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Sustainable agro-technology for enhancement of rice production in the red and lateritic soils using seaweed based biostimulants

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A B S T R A C T

A field trial was conducted to evaluate the efficacy of *Kappaphycus* and *Gracilaria* based seaweed extracts (SWEs) to enhance the yield of rice in red and lateritic soils and also simultaneously assess the sustainability of the use of SWEs through life cycle assessment. A total of thirteen treatments involving combinations of recommended rate of fertilizers (RRF) 80: 40: 40 N: P_2O_5: K_2O kg ha^{-1} and SWEs applied at concentrations (2.5, 5, 7.5, 10 and 15%) were tested along with a suitable control (water spray + RRF) in a randomized block design. The efficacy of SWEs at 7.5% was also tested with lower dose of RRF (50% RRF). The SWEs were foliar applied 25, 50, and 70 d after transplanting of rice. Life cycle impact assessment (LCIA) for the production of fertilizers and SWEs required for 1ha of rice cultivation was carried out using ReCiPe Midpoint method and were expressed as impacts t^{-1} of rice production. Combined analysis of data of the experiment revealed that SWEs from *Kappaphycus* (KSWE) and *Gracilaria* (GSWE) when applied at 15% concentration significantly increased the grain yield of rice by 29% and 28%, respectively, over control; however, SWEs at 10% gave more net benefit per unit investment compared to the control. Notably, the grain yield in the treatments involving combination of SWEs with 50% RRF was statistically at par with control. LCIA revealed that in comparison to the control, maximum reductions of 11.4% and 14.8% in climate change (CC) impact category t^{-1} of rice were obtained in treatments involving combination of RRF with 15% KSWE and 10% GSWE, respectively. Interestingly, treatments involving 50% RRF + SWEs brought about at least 43% reduction in CC impact t^{-1} of rice, which amounts to savings of about 35 kg CO_2-equivalents t^{-1} of rice. Similarly, reductions were also observed for other impact categories. SWEs offer great promise in global perspective towards mitigating climate change as well as other environmental impacts and sustainably increasing rice yield.

1. Introduction

India is the world's second largest producer and largest exporter of rice. With 44 M ha, India ranks number one globally in paddy area and with 104 Mt (Arya and Kumar, 2014) stands next only to China in total paddy production. However, the productivity of rice is low in India (3721 kg ha^{-1}) when compared to the world average of 4548 kg ha^{-1} and other leading rice growing countries like China 6775 kg ha^{-1} (Bodh and Rai, 2015). Rice productivity is constrained by edaphic (soil) conditions. It is a challenge to cultivate crops in red and laterite soils (a clayey soil horizon rich in iron and aluminium oxides) because of its low fertility, acidic pH, low plant nutrient availability and metal toxicity. Tardy (1997) calculated that laterites account for about one-third of the Earth's continental land area. India has vast stretches of land (0.246 M km^2) under the category of laterite and lateritic soils spread across diverse agro-ecological

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Abbreviations: SWE, seaweed extract; RRF, recommended rate of fertilizers; DAT, days after transplanting; MOP, muriate of potash; SSP, single super phosphate; KSWE, *Kappaphycus* seaweed extract; GSWE, *Gracilaria* seaweed extract; INR, Indian Rupees; t, Tonne.

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regions. Laterite soils in India are predominantly found in the states of Odisha, Kerala, Maharashtra and in some parts of Andhra Pradesh, Tamil Nadu, Karnataka, Meghalaya and Western part of West Bengal. To overcome the constraints posed by these soils, relatively higher use of fertilizer is required to realize optimum yield as compared to the favourable soil types. However, excessive use of inorganic inputs towards raising crop productivity has severe detrimental effects on the environment (Tilman, 1999). It is well known that rice production contributes to the bulk (55%) of the agricultural greenhouse gas emissions in the world (Alam et al., 2016). Further, Yan et al. (2015) have reported that use of synthetic fertilizers account for approximately 50% of the total carbon foot print during rice production. The strategies to improve productivity should be ideally using inputs and techniques not only with low carbon footprint but also with the potential to reduce and mitigate various environmental impacts on account of rice production. In this context, seaweed based biostimulants are a greener alternative towards sustainably increasing crop yields (Ghosh et al., 2015). Unlike the traditional organic inputs employed in rice production which usually result in increased environmental impacts, at least in the short term (Hokazono and Hayashi, 2012), these biostimulants are unique wherein stable yield improvements are observed when used along with conventional fertilizers.

Kappaphycus alvarezii and *Gracilaria edulis* are two important tropical seaweeds whose cultivation technology has been developed in India. The extracts obtained from these seaweeds contain plant growth regulators, macro-, micro-nutrients as well as quaternary ammonium compounds. They have been reported to enhance productivity in many crops such as soybean (Rathore et al., 2009); in wheat (Zodape et al., 2009); rice (Pramanick et al., 2014a); rice-potato-green gram cropping system (Pramanick et al., 2014b) and in maize (Singh et al., 2016). This extract is being used extensively in other continents also (Ghosh et al., 2015). Life cycle assessment is a tool to quantitatively measure and establish the basis of sustainability and identify the processes that contribute to greater impacts and help in mitigating them. Recently, we reported the sustainability of use of these SWEs in maize (Singh et al., 2016). The present study was undertaken to test our hypothesis that the use of SWEs can sustainably bring about incremental yield advantage over and above the recommended rates of fertilizers in rice system and also to test whether there is scope to reduce the chemical fertilizer inputs without compromising the yield advantage, which has been hitherto not carried out. The investigation also sought to quantify the changes in environmental impacts by this intervention using life cycle impact assessment.

