Journal of Advanced Zoology
ISSN: 0253-7214
Volume 45 Issue 1 Year 2024 Page 297-306

Bio-stimulants in vermicomposting: a closer look

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Abstract

This paper examines the role of bio-stimulants in vermicomposting as a viable choice to upsurge the impact of bio-stimulants and the vermicomposting in plants growth. Mankind has stepped into the 21st century, which is a century where the human race is thriving towards its peak in terms of technological as well as in terms of sustainability. With this as the aim of the modern generation, prosperous advancement in distinct field happens. The mistakes of the past hope to correct in the near future still aches us to our core. The injudicious use of synthetic products during stages of desperate measures has polluted our soil water and air which are the three factors of our habitat. The need for amendment for these has given rise to an alternative method of crop production and thus organic farming. Vermicomposting, one of the pillars in organic farming as well as organic compounds such as plant bio stimulants on blending brings into existence a much more productive compound.
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Key words: Sustainability, soil health, bio-stimulants and synthetic fertilizers.

Introduction

Organic farming methods are widely used as an integral part of achieving sustainability in all three groups of countries be it developed, developing, under-developed. The rapid growth in population waste disposal is a serious problem facing humanity in the 21st century (Palaniappan *et al.*,2018). It is estimated to have an increase in two or three folds of current waste dumping in the future years. And here comes the solution for this problem which was initially started about 2300 years in the past by a great man named Aristotle who named earthworms as the intestines of the soil. Organic fertilizers are generally derived from sources such as composts (decomposed plant materials), manure (animal excrement), biosolids, meat and bone meal, seaweed emulsions and vermicompost. Organic fertilizers generally have lower mineral nutrient contents than synthetic chemical fertilizers (nitrogen-phosphorus-potassium ratio 10-10-10), their chemical characteristics may be poorly characterized and quantified, and nutrient content may vary between production batches and methods (Jouzi *et al.*, 2017) In general, organic fertilisers have lower mineral nutrient levels compared to synthetic chemical fertilisers. Despite this lower and more uneven mineral nutrient content, organic fertiliser application has, in certain cases, increased crop output when compared to chemical fertilization.

A rise in quality of agricultural products has been attributed to the use of organic manure and bio-stimulants like vermicompost and nitrogen-fixing bacteria. Vermicompost is the result of the interaction between earthworms and microorganisms that breaks down organic matter. The majority of nutrients in vermicompost are present in their readily absorbable forms, including nitrates, phosphates, exchangeable calcium, and soluble potassium (Bashir *et al.*, 2021). The aptitude of free-living nitrogen-fixing bacteria like Azotobacter, chroococcum and Azospirillum lipoferum to release phytohormones like gibberellic acid and IAA, which can there by promote plant growth, nutrient uptake, and photosynthesis, has been discovered. Crops like medicinal plants can have their development and biomass increased by using the right nutritional sources using organic manures and biofertilizers. Bio-stimulants are substances or microorganisms that enhance plant growth and health by promoting nutrient uptake, stress tolerance and overall plant vigor. When used in vermicomposting, bio-stimulants can play a beneficial role in accelerating the composting process and improving the quality of the finished vermicompost (Yassen *et al.*, 2019).

Bio stimulants: Bio stimulants are unique, ecofriendly compound (including microbial and non-microbial bio-stimulants) having potential to significantly increase the crop yields by increasing the nutrient uptake and the metabolic pathway. These are substance or microorganism that are applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, irrespective of its nutrients content. The rhizosphere constitutes of a diverse and intimate association of biological networks comprising of plant roots, microbes and various small organisms (nematodes, earthworms, etc.). Among this complex collection of biological networks is the soil matrix and water medium, in which many biological activities and interactions occur (e.g., microbial biochemical activities such as enzyme production, plant exudations (allelopathic) and uptake, ingestion by earthworms, etc.). It is reliable that the soil matrix and water medium contain a number of naturally produced substances such as biological metabolites, including phytohormones and their precursors (Siva Lakshmi *et al.*, 2023). The entire plant underground root system could be viewed as a 'receiver' or 'reservoir' of the multitudes of biochemical signals which plants use to 'sense' the soil rhizosphere for the availability of water, mineral nutrient, phytohormone and other metabolites. Specific biochemical signals are 'received' at the root tips before being 'assimilated' and sent to the other plant parts where strong responses are induced at actively growing regions (Soliman *et al.*, 2019).

