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Life cycle impact assessment of seaweed based biostimulant production from onshore cultivated *Kappaphycus alvarezii* (Doty) Doty ex Silva—Is it environmentally sustainable?

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ABSTRACT

Seaweeds are recognized as one of the important sources of plant biostimulants and are now being increasingly used to enhance crop productivity. *Kappaphycus alvarezii* is one such seaweed whose extract (pristine sap) has been reported to improve the yield and quality of several crops. In order to evaluate whether the sap obtained from this seaweed is environmentally sustainable, life cycle impact assessment was carried out for the production of 1 kL of seaweed extract, at factory gate, from the fresh biomass of *K. alvarezii* grown onshore in open sea conditions. Financial allocation was carried out to account for the production of carrageenan, a downstream product. Impacts were also assessed for different means of transportation necessary for the movement of liquid extract to the regional storage facility. Additionally, eight different scenarios that were hypothesized to effectively reduce the environmental impacts, especially under the category of climate change, were also assessed and compared with base case scenario. Pristine sap extracted from *K. alvarezii* was found to be environmentally sustainable having a low carbon foot print of 118.6 kg CO_2 equivalents per kiloliter of its production at factory gate following price allocation. It was observed that rail, road and ship transport modes increased the impacts under the climate change category by 51.8%, 138.5% and 14.1%, respectively, when compared to base case, implying that transport through sea or rail is more environmental friendly. Unexpectedly, increase in net biomass production by 25% from 200 kg to 250 kg per raft did not have any significant impact on the reduction of carbon foot print at factory gate. The study for the first time enables to quantitatively compare the environmental benefits that can accrue following the use of this biostimulant on various crops, either by way of substitution of mineral fertilizers or by supplementation.

1. Introduction

Seaweeds, from time immemorial, have been utilized by mankind as a source of food as well as for their medicinal properties. In addition, they are the primary source of many industrially important phycocolloids such as alginates, carrageenan. Apart from this, they are an important source for iodine, potash, fuel intermediates and other phyco-supplements [1–4]. Seaweeds were also used in agriculture for improving the fertility of coastal soils, either directly or after composting to enhance the crop productivity [5]. With the advent of the techniques for extract preparation from seaweeds [2,5] and due to the presence of a wide range of organic and mineral nutrients, plant growth regulators, stress alleviators such as betaines [6,7], they are commercially exploited in agriculture as biostimulants for improving crop productivity [1]. Most of the commercially available liquid seaweed extracts are manufactured from brown algae although other algae have also been used [1,5]. Mariculture of *Kappaphycus alvarezii*, a tropical red algae, native to Philippines, is primarily carried out for its carrageenan content [8,9]. A process was developed that allowed production of sap and carrageenan simultaneously from this seaweed [10]. There are several reports that amply demonstrate that the liquid extract obtained from this seaweed when applied as a foliar spray acts as a potential biostimulant on various crop plants, enhancing their productivity significantly [7,11–13]. In order to feed the burgeoning world population, excessive use of chemical fertilizers has been resorted to, for increasing crop productivity. This practice has eventually resulted in both the deterioration of soil quality as well as having detrimental impacts on non-agricultural terrestrial and aquatic ecosystems [14,15]. Thus, the present focus of the scientific community has been to look for alternatives, which can partially or wholly substitute the use of chemical fertilizers without impacting the productivity and economic output [5]. In this context, seaweed extracts offer one of the means to effectively reduce the requirement of chemical fertilizers and sustainably enhance crop productivity. It is well known that techniques of macroalgal cultivation in open sea are less sophisticated that does not require any

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nutrients or fertilizers. In addition, seaweed aquaculture does not compete for arable land resources and have practically no freshwater requirements [16]. Further, it has also been reported that seaweed cultivation reduces coastal eutrophication in the areas of its cultivation [17]. Although less sophisticated, the cultivation of macroalgae does require certain material and energy inputs and the production of sap may account for environmental impacts as it involves mechanical extraction. In this context, the most pertinent question that should be unequivocally answered is whether the use of seaweed based biostimulants for improving agricultural productivity is indeed environmentally sustainable. Thus, in order to determine any possible reduction in the environmental impacts on account of their use, either as a replacement or supplement to chemical fertilizers, it becomes imperative to determine the various environmental impacts resulting from the production of seaweed based biostimulants (extracts). Life cycle assessment is an efficient tool for quantifying environmental impacts of many bio-based materials [18] and much of the emphasis on algae is focused on its potential as a biofuel source [19,20]. Although several liquid seaweed extracts are commercially available [5], to the best of our knowledge, till date there are no reports available in the literature dealing with quantification of the environmental impacts resulting from their production. Thus in the present study, we describe the assessment of various environmental impacts during seaweed sap production from *K. alvarezii* grown onshore. The outcome of the study would be beneficial in two different ways which formed the objective of the present study. The first is to improve the efficiency of the process in order to optimize the sap production as well as its transport for further reduction in the impacts from environmental perspective. The other important outcome of this study would be to enable quantification of the sustainability of sap in terms of impacts resulting upon its application as a biostimulant for improving crop productivity vís a vís chemical fertilizers either by the way of partial substitution or applying in conjunction with the latter. The technology developed by CSIR—CSMCRI for algal cultivation and the downstream processing of the fresh *K. alvarezii* seaweed to produce seaweed extract (sap) and carrageenan has been licensed to M/s. AquAgri Pvt. Ltd., India. This extract is being commercially used as a plant biostimulant in various continents (Asia, Australia). Recently the U.S. Agency for International Development (USAID) has supported the promotion of *Kappaphycus* sap in Africa [7]. The data used in this study are based on the production of *Kappaphycus* seaweed extract at an industrial scale.