2. Materials and methods

2.1. Experimental site, design and treatments

A field experiment was conducted on rice in the red and lateritic soil of West Bengal, India, during the *kharif* season (July to November) of 2012 and 2013, consecutively, at the research farm of Institute of Agriculture, Visva-Bharati, Sriniketan, Birbhum, West Bengal which is located at 23° 40.167′ N and 87° 39.492′ E. The variety of rice used in the experiment was Swarna (MTU 7029). The altitude was 58.9 m above mean sea level and the area falls under sub-humid, sub-tropical belt of West Bengal. The soil was moderately acidic with pH of 5.5 and it was low in available nitrogen (137.6 kg ha^{-1}) and potassium (124.7 kg ha^{-1}), while it was medium in phosphorus (15.4 kg ha^{-1}). The experiment was conducted in Randomized Complete Block Design (RCBD) having thirteen treatment combinations consisting of full or half dose of recommended rate of fertilizers (RRF) and SWEs applied as foliar spray at different concentrations (v/v) as per treatments. The treatments were replicated thrice. The net plot size was 5 m × 3 m in which the plants were transplanted at a spacing of 20 cm × 15 cm. The RRF was 80: 40: 40 N: P_2O_5: K_2O kg ha^{-1} applied manually through urea, single superphosphate (SSP) and muriate of potash (MOP). The SWEs of *Kappaphycus* (KSWE) and *Gracilaria* (GSWE) were foliar sprayed as per treatments at 25, 50, and 70 d after transplanting (DAT) of rice. The spray volume was 600 L ha^{-1} for each spray. The water spray in the control plot was also done on the same days with the same amount of spray volume. Adjuvant (additive surfactant) was mixed in the tanks before spraying. The treatments are shown in Table 1.

2.2. Preparation of seaweed extract and its composition

The KSWE and GSWE were prepared as described earlier by us in Singh et al. (2016) and the extract used in the present experiment also belonged to the same batch as described earlier. The liquid filtrates obtained as per the method were considered as 100% concentration from which appropriate dilutions were prepared as per the treatments. The KSWE principally contained indole acetic acid, zeatin, choline, glycine betaine and potassium at a concentration of 27, 20, 57, 79, 33,654 mg L^{-1}, respectively, while the corresponding values in GSWE were 8.7, 3.1, 36, 63 and 682 mg L^{-1}, respectively. Apart from this gibberellic acid (GA_3) at 24 mg L^{-1} was present only in KSWE. The SWE also contained macro- and micronutrients in variable amounts (Singh et al., 2016).

2.3. Farm operations, data collection and analysis

Hand weeding was done at different times as per requirement. Herbicides were not applied in the experimental plot. One pre-transplanting irrigation was applied for puddling followed by four irrigations at tillering (branching) (30 DAT), panicle (inflorescence) initiation (PI) (60–70 DAT), flowering (90–100 DAT) and at milking (110 DAT) stages.

Randomly five hills per plot were selected and tagged for taking biometric observations on yield components and yield at harvest. The number of panicles per 1 m^2 were counted (at harvest). Ten panicles were selected randomly from the five tagged hills and then grains were separated and counted. The mean value was expressed as number of grains per panicle. One thousand grains were counted for each treatment and their mass were recorded as test weight and expressed in g. After harvesting and threshing of rice, both seeds and straw of individual plots were sun dried. Grains were separated from the rice plants in each plot and expressed in t ha^{-1}. Similarly, straw from each net plot was taken after complete drying in the

Table 1
Various treatments tested to evaluate the efficacy of the foliar application of seaweed extracts on the rice productivity. KSWE - *Kappaphycus* seaweed extract; GSWE - *Gracilaria* seaweed extract; RRF - recommended rate of fertilizers.

Treatments	Label
Water spray + 100% RRF (Control)	T1
2.5% KSWE + 100% RRF	T2
5% KSWE + 100% RRF	T3
7.5% KSWE + 100% RRF	T4
10% KSWE + 100% RRF	T5
15% KSWE + 100% RRF	T6
2.5% GSWE + 100% RRF	T7
5% GSWE + 100% RRF	T8
7.5% GSWE + 100% RRF	T9
10% GSWE + 100% RRF	T10
15% GSWE + 100% RRF	T11
7.5% KSWE + 50% RRF	T12
7.5% GSWE + 50% RRF	T13

field and expressed in t ha^{-1}. Nutrient content in rice grains and straw were analysed according to Jackson (1973).

Since the experiment was carried out in two seasons, pooled statistical analysis (combined analysis of data for analysis of variance) was done to estimate the average response to given treatments over 2 y of experimentation. The analysis of variance was carried out by standard procedure using Randomized Complete Block Design (RCBD) as per Fisher and Yates (1963). Post hoc comparison of means was carried out by Tukey's Honestly Significant Difference (Tukey's HSD) at $p < 0.05$ using MSTATC software (Michigan State University, East Lansing). Economic benefits t^{-1} of produce were estimated based on the prevailing market price of rice *i.e.*, Indian Rupees (INR) 15,000 t^{-1} and straw valued at INR 1000 t^{-1}. The common per ha cost of cultivation excluding the fertilizer cost was INR 38,658. The variable cost was attributed to different fertilizer and SWE doses, which varied according to the treatment. The cost of 100% RRF was INR 3102 ha^{-1} while that of both the SWEs was taken at the rate of INR 30 L^{-1}.