Vermicomposting

Vermicomposting is simple, low cost, low energy biotechnology of nutrient rich vermicompost production by earthworms under optimum conditions for rapid multiplication by feeding biodegradable materials available in every household, villages and town in India. It is a rich source in several micro floras like Azospirillum, Actinomycetes and Phosporbacillus which multiply rapidly through the digestive system of earthworm. Several enzymes, auxins, and complex growth regulators like gibberellins are found in vermicompost which are not generally present in different soil environment conditions thus, Vermicomposting can be a good option for micro entrepreneurship development in converting the bio-wastes into nutrient rich compost for livelihood improvement (Lim *et al.*, 2015). It is the practice of using concentrations of earthworms to convert organic materials into usable vermicompost or worm casting is termed as vermicomposting. Not much scientific information is available on origin and on the evolution of the earthworms. This is because the body is very soft and decay quickly. Information regarding these creatures is available from the evidences gathered from fossils and the remains leftover from the past. These versatile creatures can be adapted everywhere on the planet except for desert, sea and area which is devoid of vegetation. Using these small creatures which was entitled the intestine of the soil by the great Aristotle, there came an idea to use them to our advantage by providing the suitable environment for them to produce enriched compost as an alternative for the first leap towards sustainability (Soliman and Hamed 2019).

Vermicompost is a finely divided, coffee textured, peat-like material derived from the accelerated biological degradation of organic wastes by the interactions between earthworms and microorganisms. Organic wastes are broken down into finer particles by the grinding motion of the earthworm gut during gut passage, with decomposition accelerated by microbial activity. Vermicompost generally has a low C: N ratio, and exhibits a stable physical structure with presence of soil macropores, stable macro masses and organo-mineral complexes, leading to adequate porosity, good aeration, drainage, adequate water holding capacity, microbial activity, generally balanced mineral nutrient status, and colloidal buffering capacity. The colloidal buffering capacity exhibited by vermicompost is attributed to the presence of humic and fulvic acid (Blouin *et al.*, 2019).

Vermicompost is the end product which is result of the synergy of microorganism and earthworms can be divided into two stages.

1 **Active stage**: The earthworms bring upon a change in the physical properties as well as the microbial composition of the substances.

2 **The maturation stage**: Microorganisms replaces earthworms to further degrade the substances.

Role of bio-stimulants in agriculture

Since bio stimulants are result of an incredibly diverse set of biological and inorganic materials including microbial fermentations of animal or plant feedstock, living microbial cultures, macro, and micro-alga, protein hydrolysate, humic, and fulvic substances, composts, manures, food, and industrial waste. These are prepared by using widely distinct Bio stimulants either directly interact with plant signalling cascades or act through stimulation of endophytic and non-endophytic bacteria, yeast, and fungi to produce molecules of benefit to the plant.