2. Materials and methods

2.1. System definition and inventory

2.1.1. Goal and scope

The objective of this study was to assess the potential environmental impacts resulting from cultivation of *K. alvarezii* as well as the processing of its biomass. Therefore, the study was limited to sap production at factory gate, which constituted our base case scenario. In addition, environmental impacts resulting on account of transport of sap through various means (rail, road, ship) to the regional storage as well as its overseas oceanic transport were also assessed. The functional unit was accordingly defined as the inputs required for the production of 1 kL of extract. GaBi software (version 6.0) integrated with EcoInvent database version 2.2 as well as GaBi custom data sets were used for developing the various modules in the process chain viz., seaweed cultivation, transport to the processing unit and processing of extract. Bamboo, which is one of the inputs in the cultivation module for building rafts and its disposal has not been considered and excluded from the analysis as it was assumed to have been collected from natural stands. The ReCiPe 1.07 Midpoint method with a hierarchist perspective was used for carrying out the impact assessment. Different hypothetical scenarios apart from the base case, such as productivity increase, reduction of plastic requirements at the cultivation stage, improvement in the efficiency of extraction, improvement in electrical use efficiency, distance from shore to industry, reuse of plastic packaging at bottling and the best case scenario that could effectively bring about a reduction in the carbon foot print were also assessed using the GaBi analyst option. Environmental impacts arising from carrageenan production, a downstream process was not estimated although the allocation of impacts was carried out on economic basis with 29.3% distribution of impacts for semi-refined carrageenan and 70.7% for sap (Table 1).

Notably, carrageenan was the principal product for which the alga was being cultivated before the advent of this technology, wherein the fresh seaweeds were sundried and directly processed for the polysaccharide production. We believe that the present technology is economically effective in value addition through simultaneous production of liquid biostimulant and the solid residue which can be further processed for obtaining either carrageenan or semi-refined carrageenan. In addition, a substitution method was used for the various nutrients available in the sap that can effectively substitute for the requirement of chemical fertilizers. The overview of the system is presented in Fig. 1.

2.2. Data inventory for base case scenario

All the relevant requirements for onshore cultivation of *K. alvarezii* have been determined as per the optimized raft cultivation technique that has already been reported [10] and fairly carried out at industrial scale. The cultivation and processing steps along the value chain are based on the actual data with certain assumptions on the life span of the materials concerned and packaging while the transport process is based on a hypothetical system. In cases where relevant data sets for Indian conditions were not available, data sets from the EcoInvent database v2.2 were used. The data sets for diesel, cargo and electricity grid mix pertained to Indian conditions and were sourced from M/s PE International. All the requirements were determined for the functional unit on the basis of the ratio of usage to the assumed total life span of the materials concerned and the values following price allocation are given in Table 2. Since the relevant data sets to account for the machineries of the processing unit were not available, the quality and quantity of the constituent materials in these machineries were used as a function of usage to the assumed total life span of the material. The energy required for the processing of these materials into various forms was also taken into account. The energy requirements were estimated on the basis of the rating capacity of the electrical equipment, assuming that they were utilized at their maximum potential.

2.2.1. Onshore cultivation

The cultivation of *K. alvarezii* was carried out on bamboo rafts wherein four bamboo poles (3–4 in. dia.) of 3 m length were tied along the ends using polypropylene ropes in order to obtain intact square structure. Polypropylene (PP) ropes of lesser diameter than those used for tying the bamboo poles were used for seeding purpose as shown in Fig. 2. The inventory data used for the net fresh biomass production was based on the actual average yield of 200 kg per raft obtained under tropical conditions off the coast of Thonithurai (09° 17.057″ N and 079° 10.989″ E), Tamil Nadu, India. In contrast to the report [18] which advocates round the year cultivation of seaweeds under tropical conditions, our experience revealed that the cultivation of *K. alvarezii* seaweed occurs best under relatively calm conditions of the sea. The onset of monsoon which results in turbulent weather conditions resulting from cyclonic patterns in the Indian subcontinent is generally considered as an unfavorable season for raft cultivation of the macro-algae. Hence, in the present study, only five cycles of cultivation per year, each lasting for an interval of 45 days were considered with the scope that under calmer sea conditions this can be extended to 7 cycles. During the unfavorable conditions, the biomass is generally maintained in polyethylene tube-nets (fish net stitched in the form of a tube) anchored with stones. On account of this, there

Table 1
Hypotheses used for the financial allocation (INR = Indian Rupees).