2.4. Life cycle assessment

Life cycle assessment was carried out using GaBi software, version 6.0 (PE international) integrated with Eco-invent database version v2.2, professional data sets of GaBi (PE International) as well as India specific data sets. The objective of the study was to assess ability of the SWEs, when applied at different concentrations in combination with 100 and 50% RRF, to reduce the impacts across various environmental categories. The scope of the present study was limited to determining the impacts under the various categories from cradle to gate of the processes involving the production and transport of inorganic fertilizers as well as the SWEs which are the only variable inputs required for fertilizing 1 ha of land under rice cultivation and expressed in the units of t^{-1} rice production (paddy). Since no mechanization was involved during application of fertilizers, no impacts resulted on account of their application, as all the fertilizers were applied manually. LCA was performed using the pooled data of grain and straw yield. Other common inputs for rice production such as land preparation, irrigation and pesticides were not considered in the present study. The system boundaries are depicted in Fig. 1. Price allocation was carried out in order to account for partitioning of the impacts between rice (paddy) and straw. For partitioning the impacts between grain and straw, price allocation was carried out using the ratio of market price of rice (paddy) to the sum of the market prices of straw and rice. In addition, emissions resulting following the application of inorganic fertilizers as well as SWEs (use phase) were also not considered in the present study. However, we believe that SWEs do not account for any environmental impacts following its application as the constituents are directly absorbed when applied as a foliar spray. Further, SWEs contained negligible quantities of nitrogen so as to have any significant environmental impact upon its application. Urea and SSP fertilizers unlike MOP are manufactured in India. But due to the absence of any data sets specific to Indian conditions, eco-invent datasets (for production of urea as N, SSP production as P_2O_5 and MOP as K_2O) which are already inclusive of their transport to regional storage were used as a substitute.

Since the entire potash requirement in India is sourced from other countries, an additional oceanic transport module was included to account for the impacts of its transport, assuming a distance of 5500 nautical miles. Indian data sets for electricity and diesel which account for the predominantly coal based power generation and sulphur content were used while determining the impacts of SWEs. Environmental impacts resulting from the production of KSWE, at factory gate, has been reported by us (Ghosh et al., 2015). This included various processes such as cultivation of the seaweed starting from nursery, harvesting, processing of the

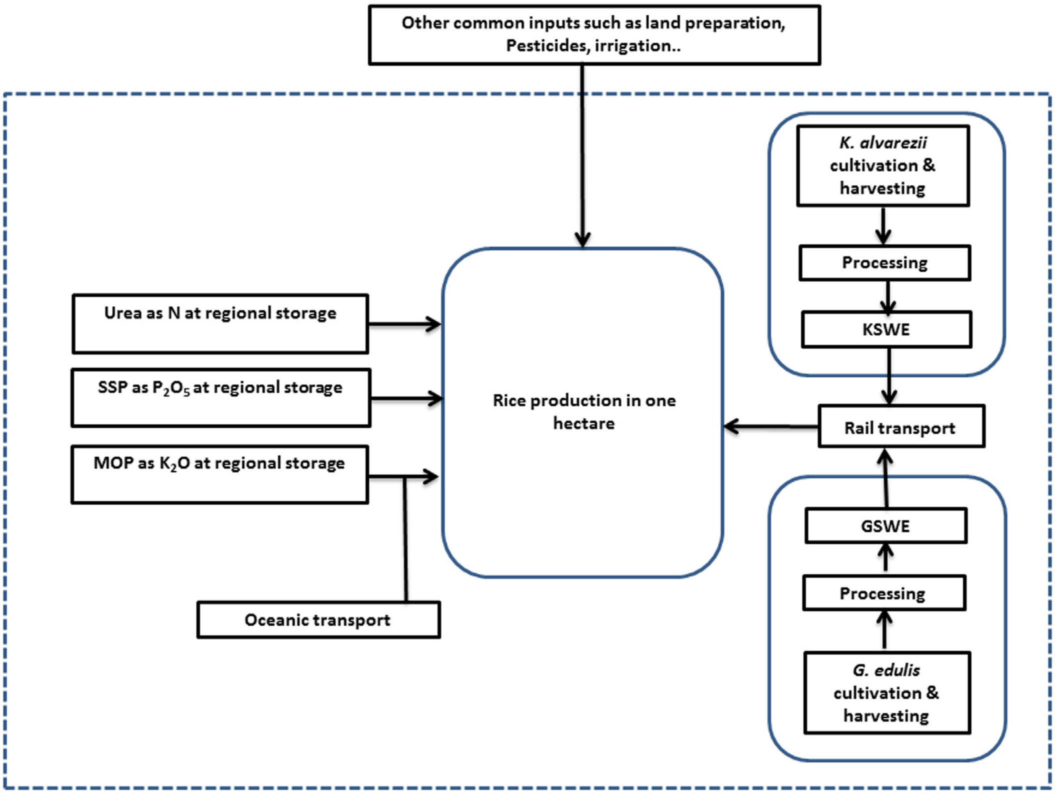

Fig. 1. Flow diagram depicts system boundaries (by broken line) in the present study. Other common inputs lie out of the system boundary.