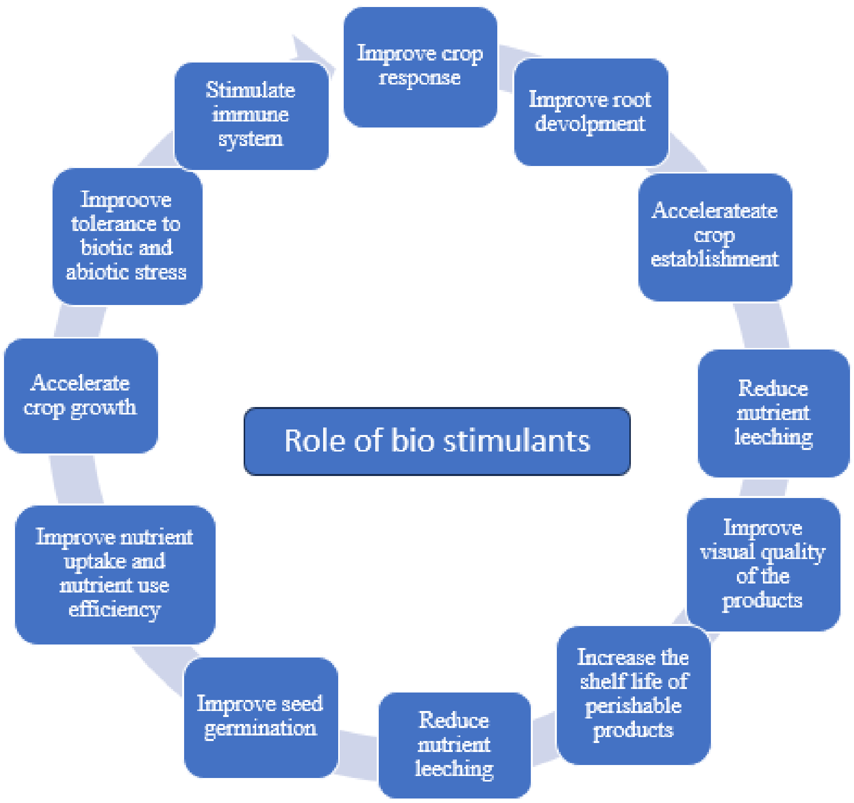

Figure 1: Role of bio-stimulants in agriculture

Types of bio-stimulants

Some major categories are widely recognized by scientists covering both substances and microorganisms. Microorganisms include beneficial bacteria, mainly PGPRs, and beneficial fungi. They can be free-living, rhizosphere or endosymbiotic.

1. Humic and fulvic acids

Humic and fulvic acids are organic compounds that can enhance nutrient availability to plants. They also improve soil structure and water retention. Adding humic and fulvic acids to vermicompost can make it more valuable as a soil amendment. Humic acid and fulvic acids are natural constituents of the soil organic matter which is a result from the decomposition of plant, animal and microbial residues, but also from the metabolic activity of soil microbes using these substrates. Humic substances are a collection of heterogenous compounds which are originally arranged according to their molecular weight (Hurtado *et al.*, 2019). Humic substances and their complexes in the soil thus result from the interplay between the organic matter, microbes and plant roots. Any attempt to use humic substances for promoting plant growth and crop yield needs to optimize these interactions to achieve the expected outputs. This tells why the application of humic substances – soluble humic and fulvic acids fractions shows inconsistency, yet positive inputs in terms of plant growth and development. Variability in terms of effects of the humic substances are due to source of the humic substance, the environmental conditions, the receiving plants and obviously the custom in application. The source for the extraction of the humic substances is from naturally humified organic matter (e.g., from peat or volcanic soils, compost and vermicompost, or from mineral deposits). Besides, from agricultural by products instead of allowing to decomposed in a soil or by composting are subjected to control breakdown and oxidation by chemical processes leading to formation of humic- like substances which are then proposed as substitute for natural humic substances (Rai *et al.*,2021). Humic substances have been recognized as an important contributor to the fertility of the soil, acting on physical, physio-chemical, chemical and biological properties of the soil. Most bio stimulant effects of the humic substances denote to the enrichment of root nutrition, via different mechanisms. One of them is the increased uptake of micro and macronutrients.

2. Protein hydrolysates and other N-containing compounds

Mixtures of amino-acids and peptides are obtained by chemical and enzymatic protein hydrolysis from agro - industrial by-products be it from both plant sources (crop residues) and animal wastes. Amino acids are essential for plant growth and can be added to vermicompost to improve nutrient content. It plays a role in stress tolerance and can help plants withstand adverse environmental conditions. Several commercial products obtained from protein hydrolysates of plant and animal origins have been placed on the market. Variable, but in many cases significant improvements in yield and quality traits have been reported in agricultural and horticultural crops (Baligah *et al.,* 2022). Chelating effects are reported for some amino acids (like proline) which may protect plants against heavy metals but also contribute to micronutrients mobility and acquisition. Antioxidant activity is conferred by the scavenging of free radicals by some of the nitrogenous compounds, including glycine betaine and proline, which contributes to the mitigation of environmental stress. Indirect effects on plant nutrition and growth are also important in the agricultural practice when protein hydrolysates are applied to plants and soils. Protein hydrolysates are known to increase microbial biomass and activity, soil respiration and, overall, soil fertility (Ahmed *et al.,* 2023).