Products	Product price		Quantity produced		Proportion of impact allocated
	Amount	Unit	Amount	Unit	
Sap	30	INR liter^{-1}	1000	liters	70.67%
Semi-refined carrageenan	300	INR kg^{-1}	41.5	kg	29.33%

was no absolute requirement of nursery for maintenance of the germplasm and hence not included in the analysis.

These rafts were anchored to the seabed by tying them to stones with PP ropes. In addition, high density polyethylene (HDPE) braider ropes and fishnets were generally used for tying seedlings to seeding ropes and for covering the bottom of the raft, respectively. The fish nets were used in order to prevent drifting down of the crop during cultivation period so as to preventing the loss of the same and also to safeguard the crop from grazers in the farm. In order to account for the PP and HDPE ropes, processes determining the impacts of their production at plant as well as their processing through extrusion have been included from the EcoInvent database. The disposal through landfill was employed to account for the disposal of plastics. A transport process using a van with less than 3 t capacity was included in the cultivation module to account for the transport of the all the raw materials such as stones, bamboo rafts, ropes, to the site of cultivation assuming a distance of 10 km.

2.2.2. Transport of biomass to processing unit

The biomass that was harvested was then transported to the processing unit which was assumed to be located at a distance of 100 km from the site of cultivation. The impacts were calculated using a customized transport process (developed by PE International) with parameters modified suitably to account for the combustion of diesel whose composition being the one produced at Indian refineries. It is worth mentioning here that the distance of the processing unit tended to influence the overall carbon foot print and hence included in the scenario analysis.

2.2.3. Inventory for sap processing plant

The inputs for the processing unit were calculated on the basis of processing capacity, life span and utilization time of the machinery. The processing plant considered in the present study is situated at Manamadurai, Tamil Nadu, India. It has a capacity of processing 30 t of fresh seaweed biomass per day in three shifts of 8 h. The sap extraction efficiency of the plant is 60% with a loss of 5%. The remaining 35% being the wet granule from which carrageenan is extracted following sun drying and other downstream processes. The shed module of EcoInvent database was utilized to account for the substructure. Manual dismantling of industrial devices was employed to account for the disposal of the conveyor system, while disposal route for recycling was considered to account for all the steel used in machineries and final disposal route was considered to account for the substructure. The process of sap expulsion from fresh seaweeds involves the transportation of the harvested seaweed biomass to the plant where it was unloaded onto a concrete platform having a volume of 62.5 m^3 that has an assumed life span of 50 years. From this platform, the biomass was loaded manually onto a conveyor system attached with a sprinkler unit that sprays fresh water to wash out any foreign particles. The freshwater requirement was considered at the rate of 1 l for every 4 kg of fresh seaweed. The water which usually becomes rich in potassium chloride (KCl) during the wash can be reprocessed either by evaporation or reverse osmosis for extraction of the KCl. However, water reprocessing and production of KCl were not accounted for in this model. The conveyor belt process of the EcoInvent database was used to account for the conveyor system, even though the actual conveyor being lighter in weight would entail much lesser environmental impact. A custom module representing Indian electricity grid mix, developed by PE International (GaBi) was used in the present study that accounts for the predominant coal based power generation in India. The important machineries that were accounted for at the processing unit are the conveyor system, crushing/grinding unit, the decanter (centrifuge), each with a processing capacity of 5 t per hour of biomass and slurry, respectively, storage tanks and piping. All were considered to be predominantly made up of stainless steel. However, the minor parts of the equipment were not accounted for. Data set from EcoInvent database was used to account for the impacts of the production of

