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Algal bio-stimulants: Towards a sustainable agriculture

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The world's population is expected to peak at nearly 10 billion by the mid-2080s, while the demand for food is predicted to rise to ~400 million tons by 2080. With no option to extend farmland any further, increasing the yield per acre at minimal environmental cost is a viable option. Bio-stimulants offer a sustainable option to synthetic chemicals to improve plant health and enhance productivity. These chemical compounds, applied even in small quantities, generate a higher crop yield and confer resistance to biotic and abiotic stressors. The algae and algae-based products enhance seed germination, plant growth, and water and nutrient uptake in plants. Soil amendment with algae-based products improves soil structure and enhances fertility by providing macro- and micro-nutrients. Algae with a bouquet of bioactive substances in their tissues and total biomass are promising bio-stimulants. Cultivation techniques for macro-algae and micro-algae culture have immense potential for biomass generation and the production of bio-stimulants. Though India, with its vast coastline, has an abundance of algae, their potential in the food and agri-industry remains underexploited. There is a need to develop marketing strategies to popularise their use in agriculture. This can go a long way in meeting the SDG goals of sustainable consumption and Zero Hunger, as well as promoting good health and well-being.

Keywords: Agri-industry, Bio-stimulants, Macro-algae, Micro-algae, Soil health, Sustainable agriculture

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Introduction

There is a rapid increase in food, feed and fuel demand, which has put pressure on the agricultural produce[1]. With an estimated increase in population to 9.5 billion by 2050[2], which could peak at nearly 10.4 billion in the mid-2080s, the demand for food, feed and fuel is expected to grow by 70 percent[3]. In the past few decades, to increase crop productivity, the emphasis has been on the application of chemical fertilisers, pesticides, weedicides and intensive irrigation besides bringing more land under agriculture[4]. However, these practices have exacerbated pollution of soil and water bodies and are adversely impacting the environment and human health[5]. The low-input nature-based agriculture (biotic or organic agriculture) is eco-friendly and is therefore gaining momentum. Recent focus on Climate Smart Agriculture (CSA) to augment the agriculture practices in the face of climate change for sustainability is seen as a good strategy[6].

Application of bio-fertilisers (living or latent cells) for improving nutrient availability and uptake from soil is on the rise. Bio-fertilisers are composed either of a single microbial strain or more than one strain, the consortia which may include *Acetobacter*, *Azotobacter*, *Pseudomonas* and arbuscular mycorrhiza. Despite the benefits offered by the group of microorganisms, the independent use of microbe-based bio-fertilisers is not enough to meet the demands of a growing population. Therefore, integrated farming practices, along with new innovations such as the use of bio-stimulants, are sustainable options that contribute to smart agricultural practices.

Bio-stimulants are biologically derived products that improve plant productivity because of novel properties offered by constituent complexes. They are a discrete class of products with essential nutrients, plant growth regulators and plant protective compounds that are important for plant metabolic processes[7]. They are not considered as fertilisers because they do not provide nutrients directly to the plants; instead, they stimulate metabolic processes in plants that improve nutrient uptake (Fig. 1). Their primary function is to facilitate nutrient uptake by modifying rhizosphere and plant metabolism, besides offering tolerance to stressors and improving crop quality. European Bio-stimulant Industry Council

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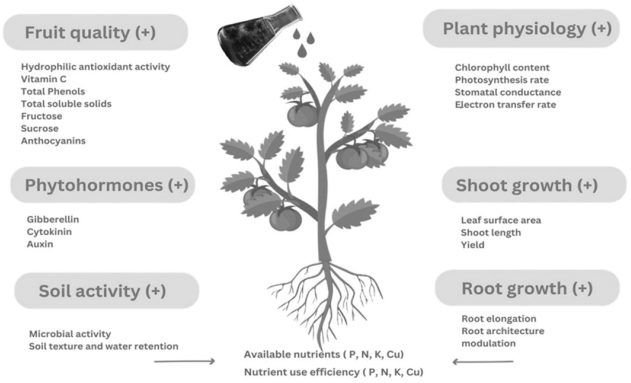

Fig. 1 — Diagrammatic representation of the overall amelioration of plant growth by bio-stimulants.