Table 2
Influence of foliar application of seaweed extracts on the yield components, grain yield, straw yield of rice and monetary returns per hectare. Values followed by different superscript alphabets are significantly different at $p < 0.05$ by Tukey's HSD. KSWE - *Kappaphycus* seaweed extract; GSWE - *Gracilaria* seaweed extract; RRF - recommended rate of fertilizers, INR – Indian Rupees (1 US$ = 67 INR).

Treatments	Panicle per 1 m^2	Grains per panicle	Test weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Cost of cultivation (INR)	Gross return (INR)	Net Return (INR)
T1–Water spray + 100% RRF (Control)	385.9^{def}	134.2^{bcd}	18.65^{a}	4.44^{cd}	5.51^{bc}	41,760	72,110	30,350
T2–2.5% KSWE + 100% RRF	441.0^{cdef}	147.2^{abcd}	18.94^{a}	4.76^{abcd}	5.89^{abc}	43,110	77,290	34,180
T3–5% KSWE + 100% RRF	485.6^{abcd}	156.8^{abcd}	19.27^{a}	5.00^{abcd}	6.16^{abc}	44,460	81,160	36,700
T4–7.5% KSWE + 100% RRF	509.1^{abc}	166.6^{abc}	19.65^{a}	5.30^{abc}	6.51^{abc}	45,810	86,010	40,200
T5–10% KSWE + 100% RRF	569.0^{ab}	176.5^{a}	19.82^{a}	5.47^{ab}	6.71^{ab}	47,160	88,760	41,600
T6–15% KSWE + 100% RRF	599.8^{a}	188.5^{a}	20.33^{a}	5.74^{a}	7.02^{a}	49,860	93,120	43,260
T7–2.5% GSWE + 100% RRF	433.4^{cdef}	148.2^{abcd}	18.89^{a}	4.72^{bcd}	5.86^{abc}	43,110	76,660	33,550
T8–5% GSWE + 100% RRF	461.5^{bcdef}	155.3^{abcd}	19.55^{a}	4.93^{abcd}	6.10^{abc}	44,460	80,050	35,590
T9–7.5% GSWE + 100% RRF	481.3^{abcde}	163.5^{abcd}	19.74^{a}	5.22^{abcd}	6.42^{abc}	45,810	84,720	38,910
T10–10% GSWE + 100% RRF	525.5^{abc}	174.2^{ab}	19.93^{a}	5.61^{ab}	6.89^{a}	47,160	91,040	43,880
T11–15% GSWE + 100% RRF	578.5^{ab}	183.8^{a}	20.29^{a}	5.69^{a}	6.94^{a}	49,860	92,290	42,430
T12–7.5% KSWE + 50% RRF	362.4^{ef}	125.0^{cd}	19.13^{a}	4.42^{cd}	5.45^{c}	45,810	71,750	25,940
T13–7.5% GSWE + 50% RRF	346.8^{f}	123.3^{d}	19.08^{a}	4.33^{d}	5.37^{c}	45,810	70,320	24,510

seaweed to KSWE with appropriate allocation to the downstream co-product (Semi-refined carrageenan) while that of GSWE was estimated in a similar way (manuscript under preparation). A distance of 2275 km was assumed for the transport of SWE by rail from the site of its production to the experimental site. The ReCiPe Midpoint method with a hierarchist perspective was used for assessing the impacts as it has the broadest set of midpoint impact categories that have a global scope.

3. Results and discussion

3.1. *Effect of SWE on yield, yield attributes and nutrient content of rice*

Data recorded on yield and yield attributes are presented in Table 2. The number of panicles per unit area (1 m^2) varied from 346.8 to 599.8 across different treatments. Significant differences in number of panicles per 1 m^2 between control and other treatments were observed only at concentrations higher than 7.5% for both the SWEs applied in combination with RRF. In the case where KSWE was applied at 10 and 15%, the increases were 47.4% and 55.2%, respectively over control, while it was 36.2% and 49.9% for GSWE applied at respective concentrations. Notably, for this parameter, the treatments involving combination of either of the SWE's applied at 7.5% along with 50% RRF were at par with control (Table 2) suggestive of the fact that lowering the RRF even to an extent of 50% did not have a detrimental effect on the number of panicles per 1 m^2. Statistical differences between control and both the SWEs applied at the highest concentration, that is 15%, were significant for grains per panicle, while 10% KSWE + 100% RRF was also found superior (Table 2). All the treatments involving RRF in combination with either of the SWEs were, however, statistically at par to each other with respect to number of grains formed per panicle. Following the trend of the number of panicles per unit area, there was improvement in grain yield with increase in concentration of the SWEs, however, significant enhancement in grain yield over control was observed only in the treatments involving combinations of RRF with either of the SWEs applied at concentrations equal to or more than 10% with the maximum grain yield being observed in 15% KSWE and GWSE which was at 5.74 t ha^{-1} and 5.69 t ha^{-1}, respectively. This increase was about 29% and 28% over control for KSWE and GSWE, respectively. However, SWE applied at 10% and 15% concentrations were statistically similar with respect to grain yield. A very intriguing and a significant outcome of the present study was that the application of either of the SWEs even with half the RRF was able to maintain yield parity with control (4.44 t ha^{-1}) as observed for the treatments 7.5% KSWE + 50% RRF (4.42 t ha^{-1}) and 7.5% GSWE + 50% RRF (4.33 t ha^{-1}) under the given conditions. This would be at large beneficial to the marginal and resource constrained farmer of the region in order to achieve better productivity coupled with less inputs. The dry straw yield was found to be significantly increased over control by application of KSWE only at the highest concentration of 15% (27%), while GSWE was effective in enhancing dry straw yield by 25% at 10%