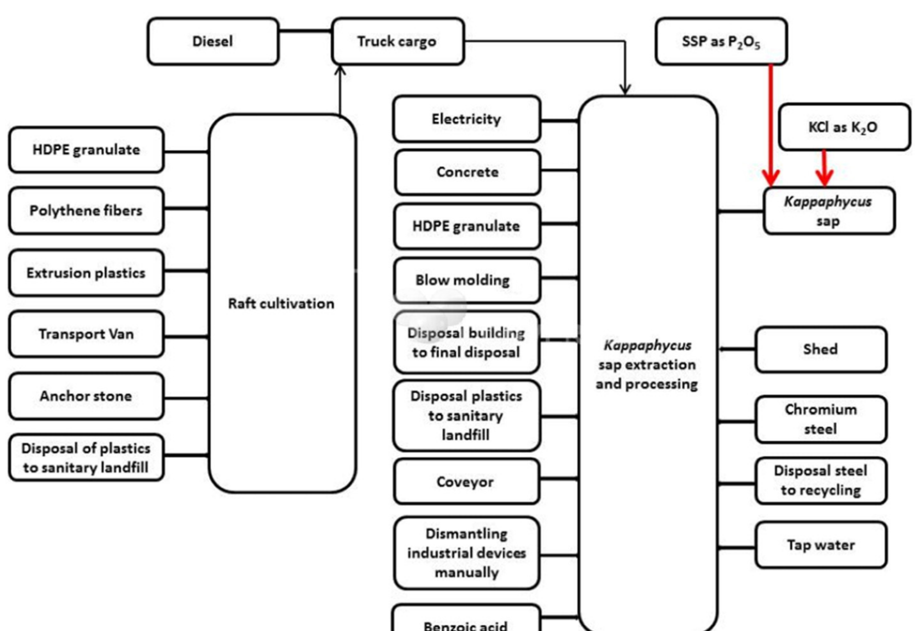

Fig. 1. Overview of sap production system from fresh *K. alvarezii* cultivated under onshore condition. Red arrows in bold indicate substitution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Inputs for production of biomass, its transport and processing for 1 kL of sap production at factory gate following price allocation.

Process	Material requirements	Quantity	Unit	Life span
Cultivation	Number of rafts required	8.33	Nos.	
	Polypropylene ropes	0.971	kg	10 cycles
	HDPE granulate	0.676	kg	10 cycles
	Transport	0.321	t km	
	Extrusion of HDPE into ropes	0.676	kg	
	Disposal of plastics to landfill	1.65	kg	
	Anchoring stone	1.06	kg	500 cycles
	Seaweed biomass	1180	kg	
Transport	Distance to processing unit	100	km	
	Cargo	1180	kg	
	Diesel	2.44	kg	
Sap extraction	Concrete platform	4.48×10^{-5}	m^3	50 years
	Shed	1.07×10^{-5}	m^2	50 years
	Electricity	68.9	MJ	
	Disposal building to final disposal	1.07×10^{-5}	m^2	
	Conveyor	1.58×10^{-5}	m	30 years
	Dismantling industrial devices manually	0.00789	kg	
	Chromium steel in crusher	6.72×10^{-4}	kg	30 years
	Steel in decanter	1.79×10^{-3}	kg	30 years
	Steel tank and piping	8.70×10^{-4}	kg	100 years
	Disposal of steel to recycling	0.0033	kg	
	Water	294	kg	
	Benzoic acid	0.706	kg	
Bottling/packaging	HDPE granulate	21.2	kg	
	Blow molding	21.2	kg	
	Disposal of plastics to sanitary landfill	21.2	kg	
Transport to regional storage	Distance	1500	km	
Transport overseas	Distance	7200	km	
Substitution	Potassium chloride as K_2O	25.3	kg	
	Single super phosphate as P_2O_5	0.0665	kg	

benzoic acid which was assumed as the preservative used in the extract although the commercial product in the market uses a proprietary organic preservative. The final packaging was assumed to be done in 5 l plastic carboys made up of HDPE.

2.2.4. Nutrient substitution

Since *K. alvarezii* tends to absorb nutrients especially N and P which play a role in eutrophication, the net amount of P (29 mg L^{-1}) present in the extract [7] was subtracted to account for the gains in eutrophication potential, although, the N was not accounted for, as the accumulation of N in this seaweed at 85 mg L^{-1} was negligible. In addition, the sap contained high amounts of potassium [7] which was assumed to substitute for potassium fertilizer requirement. Thus, for the substitution module, the amount of potassium and phosphorus present in the sap (21 g L^{-1} and 29 mg L^{-1}, respectively [7]) was converted to K_2O and P_2O_5, respectively, and the impacts for the equivalent amount of fertilizer production viz., potassium chloride for K_2O and single super phosphate (SSP) for P_2O_5 were deducted from the overall impacts. As mentioned in the Goal and scope section, eight different scenarios were analyzed which can effectively bring about a decrease in the carbon foot print against the base case scenario and are presented in Table 3.

2.3. Transport of sap to regional storage

Three different hypothetical modes of transport system (rail, road and ship) have been considered for the transport of sap to regional storage located at an assumed distance of 1500 km. In addition, to simulate overseas export of sap, another hypothetical module involving long distance oceanic transport was also studied with an assumed distance of 7200 km.

2.4. Scenario analysis

Increase in average net biomass productivity from 200 to 250 kg was assumed in productivity increase scenario, which is a realistic figure. The increase in sap extraction efficiency from 60 to 65% was considered in another scenario that can overcome the original 5% loss observed during the extraction process. A 5% reduction in the total electricity requirement for running the machineries was also considered in one of the scenarios which can account for the use of improved or efficient motors and pumps. Reuse of plastic packaging's at bottling stage, at least once, reduction in HDPE plastics by 5%, location of the processing plant at distance of 0.5 km which would be nearer to the cultivation site were also considered in the scenario analysis. It must be noted that there is absolutely no requirement of water when the processing unit is located close to shore because seawater itself can be used for washing the biomass.