(EBIC) explains that bio-stimulants increase nutrient use efficiency, help plants tolerate abiotic stressors and improve the quality and yield of crops. Plant bio-stimulants are derived from humic substances, algal extracts, protein hydrolysates and microorganisms[8].

The potential of bio-stimulants to meet the Sustainable Development Goals (SDGs) set for 2030 has also added impetus to the research in the area. The research on food and vegetable crops, legumes, wheat and tomato plants has shown an increase in yield with bio-stimulant application[9]. Additionally, the bio-stimulants, even if leached to groundwater or run off to surface water, do not cause water pollution, catering to SDG 6. Therefore, exploring the newer sources of bio-stimulants, such as algal flora, standardising the extraction procedures and developing efficient purification protocols is important.

The present review projects the efficacy and potential of algal bio-stimulants with special emphasis on macro-algae, which are presently the basis of intensive research in agri-industry[7,9].

Algal bio-stimulants

The right to safe and healthy food is a fundamental right of every citizen. However, soil and water pollution on account of excessive use of agri-chemicals is contaminating the food resources. The Food and Agricultural Organization (FAO) advocates for the adoption of eco-friendly practices in agriculture so that human health is not compromised. Therefore, over the last few years, organic and eco-friendly practices have been adopted by farmers all across the world to increase the yield. Compost, mulch, bio-fertilisers and more recent bio-stimulants are being used for improving the soil fertility without compromising on soil health[10]. Algae have long been considered as potential soil conditioners and bio-fertilizers[11]. Furthermore, the profiles of algal extracts do not contain compounds at a level to qualify them as fertilizers[12]. Whether liquid extracts from macro-algae should be considered as bio-fertilisers or bio-stimulants has been investigated in detail by several workers[13]. The minimum concentration of hormones that elicits phenotypic changes within plants is given as 100 nM for auxins[14,15], 10 nM for cytokinins[16,17,18] and 100 nM for brassinosteroids[19]. According to the literature available[20], the hormone concentration is too low in the algal liquid extracts (nanograms or picograms per mL) and in some cases, it may be even below the detection level. The role of these extracts as bio-fertiliser is therefore unconvincing. Algal bio-stimulants are largely derived from three major groups - Chlorophyceae, Phaeophyceae and Rhodophyceae, though some Cyanophycean members are also the source of biomass for extract preparation[21]. These bio-stimulants are effective in minute quantities and can tweak some fundamental developmental cascades in plants, enhancing the vegetative growth and reproductive processes. Unlike bio-fertilisers, they even help to mitigate stress tolerance, due to which these extracts have gained a lot of importance in agri-industry[8,22]. The role of Cyanophyceae or blue-green algae is unparalleled and well established in soil reclamation and amelioration of soil health.

Micro-algal bio-stimulants

Micro-algae such as *Spirulina platensis, Nostoc* spp*., Phormidium* spp*.,* and *Plectonema* spp. have been used for decades as bio-fertilisers and soil conditioners. The nutrient-rich profile of algal biomass has effectively enhanced soil health. The biomass has been widely used to improve soil physico-chemical properties that have an impact on plant growth[23]. The micro-algal polysaccharides secreted into the surrounding medium are termed exopolysaccharides (EPS). The exopolysaccharides from *Chlorella vulgaris*, *Porphyridium cruentum* and *Dunaliella salina* have a bio-stimulatory effect. Such polysaccharides may activate regulatory mechanisms required to stimulate defence mechanisms and mitigate ROS toxicity. Further, *Chlorella vulgaris* and *C. sorokiniana* produce polysaccharides with β-1,3-glucanase activity, having the potential to break down pathogen cell wall[24,25]. As a result of these properties, micro-algae-based bio-stimulants are an integral tool in agriculture. Single-celled algae such as *Chlorella* and *Spirulina,* which are easy to culture, are used in