Table 3
Influence of foliar application of seaweed extracts on the nutrient content of rice. Values followed by different superscript alphabets are significantly different at $p < 0.05$ by Tukey's HSD. KSWE - *Kappaphycus* seaweed extract; GSWE - *Gracilaria* seaweed extract; RRF - recommended rate of fertilizers.

Treatments	N content (%)		P content (%)		K content (%)	
	Grain	Straw	Grain	Straw	Grain	Straw
T1–Water spray + 100% RRF (Control)	0.63^{a}	0.33^{e}	0.27^{c}	0.06^{b}	0.41^{bcd}	0.62^{ef}
T2–2.5% KSWE + 100% RRF	0.64^{a}	0.36^{cde}	0.29^{bc}	0.07^{ab}	0.42^{abcd}	0.63^{def}
T3–5% KSWE + 100% RRF	0.67^{a}	0.39^{bcd}	0.32^{abc}	0.07^{ab}	0.43^{abc}	0.66^{bcdef}
T4–7.5% KSWE + 100% RRF	0.69^{a}	0.41^{ab}	0.33^{ab}	0.08^{a}	0.45^{ab}	0.69^{abcdef}
T5–10% KSWE + 100% RRF	0.71^{a}	0.44^{ab}	0.35^{a}	0.08^{a}	0.45^{ab}	0.73^{abcd}
T6–15% KSWE + 100% RRF	0.73^{a}	0.46^{a}	0.36^{a}	0.08^{a}	0.47^{a}	0.77^{a}
T7–2.5% GSWE + 100% RRF	0.65^{a}	0.35^{de}	0.28^{bc}	0.06^{b}	0.42^{abcd}	0.64^{cdef}
T8–5% GSWE + 100% RRF	0.66^{a}	0.39^{bcd}	0.29^{bc}	0.07^{ab}	0.43^{abc}	0.66^{bcdef}
T9–7.5% GSWE + 100% RRF	0.67^{a}	0.41^{abc}	0.31^{abc}	0.07^{ab}	0.44^{abc}	0.72^{abcde}
T10–10% GSWE + 100% RRF	0.70^{a}	0.43^{ab}	0.33^{ab}	0.07^{ab}	0.46^{ab}	0.74^{abc}
T11–15% GSWE + 100% RRF	0.72^{a}	0.45^{a}	0.35^{a}	0.08^{a}	0.47^{a}	0.76^{ab}
T12–7.5% KSWE + 50% RRF	0.63^{a}	0.35^{de}	0.29^{bc}	0.06^{b}	0.39^{cd}	0.62^{ef}
T13–7.5% GSWE + 50% RRF	0.61^{a}	0.34^{de}	0.28^{bc}	0.06^{b}	0.37^{d}	0.61^{f}

