliter of GSWE production while the least was observed in case of ULO (2%). Elimination of plastics in the process by employing other alternatives would not only halve the carbon footprint of the product rendering it more sustainable but also reduces the human toxicity potential by 47% (Fig. 5b). However, it has to be borne in mind that these alternatives do have some environmental footprint and the present hypothetical scenario may not reflect the exact picture of the use of alternatives for plastics in GSWE production. It is plausible to use bio-degradable plastics with technological advancements, however, none of these at the present juncture have been reported to be environmentally friendly (Álvarez-Chávez et al., 2012).

Further, marketing of GSWE in concentrated formulation (5-10X) or as a dehydrated powder would further lower the environmental burden associated with the transport and packaging, thus rendering the SWE even more sustainable. However, it has to be borne in mind that concentration would also entail energy expenditure which is beyond the scope of the present work.

4. Conclusions

Gracilaria seaweed based biostimulant was found to be environmentally friendly with associated lower carbon footprint after price allocation. Plastics used in the value chain contributed more to environmental profile and their replacement with alternatives would further render the product sustainable. From policy angle, the estimation of impacts would enable an informed decision on how eco-friendly the seaweed biostimulant is and would make it possible to assess the overall beneficial impact with respect to sustainable improvement of agricultural productivity.

Acknowledgements

The authors wish to thank CSIR for funding the project MLP0016. Dr. C.R.K. Reddy is acknowledged for his kind support and encouragement. Dr. Shanmugam of M/s. Aquagri Pvt Ltd, India is thanked for providing information on the price of agar and extract. This manuscript bears CSIR-CSMCRI PRIS communication no. 048/2017.

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