promoting a positive physiological response in plants. Commonly, the micro-algae-based bio-stimulants in the market are produced from *Arthrospira platensis* (blue-green algae) and *Chlorella* spp. (green algae)[26]. The extracts or hydrolysates or protein hydrosylates thus produced using enzymatic methods can be applied directly by foliar methods (or fertigation) to the plants. The efficacy of bio-stimulants in enhancing plant growth is dependent on the micro-algae species used and the environmental conditions in which these algae are naturally found or are cultured[27]. A study conducted on lettuce with *Scenedesmus quadricauda* extract as a bio-stimulant resulted in increased growth and enhanced biochemical parameters[28]. Such an increase was observed in shoot length, chlorophyll, carotenoid and protein contents. The positive effect on the enzymatic activities of glutamate synthase (GOGAT in nitrogen metabolism), citrate synthase (CS in carbon metabolism), and phenylalanine ammonia lyase (PAL in secondary metabolism) probably stimulated these effects[28].

Bio-stimulants from micro-algae led to enhanced growth and yield in green gram[29], bean[30] and several other plants. Although the micro-algal bio-stimulants are commonly listed in natural agri-products, the products need to be cost-effective. It would also be interesting to unravel the synergistic effect of micro-algae bio-stimulants in combination formulations.

Role in enhancing soil health

Since Cyanophyceae secrete polysaccharides in copious amounts in the soil, they act as soil binders and conditioners. The mucilage, which binds soil particles, is also able to retain water for a long time and check desiccation[31]. The improved soil structure is more stabilised and less prone to erosion[32]. Soils mixed with micro-algae are enriched in available N, organic matter, and other nutrients[33,34]. They can form Cyanophycean soil crusts in desert soils as a result of the formation of soil aggregates by Cyanophyceae due to the sticky polysaccharides. This reduces desert soil vulnerability to soil and water erosion[35].

The unmatched role of Cyanophyceae as soil conditioners is an attribute of EPS, which is composed of a wide range of monosaccharides. Various hexoses, pentoses and uronic acids present in EPS confer a hydrophobic nature, while phosphates, sulphates, and peptides render them negatively charged[36]. The micro-algae are considered a renewable resource for agriculture. They can help meet demands such as biological nitrogen fixation, soil phosphorus cycling, rhizosphere flora, soil nutrient recycling, root associations, biocontrol and fighting the abiotic stressors.

Macro-algal bio-stimulants

There are four main segments in the bio-stimulant market: macro-algae extracts, fulvic or humic acids, microbial bio-stimulants, and amino acids. Of these, macro-algae extracts offer the largest, accounting for around 40 per cent of the total market. Europe is considered one of the biggest markets for bio-stimulants, valued at USD 2.6 bilion in 2019, the market is expected to gain further momentum in the coming years[37,38].

Data Bridge Market Research indicates an increase in global macro-algae extract used as bio-stimulant from USD 1.11 billion in 2023 to USD 2.94 billion by 2031[39]. According to the literature available[40], macro-algae bio-stimulant industry is estimated to reach US$4.14 billion by 2025. Interestingly, a plethora of studies conducted in India have also demonstrated the growth regulatory properties of macro-algae extracts. Investigations have shown that application of macro-algae biomass and extracts below the soil or as foliar sprays simulates the production of plant hormones. The research on marine bio-stimulants is gaining momentum due to their phyto-elicitor activity[41].

Macro-algae extracts are primarily used as bio-stimulants as they evoke defence responses in plants and help build resistance against abiotic stresses such as high temperature, moisture and salinity (Fig. 2). They are also compatible with other crop inputs and are effective with other microbial formulations, which paves the way for an integrated management geared towards sustainability[41]. A quick chemical analysis of Liquid Extract shows (Table 1) the presence of broad-spectrum phytohormones, betaines, enzymes, vitamins,

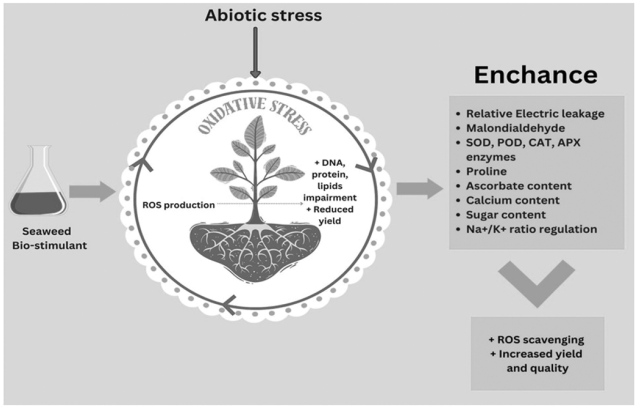

Fig. 2 — Macro-algal bio-stimulants are scavengers of ROS and trigger several mechanisms that help plants mitigate abiotic stress.