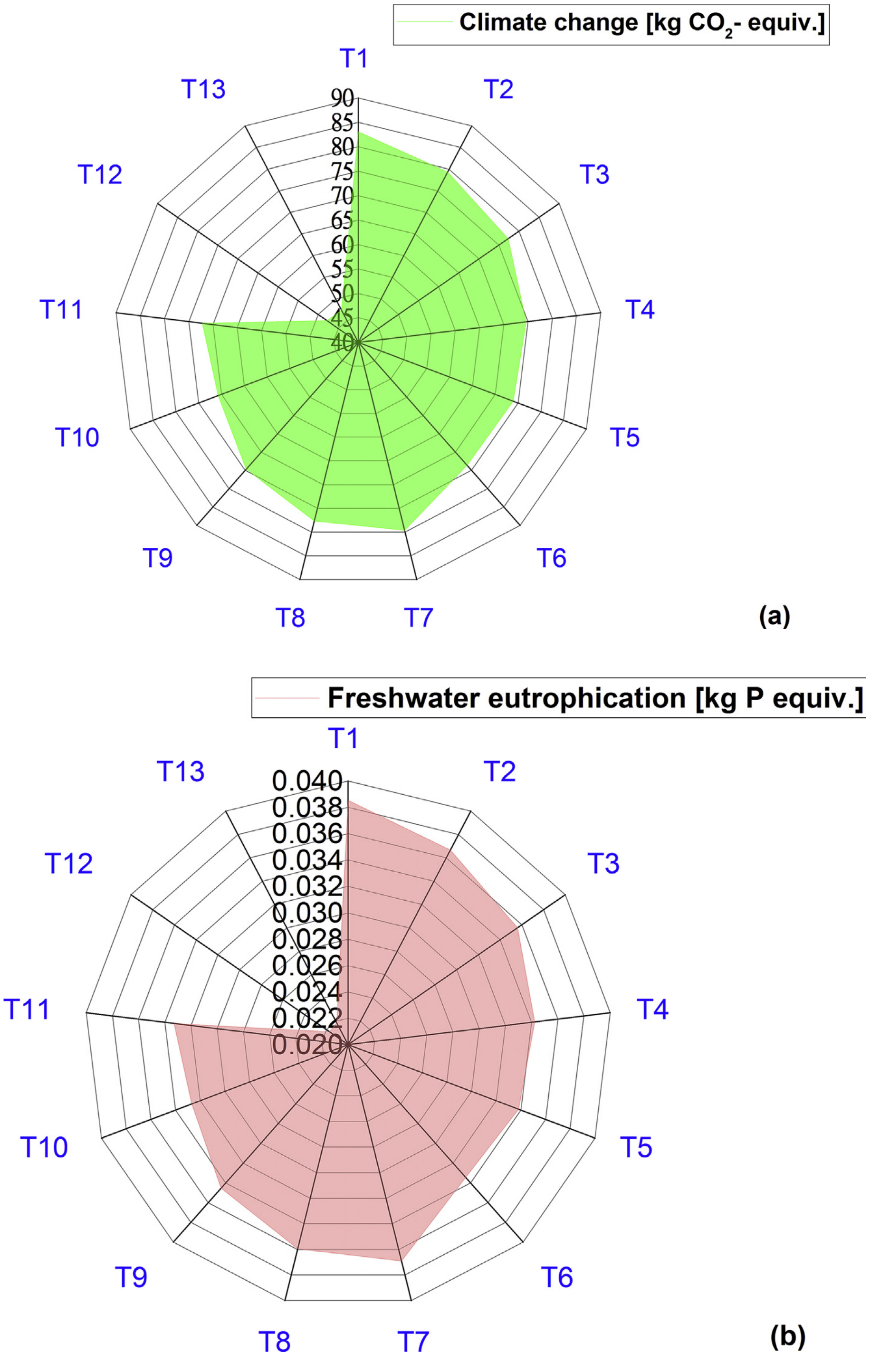

Fig. 2. Environmental impacts after price allocation per tonne of rice (paddy) production resulting on account of production of seaweed extracts and mineral fertilizers applied as per treatments given below (a) Climate Change (b) Freshwater eutrophication (c) Freshwater ecotoxicity (d) Water depletion. Treatment labels are the same as described in Table 1.

concentration and further increase in dosage did not alter the dry straw yield (Table 2). The SWEs apparently did not bring about any change in test weight (Table 2). The results of this experiment revealed that use of SWEs along with the RRF for rice crop in red and laterite soils was beneficial with respect to enhancement of grain and straw yield, however, the yield response is observed above a minimum threshold of SWE concentration (more than 7.5%). Evidently, the yield response due to application of SWEs was predominantly on account of increase in the number of panicles per unit area and the number of grains formed per panicle. Although not evident from the present study, it may be noted that the SWEs contain cytokinins which might be responsible for the increase in tillering and grain filling in panicles. SWEs are reported to stimulate endogenous concentration of cytokinins (Wally et al., 2013) which might also be responsible for the observed behaviour. Endogenous cytokinin production in rice was shown to be closely associated with tiller bud growth (Liu et al., 2011) and grain filling (Yang et al., 2000). Further, the higher leaf area index (LAI) observed at different duration of the crop cycle (data not shown) might also have supported the increase in the number of panicles per unit area and grains by allocating higher photosynthates. For either of the SWEs, higher net returns were obtained when KSWE was applied at the highest concentration, while it was 10% for GSWE (Table 2). The treatment 10% GSWE + 100% RRF recorded the highest return per unit investment.