3. Results and discussion

3.1. Impacts under climate change at factory gate

Environmental impacts under different categories resulting from the various processes involved in sap production at factory gate, which is the base case scenario, are shown in Table 4. Life cycle impact assessment revealed that the carbon foot print of 1 kL of K-sap production is 118.6 kg CO_2 equivalents following price allocation. Percent contribution to the impacts by each of the processes in the sap value chain has been depicted in Fig. 3. Analysis of the individual processes in the value chain revealed that the processing and bottling of the extract accounted for 99.4% of the total impacts under the climate change category at factory gate while the other processes such as transport to the processing center and cultivation accounted for 7.5% and 3.9% of impacts, respectively, under this impact category. The nutrient substitution module accounted for a reduction of 10.8% CO_2 equivalents during extract production. This reduction or gain in CO_2 equivalents is mainly on account of the presence of significant amount of potassium (21 g L^{-1}) present in the seaweed extract that can effectively offset the requirement of chemical fertilizers by 25.3 kg per 1000 l sap when applied as a foliar spray on crop plants. A similar substitution method was used by Langlois et al. [18] to account for the phosphates, ammonium and potassium leachates produced during anaerobic digestion that can be used as fertilizers. The 3.9% impact under climate change in the cultivation process is predominantly due to the use of plastics (polypropylene ropes and HDPE ropes and nets) which accounted for 83.7% of the total in this process (cultivation phase), while transport of the raw materials accounted for 13% impact under this category in this value chain.

It has to be noted that carbon foot print for production of bamboo as well as its disposal were not included as many reports have considered the biomass as carbon neutral [21,22]. In the processing module, plastic packaging (HDPE production and blow molding process), electricity and shed accounted for 97.3% of the total impacts under climate change for this module with plastic packaging alone accounting for 54.2% and electricity accounting for 25.2% of impacts under this category. Hence, these parameters were included in the scenario analysis where reuse of these packaging bottles and use of efficient motors and pumps in a

b

Fig. 2. Onshore raft cultivation of *Kappaphycus alvarezii* a) at initial stage after seeding and b) at harvest.
(Photo courtesy: M/s. AquAgri India Pvt. Ltd.)

the machineries were envisaged in order to reduce the carbon foot print.

3.2. Environment impacts resulting from transport of sap

Among the different modes of transport, viz., rail, road and ship hypothesized for the movement of sap from factory to the regional storage, it was found that each mode of transport increased the impact under the climate change category by 51.8%, 138.5% and 14.1%, respectively, as compared to the impacts at factory gate (Fig. 4). Thus, it is obvious that transport of sap through ship is eco-friendly as compared to rail and road transports if the regional storage is located nearer to the seaport. Economy in GHG emissions by transporting goods through sea route compared to that by road, rail and air has also been discussed by Ghosh [23]. Further, even overseas oceanic transport (considered primarily to account for export of sap to other countries) assumed at a distance of 7200 km resulted in a modest 67.5% increase in impact over factory gate under the category of climate change (Fig. 5), emphasizing that even long distance oceanic transport may still be carbon friendly as compared to inland road transport over a distance of 1500 km.

Transport accounted for nearly 77% impacts under ODP in the cultivation module while blow molding and shed accounted for 97% impacts under the processing module. However, a significant gain of 173% in terms of ODP was obtained from the nutrient substitution module. This was predominantly attributed to a reduction in oceanic transport of potassic fertilizers which is the case in India. Further, it has been observed in the transport scenario that transport of sap through truck contributes to an increase of nearly 27.5 times in ODP with respect to impacts at factory gate (Fig. 3). It is well known that transport results in production of nitrous oxide which plays an important role in depleting the ozone layer [24].

3.3. Scenario analysis and climate change

Among the different scenarios hypothesized for reduction in the impacts, especially the carbon foot print, except for the scenarios involving reuse of plastic packaging and transport of biomass to the processing center, the rest of them reduced the overall impact under CC by less than 2% (Fig. 6). Surprisingly, even an increase in net biomass production by 25% from 200 to 250 kg per raft also did not have any significant impact on the reduction of carbon foot print at factory gate, as a mere 0.79% reduction was observed. However, the hypothesis of reuse of plastic packaging at bottling stage reduced the net carbon foot print by 28% compared to the impact in base case scenario, while reduction in transport distance from shore to processing unit reduced the impacts by 7.5%.