Table 1 — Some commercial macro-algae bio-stimulants

Macro-alga	Bioactive compound	Commercial product
Ascophyllum nodosum	PGRs (Plant Growth Regulators) – Gibberellins, Betaines, Cytokinins	Acadian®, Actiwave®, AlgaeGreen™, Algamare®, Algifert®, Seasol®, Tasco®, WUXAL®
Ecklonia arborea	PGRs – Cytokinins	Kelpak®
Macrocyctis pyrifera	PGRs – Cytokinins	GaiaAT®
Kappaphycus alvarezii	Plant Bio-stimulant	SAGARIKA, SIVARIKA, Nutrisap, Deep gel, AgroGrain WP

hydrolysed proteins, sterols, osmo-protectants, carbohydrates, polysaccharides, lipids, polyphenols, macro- and micro-nutrients and proteins[12]. Significant increase is observed in the activity of soil enzymes such as urease, acid phosphatase, FDAse, dehydrogenase, catalase, and improved biological index of fertility in the rhizosphere of soils treated with bio-stimulants[42]. Another valuable bioactive compound is kahydrin, a derivative of vitamin KI. This compound favours H^+ secretion into the apoplast, which brings acidification of the rhizosphere. The acidification changes the redox state of soil, affecting the nutrient availability to the plant[43]. The bioactive substances that aim at alleviating abiotic stress in plants help in improving crop yield. In cherry tomato pretreatment of seeds with an *Ascophyllum nodosum*-based bio-stimulant enhanced fruit quality by up to 65%[44]. It also increased fruit yield even under drought stress. Similarly, wheat grown under drought with seeds subjected to foliar treatment from extracts of either *Gracilaria dura* or *Kappaphycus* spp. showed improved yield by 70 and 200% (double the initial yield), respectively[45,46]. Commonly referred to as G-sap and K-sap, the stimulatory effect is seen on rice[47] and *Vigna mungo*[48]. The *Brassica napus* (Rapeseed) seeds treated with any of the extracts from *Ulva lactuca, Cystoseira* spp. or *Gelidium crinale* and grown under mild (75 mM NaCl) to severe (150 mM NaCl) salinity also showed improved growth[49]. Several studies revealed that the application of the extract of *Ascophyllum nodosum* to crops like soybean resulted in enhanced crop's tolerance to severe drought conditions, turgor and leaf temperature[50]. In wheat, the application of *Ulva prolifera* extract resulted in a reduction in oxidative damage due to drought. This protection is through activating the anti-oxidative system, essential hormones and minerals for crop growth[51]. Extract from *Ascophyllum nodosum* is a preferred bio-stimulant because of a wide range of ameliorative effects on crop plants. It increases proline levels, upregulates the ethylene signalling pathway while downregulating the Jasmonic acid pathway and reduces the accumulation of ROS (Fig. 2). Further, it preserves cell membrane integrity and increases chlorophyll content[52]. A better growth of *Arabidopsis thaliana* is observed under drought stress with macro-algae bio-stimulant[53]. The *Kappaphycus alvarezii*, bio-extract demonstrated a novel bio-stimulant activity which facilitated seed germination, cotyledon expansion and seedling growth in experimental plant systems[54]. Recently, the alga has been bioengineered, and extraction procedures of bio-stimulants have been modified to enhance the efficacy of the bioactive constituents[55].