Laterite soils are well known to be low in organic matter, macro-

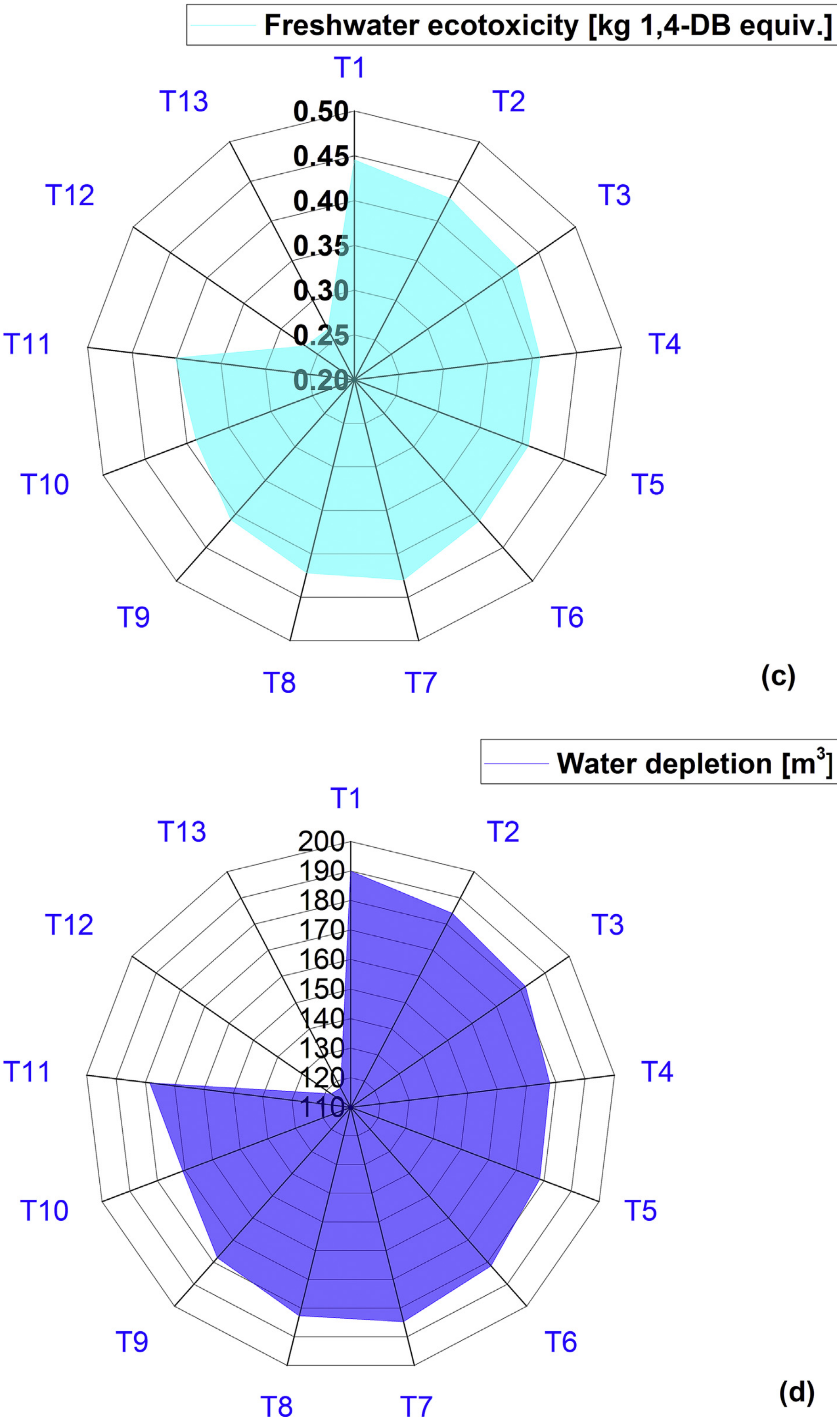

Fig. 2. (*continued*).

Table 4

ReCiPe Midpoint (H) values of the impact categories on account of production and transport of seaweed extracts and mineral fertilizers in treatments t^{-1} of rice production (paddy) following price allocation. KSWE - *Kappaphycus* seaweed extract; GSWE - *Gracilaria* seaweed extract; RRF - recommended rate of fertilizers; t – tonne (1 tonne = 1000 kg); FD - Fossil depletion [kg oil equiv.]; HT - Human toxicity [kg 1,4-DB equiv.]; IR - Ionizing radiation [kg U235 equiv.]; MECO - Marine ecotoxicity [kg 1,4-DB equiv.]; MEU - Marine eutrophication [kg N-equiv.]; MD - Metal depletion [kg Fe equiv.]; OD - Ozone depletion [kg CFC-11 equiv.]; PMF - Particulate matter formation [kg PM10 equiv.]; POF - Photochemical oxidant formation [kg NMVOC]; TA- Terrestrial acidification [kg SO_2 equiv.]; TECO - Terrestrial ecotoxicity [kg 1,4-DB.equiv.].

Treatments	Impact categories values t^{-1} of rice production										
	FD	HT	IR	MECO	MEU	MD	OD	PMF	POF	TA	TECO
T1–Water spray + 100% RRF (Control)	34.1	14.3	5.42	0.403	0.095	7.69	0.0000113	0.211	0.273	0.613	0.013
T2–2.5% KSWE + 100% RRF	32.6	13.6	5.29	0.388	0.092	7.30	0.0000106	0.200	0.264	0.580	0.012
T3–5% KSWE + 100% RRF	31.8	13.2	5.27	0.381	0.090	7.07	0.0000101	0.194	0.260	0.561	0.011
T4–7.5% KSWE + 100% RRF	30.7	12.7	5.18	0.371	0.088	6.79	0.0000096	0.187	0.253	0.537	0.011
T5–10% KSWE + 100% RRF	30.4	12.6	5.23	0.370	0.088	6.68	0.0000094	0.184	0.253	0.528	0.011
T6–15% KSWE + 100% RRF	30.2	12.4	5.38	0.372	0.089	6.58	0.0000090	0.182	0.255	0.518	0.011
T7–2.5% GSWE + 100% RRF	32.7	13.7	5.31	0.389	0.092	7.37	0.0000107	0.201	0.265	0.583	0.012
T8–5% GSWE + 100% RRF	31.8	13.4	5.28	0.383	0.091	7.19	0.0000103	0.196	0.260	0.565	0.012
T9–7.5% GSWE + 100% RRF	30.6	12.8	5.17	0.370	0.088	6.91	0.0000098	0.188	0.252	0.540	0.011
T10–10% GSWE + 100% RRF	28.9	12.1	4.99	0.353	0.084	6.54	0.0000092	0.177	0.241	0.509	0.010
T11–15% GSWE + 100% RRF	29.4	12.3	5.26	0.365	0.087	6.67	0.0000092	0.180	0.250	0.513	0.011
T12–7.5% KSWE + 50% RRF	19.6	8.1	3.49	0.242	0.058	4.27	0.0000059	0.118	0.166	0.336	0.007
T13–7.5% GSWE + 50% RRF	19.3	8.1	3.46	0.240	0.057	4.38	0.0000060	0.118	0.164	0.337	0.007