3.4. Use of plastics and their impacts

Recovery of energy for disposal of plastics during incineration is widely practiced in the developed countries. However, this route of disposal is not prevalent in India and the most common disposal route is through landfill. Hence the landfill route was considered here. Our study revealed that the production of plastics, its processing as well as their disposal had the propensity towards increasing the impacts under the category of freshwater ecotoxicity (FECO) as well as marine ecotoxicity (MECO) potentials. The expulsion of sap at the processing unit and the cultivation module accounted for 82% and 92% of impacts, respectively under the category of FECO. Similarly, MECO potential was increased by 79% and 90% for processing and cultivation modules, respectively, in the value chain due to the production and use of plastics. Further, among the contributions made by plastics, the disposal of plastics through sanitary landfill alone in particular accounted for a greater proportion of impacts under FECO and MECO potentials. Thus, sanitary landfill of plastics alone accounted for 78.6% and 44.6% of impacts, respectively, in the cultivation and processing modules for

Table 3
Values (unallocated) of parameters used in scenario analysis of sap production at factory gate.

Parameter	Base case	Productivity increase	Reduction of plastic requirements in cultivation	Improvement in the efficiency of extraction	Improvement (5%) in electrical use efficiency	Distance from shore to processing unit	Reuse of plastic packaging at bottling	Best case
Biomass (kg)	200	250	200	200	200	200	200	250
HDPE ropes and nets (kg)	0.96	0.96	0.912	0.96	0.96	0.96	0.96	0.912
Extraction efficiency (%)	60	60	60	65	60	60	60	65
Electricity (MJ)	97.56	97.56	97.56	97.56	92.68	97.56	97.56	92.68
Distance (km)	100	100	100	100	100	0.5	100	0.5
HDPE carboys (kg)	1.5	1.5	1.5	1.5	1.5	1.5	0.75	0.75
Water (kg)	416.7	416.7	416.7	416.7	416.7	0	416.7	0

Table 4
Absolute values of various environmental impacts under different processes during preparation of 1 kL of sap as measured by ReCiPe 1.07 Midpoint (H) method.

Environmental quantities (ReCiPe 1.07 Midpoint (H))	Seaweed cultivation	Transport to processing center	Sap processing	Substitution	Total
Agricultural land occupation [m^2]	0.119	0.001	75.940	−0.563	75.497
Climate change [kg CO_2-equiv.]	4.652	8.841	117.858	−12.756	118.594
Fossil depletion [kg oil eq]	3.164	2.984	52.985	−4.519	54.614
Freshwater ecotoxicity [kg 1,4-DB eq]	0.038	0.000	0.852	−0.107	0.783
Freshwater eutrophication [kg P eq]	0.000	0.000	0.027	−0.005	0.023
Human toxicity [kg 1,4-DB eq]	0.937	0.059	35.655	−6.312	30.340
Ionizing radiation [kg U235 eq]	1492.711	22.208	9251.294	−609.669	10,156.544
Marine ecotoxicity [kg 1,4-DB eq]	0.033	0.001	0.783	−0.110	0.707
Marine eutrophication [kg N-equiv.]	0.011	0.004	0.148	−0.002	0.160
Metal depletion [kg Fe eq]	1.067	0.017	6.303	−2.570	4.817
Natural land transformation [m^2]	1.446	0.000	27.164	0.005	28.614
Ozone depletion [kg CFC-11 eq]	0.00000011	0.00000000	0.00000268	−0.00000177	0.00000102
Particulate matter formation [kg PM10 eq]	0.005	0.005	0.218	−0.019	0.210
Photochemical oxidant formation [kg NMVOC]	0.017	0.014	0.480	−0.051	0.459
Terrestrial acidification [kg SO_2 eq]	0.014	0.013	0.531	−0.044	0.514
Terrestrial ecotoxicity [kg 1,4-DB eq]	0.000	0.000	0.008	−0.002	0.007
Urban land occupation [m^2]	0.027	0.000	14.893	−0.718	14.202
Water depletion potential [m^3]	5.866	0.728	287.768	−32.157	262.205

FECO and 75.2% and 40.8% of impacts in the cultivation and processing modules for MECO. Moreover, the process of the disposal of plastics through sanitary landfill was responsible for more than 95% and 87% of impacts under marine eutrophication category in the cultivation and sap processing module, respectively. Thus, it becomes imperative to replace plastics by other substances that can reduce the environmental impacts. In this direction, the use of biodegradable polymers or bioplastics [25] to substitute the plastic requirement might enable lowering of impacts pertaining to this process, albeit only after ascertaining their ecofriendly nature as it has been reported that none of the commercially available bio-based plastics are sustainable [26].

Evidently, transportation of pristine extract as a liquid considerably increases impacts under many of the impact categories, especially CC and ODP. Hence, even though this extract is extremely effective as a biostimulant, it would be desirable to concentrate it for accruing further environmental gains. This would also enable further reduction in the use of plastics as packaging material which had significant impacts. Another intriguing result was that location of the processing unit closer to shore did not have a significant impact on water depletion potential as the blow molding process of plastics was observed to be the major water consuming process rather than water requirement for washing of seaweeds.