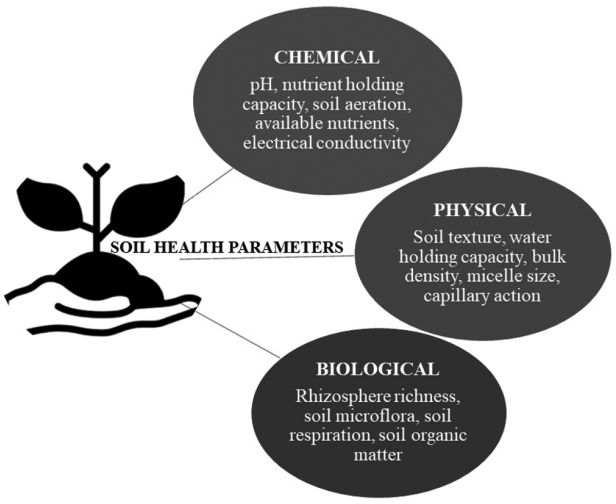

Fig. 3 — The soil parameters that result in crop improvement are enhanced upon application of algal bio-stimulants.

Among the commercial bio-stimulants, Kelpak, from the brown alga, *Ecklonia maxima* Osbeck, containing a variety of bioactive substances, is widely used. It is also classified as Terra Sorb Complex, characterised by a high content of free amino acids (aliphatic amino acids, aromatic amino acids, acidic amino acids, and basic amino acids) synthesised via enzymatic hydrolysis. Terra Sorb Complex also contains organic nitrogen, boron, magnesium, iron, zinc, manganese, molybdenum, and many microelements[56].

Role in enhancing soil health

This group of algae facilitates aggregation of soil particles, which directly improves the soil characteristics like nutrient availability, aeration and water holding capacity (Fig. 3). It also improves the soil microbiome,

which absorbs free amino acids to a higher extent than plants. This benefits plants indirectly by increasing the activity of beneficial organisms[57]. The phenolic compounds and antibacterial compounds in the extracts relieve soils of the soil-borne pathogen pressure[58] (see Box 1).

The chemical fertilisers, when intensively used, have a long-term adverse effect on soil health. The soil becomes compact and acidic, showing decreased fertility[59]. Since macro-algae biomass is biodegradable, it is part of a sustainable soil management system[60]. The biomass is a storehouse of nutrients. When the macro-algae extract from *Saccharina japonica* was applied to a loamy soil, it resulted in increased soil organic carbon and total nitrogen[61]. The granular biomass from *Sargassum johnstonii* increased K, Mg, Ca, and Zn in the amended soil by 268, 122, 138, and 188%, respectively[62]. A combination of macro-algae (*Ulva* spp., *Codium vermilara*, *Dictyota dichotoma* and *Ceramium rubrum*) resulted in 'compost' formation, which not only increased nutrient availability, but also improved pore size and probably amelioration of hydric conditions[63]. A combination of *Laminaria digitata* and *S. johnstonii* yielded soil with a near neutral pH, aggregate stability, higher total pore volume and water-holding capacity[62,64]. Additionally, commercial macro-algae provide feedstock for the production of biochar to improve soil fertility[65]. The biochar has been popularised due to the high concentrations of exchangeable nutrient contents, particularly N, P, K, Ca, and Mg[66]. This biochar also has a high cation exchange capacity, making it highly effective in retaining nutrients in agricultural soils[67]. The algin, alginate, mannitol, and other bioactive compounds with molecular chains have a large number of hydroxyl and carboxyl chemical groups. These compounds, combined with metallic radicals, are known to form a cross-linked polymer of increased molecular weight possessing a higher moisture retention property[68]. These complexes promote the formation of a crumb structure, which facilitates aeration and capillary action within soil pores, thereby enhancing nutrient availability and soil pH[69]. Macro-algae are decomposed to soluble organic matter, e.g. algal oligosaccharides to provide the soil organic matter and humus. It largely contributes to the formation and stability of soil aggregates, which helps the soil accumulate organic matter and stay fertile over time[70]. Abundant nutrients, polysaccharides and trace elements from decomposed biomass encourage the growth of soil microbes, and such amended soils show a high population of beneficial bacteria[71].