and micro-nutrients including potash. They have high Fe and Al content resulting in P fixation. These constraints coupled with low cation exchange and water retention capacity necessitates higher fertilizer requirements to achieve optimal yields which adversely costs environment and is therefore unsustainable in the long run. Here we demonstrated that these challenges could be overcome effectively by foliar application of SWE in order to obtain optimum yield. The SWEs are a concoction of various plant growth regulators, stress alleviators such as glycine betaine and also contain various micro- as well as macro-nutrients. These might have either contributed to direct uptake or stimulated enhanced uptake of nutrients from the soil as evident by higher mineral content in plant biomass (Table 3). The constraint of P availability to the plants in acid laterite soil was especially ameliorated by SWE application as it was found that at least 30% increase in P content in grain as well as straw over control was effected by either of the SWEs at the rate of 15%. Even lower dosage of P application in these high P-fixing soils also did not cause any reduction in P content of the rice plants as these treatments conjugated with SWE applications were observed to be at par to the control. A similar improvement in N and K content in grain and straw of rice was also observed by SWE treatments with the straw recording higher percentage improvement than grains (Table 3) which eventually might have contributed in recording higher yields.

3.2. Environmental benefits on account of SWE use

Any improvement brought out by agronomic intervention must also be environmentally benign and sustainable. Life cycle thinking is the need of the day in identifying sustainable solutions for global food security (Sala et al., 2017). In order to assess the sustainability angle of the use of SWE in enhancing the crop productivity, life cycle impact assessment was performed. The carbon footprint for the production of the inorganic fertilizers required for growing rice in 1 ha land area under the given conditions was found to be 393 kg CO_2-equivalents. The environmental impacts t^{-1} of rice on account of fertilizer and SWE are presented in Fig. 2 and Table 4. Compared to the control, the maximum reductions of 11.4% and 14.8% in CC impact category t^{-1} of rice were obtained in treatments involving combinations of RRF with 15% KSWE and 10% GSWE, respectively (Fig. 2a). Interestingly, a reduction of 50% inorganic fertilizer use in combinations with either of the SWEs brought about 43% reduction in CC impact t^{-1} of rice, which amounts to savings of about 35 kg CO_2-equivalents t^{-1} of rice (Fig. 2a). The results connote far reaching implications as rice is the major food crop in India and cultivated in at least 44 M ha with a production of 107 Mt. *Kappaphycus* and *Gracilaria* seaweed based biostimulants have also been reported to enhance grain yield of rice at other agro-ecological conditions (Pramanick et al., 2014a, 2014b). Recent multi-locational trials on rice conducted across various agro-ecological regions of India revealed that the use of SWEs in combination with 100% RRF resulted in ca. 20% yield improvement (unpublished results). Recently, we have a reported a reduction of 17.5 and 23.1% over control, in terms of global warming potential per unit of produce in 7.5% KSWE and 5% GSWE treatments, respectively, in maize, when used along with RRF (Singh et al., 2016). Assuming savings of 9.5 kg of CO_2-equivalents t^{-1} of rice as obtained in 15% KSWE treatment, enormous reduction to the tune of 1.01 Mt of CO_2-equivalents can be expected for rice production in India alone. The gains accrued would be much more if farm emissions due to use phase of inorganic N fertilizer is also considered. Notably, we believe that there are no emissions due to the use of SWE application to crops. The maximum percentage reductions of 13.2 and 15.2% in freshwater eutrophication (FEU) t^{-1} of rice were observed in 15% KSWE and 10% GSWE (Fig. 2b). Halving the inorganic fertilizer dose and conjugating with SWEs resulted in a reduction of at least 43% in FEU t^{-1} of rice. This amounted to an absolute reduction 0.02 kg P-equivalents t^{-1} of rice. Similarly, the reductions in freshwater ecotoxicity with respect to the control were 8.5% and 12.7% in 15% KSWE and 10% GSWE, respectively (Fig. 2c). Most strikingly, the use of SWEs in conjunction with 50% RRF resulted in a net reduction of about 77 m^3 in water depletion category t^{-1} of rice with respect to the control (Fig. 2d). Even when used with 100% RRF, 7.5% KSWE and 10% GSWE brought about a reduction of 12.8 and 20.4 m^3, respectively, in water depletion potential t^{-1} of rice. Similarly reductions were also observed in case of other impact categories like fossil depletion, freshwater ecotoxicity, human toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial ecotoxicity by combined dose of SWEs with 100% or 50% RRF. Thus SWEs offer great promise in global perspective towards mitigating climate change as well as other environmental impacts.

4. Conclusion

The use of SWEs sustainably increased yield of rice by 28–29% in fertility constrained red and laterite soils. The most striking feature of the present investigation was that yield parity with control was achieved by the combination of SWE's with 50% RRF that resulted in monetary and environmental gains. The results have immense global implication as significant reduction in carbon foot print t^{-1} of rice production can be achieved by using SWEs. Till now, the benefits of the use of seaweed biostimulants have not been focussed from the perspective and challenges of reducing environmental impacts in agriculture. Our result unequivocally brings out the immense possibility of effecting change on a global scale by use of such affordable and sustainable products.

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