The life cycle assessment of *Kappaphycus* based liquid seaweed extract carried out in the present study would enable to quantitatively compare the environmental benefits following the use of this biostimulant on various crops, be it by way of substitution of chemical fertilizers or by supplementation. The importance of sap in enhancing grain production in an environmentally sustainable manner can be gauged from one of our earlier studies which brought out the fact that cultivation of maize on one hectare of land entails 599 kg CO_2 equivalents on account of fertilizer production and transport even without accounting for farm emissions from soil after application (assuming recommended rate of fertilizers at 150:60:40 kg N:P_2O_5:K_2O ha^{-1} applied through urea, di-ammonium phosphate (DAP) and muriate of potash (MOP)). In contrast, foliar spray of 142.5 l *Kappaphycus* sap, equivalent to an emission of 25.65 kg CO_2 equivalents per hectare (assuming transport through rail for a distance of 1500 km), significantly increased the grain yield of maize by 21.4% over and above the

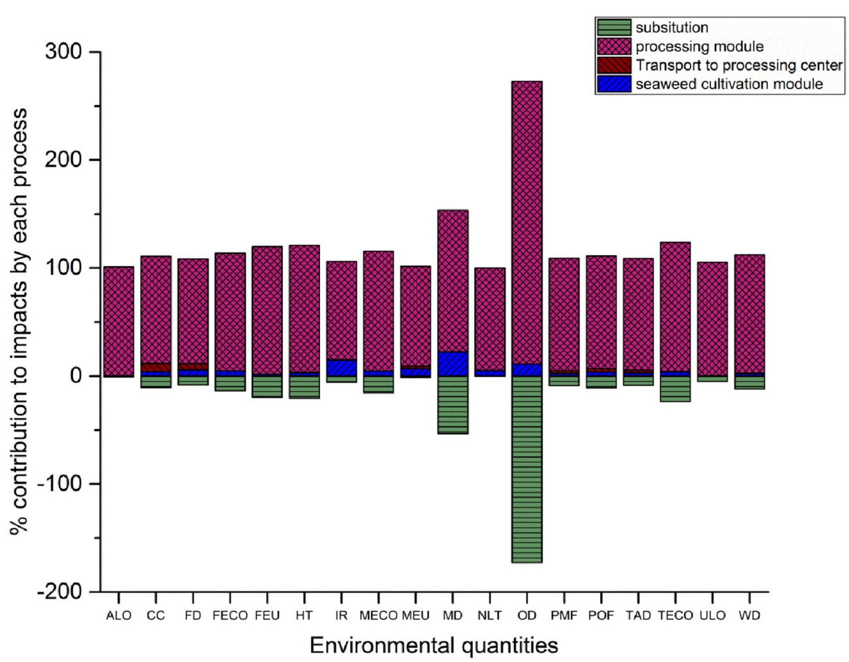

Fig. 3. Percentage contribution of the processes to various environmental impacts during production of 1 kL of sap at factory gate.

Fig. 4. Influence of the various modes of transport of *Kappaphycus* sap to regional storage on the environmental impacts compared over factory gate (top left—factory gate—the base case; top right is truck transport; bottom left—rail transport; bottom right—ship transport). The scales for all the impacts are same as that in CC unless otherwise indicated.

recommended rate [27]. This was a mere 4.3% addition of impact under CC over that produced on account of the required fertilizer inputs. We opine that a similar enhancement in yield through additional use of chemical fertilizers, if at all, would have involved much higher environmental impacts. Further, unlike chemical fertilizers, the foliar spray of seaweed based biostimulants does not entail any further environmental emissions after its application.

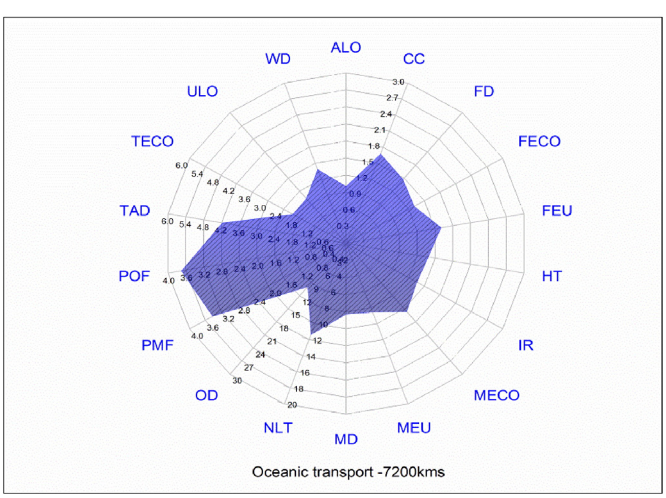

Fig. 5. Influence of overseas oceanic transport of *Kappaphycus* sap on the environmental impacts compared over factory gate. The scales for all the impacts are same as that in CC unless otherwise indicated.