Challenges ahead

There is a growing interest within both the agri-industry and the scientific community about the various benefits that algae may offer as a bio-stimulant. This could be a revolutionary tool in the agricultural landscape, with long-term potential to help resolve the predicted food crisis. However, there are some concerns that need to be understood and addressed, for which scientifically sound strategies must be adopted. The concerns are given below:

- The process of production of micro-algal extracts requires optimisation, which may vary from species to species for it to be economically viable.
- Lack of awareness among farmers regarding the use of algae as a bio-stimulant must also be worked out if higher yields are to be achieved through integrated or sustainable agriculture[74].
- The algal biomass, if contaminated with heavy metals and persistent organic pollutants, would yield a bio-stimulant that might pose a threat to consumers. Therefore, it is essential to ensure that

Box 1 – MACRO-ALGAL BIO-STIMULANT: A CASE STUDY

Vineyards worldwide take the brunt of climate changes as they face a shift in pathogen distribution exposing them to an increased dependence on phytochemicals and pesticides harmful for environment. The produce is attacked by two fungal pathogens, namely downy mildew and powdery mildew. The European Commission suggested these pathogens be controlled without adverse effects on the environment. To combat the attack in a sustainable manner, SEAWINES, a three-year project was launched led by the University of the Basque Country and Instituto de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (IFAPA). The study aimed to fight fungal disease of vines with a sustainable ecological alternative. The most significant point of this project is the use of invasive macro-algae *Ulva ohnoi* which is known to form green-tides[72] and *Rugulopteryx okamure*, which originates from Asia and is widespread along the Mediterranean coast. SEAWINES is evaluating the efficacy of foliar application of *Ulva ohnoi* and *Rugulopteryx okamure* extracts to control powdery mildew in addition to testing the wine quality[73].

the biomass is collected from safe water bodies.

- The concentration of bioactive components in macro-algae greatly varies due to seasonal variations in light and temperature, impacting the polysaccharide, polyamine, lipid and protein content in multiple algal species[75-77]. The extraction should therefore be done with cost-effective strategies.
- There is also variability in source material obtained from wild macro-algae growing in natural waters, and the one that is derived from cultured farms. Under controlled conditions, a more constant chemical composition of the source material is produced, while the natural waters affect both the spectrum and quality of the compounds.
- The important drawback from a commercial aspect is that often, the macro-algae liquid formulations become less stable over time. It is obligatory to work out suitable stabilisers and additives that need to be added to enhance the shelf life and stability of LE quality[41].
- A nonspecific collection is made from natural waters where macro-algae from various species co-exist. This results in a heterogeneous bio-stimulant with extract from more than one species. Macro-algal cultivation (mariculture) provides a monoculture of a marine species. It has benefited the agri-industries[78,] and the breeding programs need to be encouraged.
- The process of extraction of bio-stimulants needs to be optimised in order to obtain desired quality products, and the industry should move towards self-reliance.
- To commercialise the bio-stimulants, a proper certification by the testing authority is required[79,] and therefore it should be made a mandatory requirement for its sale.
- Alternative methods of bio-stimulant application need to be worked out as the foliar spray method is not too precise, and some amount may be lost as drift, besides limited absorption through stomata.

Macro-algal resources in India

The 11,098.81 Km long Indian coastline[80] has abundant resources along the southeast coast of Tamil Nadu including 21 islands in the Gulf of Mannar, Okha, Dwarka, Porbandar, Veraval and Gopnath. The east-west coast covers Mumbai, Karwar, Ratnagiri, Goa, Varkala, Vizhinjam, Pulicat and Chilka. The Kerala coast also offers economically important macro-algae from waters of Kollam, Alappuzha, Thalapady and Kasaragod[81]. Besides these places, the luxuriant growth of macro-algae is also reported from Lakshadweep and Andaman Nicobar[82]. With 844 species belonging to 217 genera of 69 families[83], there is a total of 434 species of red algae (Rhodophyceae), 216 species of green (Chlorophyceae), and 194 species reported under brown algae (Phaeophyceae)[84]. Considering the wet harvestable macro-algae biomass available in the Indian marine waters, around 0.26 million tons is reported from Tamil Nadu, leading in macro-algae standing stock, followed by Andaman and Nicobar Islands, Gujarat, Maharashtra and Lakshadweep Islands.

With abundant macro-algae resources available in Indian waters, it is the lack of awareness amongst farmers that has led to agricultural practices with chemical agri-inputs. Though the local people near the coast occasionally apply either the dried form (powdered or flakes) of macro-algae to the soil or spray filtrate obtained after grinding the macro-algae, yet these algae remain commercially underexplored as popular agri-inputs. The farmers residing away from the coastal belt or living in the interior of Indian are generally unaware of the availability and importance of macro-algae agri-products[85]. According to Prashant Kharwadkar, Regional Business Director of Acadian Plant Health, reaching out and connecting with farmers is the biggest challenge in the Indian bio-stimulant market. The farmers spread over about 600,000 villages perceive bio-stimulants as an ordinary agri-input. This perception needs to be changed if speedy growth in the agri-industry is to be achieved[86].

Macro-algal bio-stimulants – Government of India (GOI) initiatives

The GOI (Government of India) is set to bring 'The Bio-Agri Revolution and has emphasised the need for bio-inputs as sustainable alternatives to chemical fertilizers[87].

To take up this challenge of popularising macro-algae agri-inputs, the GOI incorporated bio-stimulants under the Fertilizer Control Order (FCO) in the year 1985. The aim was to ensure a supply of good-quality bio-stimulants to the farmers. Under this order, the Government is empowered to specify and also regulate the quality of macro-algae. The amended order came into force on 26th May 2025, and Schedule IV, Part A of this order outlines the 'Specifications of Bio-stimulants'. The new formulations have been recommended with *Ascophyllum nodosum* and *Kappaphycus alvarezii* in the ratio 7.2:9.5%. A mix of

BOX 2 – Projects at National Level

- Sea6Energy is pioneer of innovative technologies for large scale mechanized Ocean farming.
- It is the first and only company to have patented macro-algae-based bio-stimulants.
- One of the patented products is AgroGrain from the red macro-alga.
- CSIR-CSMCRI, Bhavnagar is working on macro-algae-based bio-stimulants.
- CSMCRI with AquAgri Processing Private Ltd. is working on 'seaweed sap'.
- Biostadt India Ltd has company's flagship brand 'Biozyme' a novel macro-algal extract-based bio-stimulant launched under parent company Wockhardt Ltd in 1986.
- Biostadt became an independent company in 2003.
- Biostadt also developed Plant Growth Stimulant – Amaze-x and Nanozim.

Kappaphycus alvarezii and *Sargassum swartzii* (1:1) with specific gravity, pH and chemical parameters has been advised for target crops such as tomato, cucumber and paddy at a specific dose. *Sargassum tenerrimum* extract mixed with that of banana is recommended for brinjal, cotton and tomato[88].

Besides these efforts of the Government of India, Department of Fisheries, Ministry of Fisheries, and Animal Husbandry and Dairying are promoting macro-algae cultivation in the country[89].

Majority of indigenous commercial macro-algae-based bio-stimulants are produced from naturally harvested *Sargassum* (Phaeophyceae) by SNAP Natural and Alginate Products Pvt. Ltd. However, macro-alga *Kappaphycus alvarezii*, is promoted as an excellent raw material for producing low-cost bio-stimulants in India. Bio-stimulant sap from red algae and carrageenan has been patented (US patent No 6893479). The Council for Scientific and Industrial Research (CSIR) and Central Salt and Marine Chemical Research Institute (CSMCRI) have contributed towards the technology to extract sap (Aquasap) from *Kappaphycus alvarezii.* This sap has been validated on at least 10 agricultural crops and executed in 20 states of India[90]. The two bio-stimulants Sivarika and Sagarika, obtained as a mix of red and brown algae (*K. alvarezii* and *Sargassum* species), are developed by CSIR-CSMCRI and manufactured by Krishak Bharati Cooperative Limited (KRIBHCO). The products are marketed by the Indian Farmers Fertilizer Cooperative Limited (IFFCO) (Table 1). They are known for their antioxidant properties, for enhancing crop growth and yield. This is the initiative under Atma Nirbhar Bharat Abhiyan[91].