4. Conclusions

Pristine sap extracted from the seaweed *K. alvarezii* was found to have a low carbon foot print of 118.6 kg CO_2 equivalents per kiloliter of its production at factory gate. Transportation of sap by road to the regional storage was found to have higher environmental impacts compared to that by rail and sea routes. Formulation of concentrated extract albeit without loss of its active ingredients would result in considerable reduction across several environmental impact categories. Reducing the use of fossil based plastics in the process by substituting with other bio-based products or by reusing the storage containers would apparently render the product even greener. The present investigation would enable to quantitatively assess the hypothesized reduction in environmental impacts upon partial substitution or supplementation of chemical fertilizers by *Kappaphycus* seaweed extract.

Conflict of interest

The authors declare that they do not have any conflict of interest.

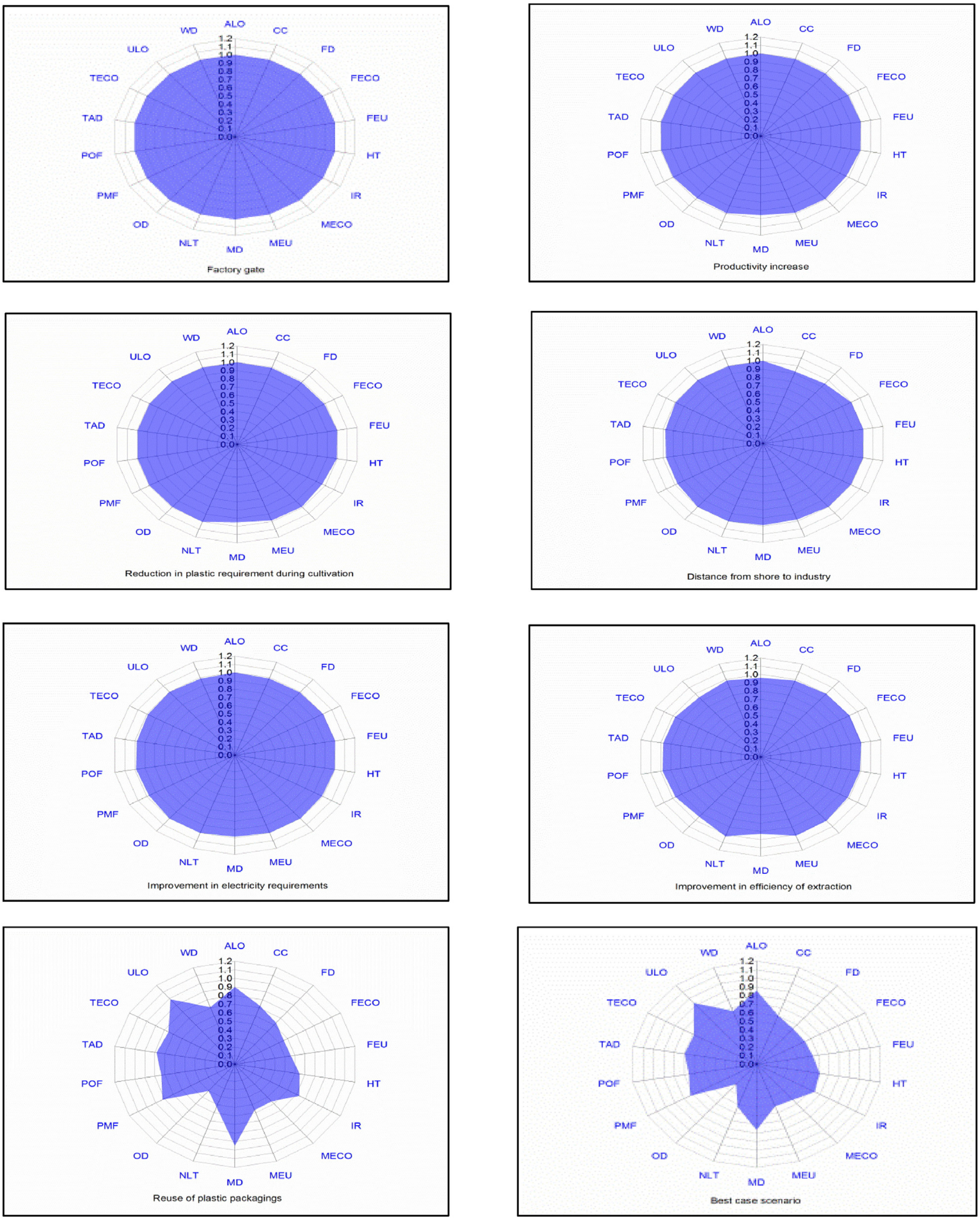

Fig. 6. Influence of process improvement parameters on the environmental impacts of *Kappaphycus* sap production compared to base case scenario at factory gate. The scales for all the impacts are same as that in CC unless otherwise indicated.

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