The technology licensed in the year 2009 to AquAgri Processing Pvt. Ltd. was later transferred in 2013 to Prasmo Agri, Kumbakonam, Tamil Nadu. In 2019, Pushpa J. Shah of Ankleswar, Gujarat, and Vikas Crop Care of Bhavnagar, Gujarat, acquired the rights to this technology. The bio-stimulant/biofertiliser market in India is currently valued between Rs. 1,500 and Rs. 1,700 crores[92]. The CSIR-CSMCRI also developed and transferred *Sargassum*-based Liquid Seaweed Plant Bio-stimulant (LSPB) technology to more than nine industries (See Box 2).

Most of the macro-algae processing industries in India are micro-enterprises and mainly use wild-harvested algae as raw material. The Department of Fisheries, Government of Tamil Nadu, has established a macro-algae sap extraction unit at a cost of Rs. 3.96 crores through the Fisheries Management for Sustainable Livelihoods Project (FIMSUL-2). It is a collaborative initiative between the Government of Tamil Nadu and the Food and Agriculture Organisation of the United Nations (FAO)[93] with technical know-how for the unit provided by CSIR-CSMCRI. The unit, having a capacity to process one ton of fresh macro-algae per day, can provide a livelihood to approximately 1,500 fisherwomen[94].

With a large macro-algae resource and technological know-how, it is easy for companies to churn out sustainable bio-stimulants. However, it is at the same time extremely important that the quality standards and the safety issues are regulated. To make it possible, certain guidelines are set. In India, manufacturers or importers of bio-stimulants are required to provide a set of information to the Central Bio-stimulant Committee (CBC) on chemistry, bio-efficacy trials, toxicity and heavy metal analysis for specification of the bio-stimulant[95].

In spite of the efforts made by the Indian bio-stimulant market, currently, bio-stimulants are mostly imported and subsequently marketed to farmers. Extracts of macro-algae such as *Ascophyllum, Kappaphycus*, and *Ecklonia*, valued at Rs. 150-160 crores, are imported annually from Canada, Indonesia,

Norway, the Philippines, and China[96]. However, the Technology Information Forecasting and Assessment Council (Think tank under, Department of Science & Technology) believes that India can be a global leader in seaweed production and trade if a policy framework is developed to support the cause[97]. Keeping these constraints in view, and the wide applications of seaweed biomass, the council submitted its recommendations in a report for a decade (2011-2020). It suggests that short term, mid-term and long term plans would help create 'Centres for Excellence in Seaweed Bio-products Development'. Such efforts have the potential to establish sustainable seaweed value chains and a self-reliant seaweed industry in India[95]. Steps in this direction would certainly help to develop and expand the bio-stimulant industry to meet the domestic demand of the agri-industry, which is entrusted with the responsibility of feeding a huge population.

Conclusion

With the ever-growing demand for safe and balanced food, sustainable agricultural practices are to be adopted. Novel agricultural practices, that are site-specific and mitigation measures that can give excellent results, need to be taken up. To address the sustainability and production challenges of modern agriculture, the use of plant bio-stimulants has a vital role to play. Algal formulations have emerged as promising bio-stimulants. Macro-algae bio-stimulants make up around one-third of the bio-stimulants available in the market. Macro-algae such as *Ulva, Ascophyllum, Sargassum* and *Gracillaria* and micro-algae such as *Spirulina* and *Chlorella* have immense potential to be the front runner of this sustainable production. The bio-formulations act as insurance against crop loss on account of any stress. However, despite the various benefits these agri-inputs provide, significant challenges are faced by the macro-algae-based companies. Standardisation of formulations, detection of heavy metal presence, and optimisation of dosage and the stage of the plant life cycle at which the bio-stimulant should be applied require further research inputs. Considering the benefits and commercial feasibility of algal bio-stimulants in agriculture, they could be the next revolutionary step for the agri-industry and a source of new-age employment opportunities for women and youth.

Conflict of interest

There is no conflict of interest, as all authors have contributed to the review preparation.

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