3. Seaweed extracts and botanicals

Seaweed extract bio stimulants are one of the best bio stimulants, eliminating plant disease and abiotic stresses in turn leading to maximum yields. Additionally, they have been listed as ecofriendly. Modern agriculture shows a distinct face compared to the agriculture techniques of the past. The incorporation of novel approaches such as applying plant bio effectors formally known as plant bio stimulants, seeking safe environmentally friendly and brighter sustainable represents a high priority facing modern plant production (Kumari *et al.*, 2022). Sea weed extracts are rich in growth-promoting compounds like cytokinin, auxins, and gibberellins. When added to vermicompost, they can stimulate plant growth and improve nutrient content in the compost. Being one of the most commonly used important plant bio stimulants the employment of seaweed in agriculture is not something rather goes back to the ancient days but bio stimulant effects have been recorded only recently. Algae cells (either microalgae or seaweeds) on the basis of their nutritive value represent as a treasury of sources of dyes, proteins, fats polyunsaturated fatty acids (PUFA), polysaccharides, minerals and antioxidants as well as plenty of biological components. Seaweed shows the calibre to be used as biofertilizers, not only because they have a biological impact but also because of their biocompatibility as they are capable of sharing common biological compounds with the plants. The major advantage has put seaweeds on top of the bio stimulants and facilitated many plant treatment processes mainly for serving and facilitating organic agriculture and sustainability (Tang *et al.,* 2022). Although there are numerous seaweed extract supplements for plants, foliar spray administration has been sufficiently and widely employed in modern agriculture to boost the production of many commercial crops, with extremely encouraging results. As previously said, seaweed liquid fertilizers could boost the amount of chlorophyll, raise overall yield, and strengthen the root system. The applicability of seaweed extract foliar spraying has been investigated, along with its quick and simple handling procedure, with an emphasis on promoting growth and raising the productivity of various significant vegetable crops (Mathukiya *et al.,* 2022).

Micronutrients, macronutrients, sterols, N-containing chemicals, and hormones are all included in these substances, which support the encouragement of plant growth. Seaweed extracts can be used as foliar treatments, hydroponic solution applications, and soil applications. They have favourable effects on soil characteristics such the production of gel, water retention, and soil aeration. They can also encourage the growth of good bacteria and pathogen-opposing organisms. Seaweed extracts contain hormonal actions that promote seed germination, plant establishment, and subsequent growth and development in plants. They also act as fertilizers. The primary genera employed as seaweed bio stimulants are the brown algae species, which include Ascophyllum, Fucus, and Laminaria (Ali *et al.,* 2023).

4. Chitosan and other biopolymers

Chitosan is a linear, deacetylated form of the biopolymer chitin composed of randomly distributed β-liked D-glucosamine and N-acetyl-D-glucosamine. It is made by treating the chitin shells and other crustaceans with an alkaline substance like sodium hydroxide. Chitosan raises a number of commercial and possible biomedical uses (food, cosmetic, medical and agricultural sectors). Deacetylated form of the biopolymer chitin (chitosan), which is produced naturally and industrially. Chitosan oligomers provide a range of physiological effects in plants and the results of the capacity of this polycationic compound to connect a wide range of cellular components including DNA, plasma membrane and cell wall constituents, in addition to this functions to bind specific cell receptors concerned in defence gene activation, in a similar way as plant defence elicitors (Vambe *et al.,* 2023). Chitosan and chitin seemingly use distinct signalling pathways and receptors. Among the cellular effects of chitosan binding to more or less specific cell receptors are hydrogen peroxide accumulation and Ca^{2+} leakage into the cell. These effects are anticipated to result in significant physiological changes because they are important players in the signalling of stress responses and in the regulation of development. In the advancement of the recent years several agricultural applications of chitosan have been developed giving emphasis on plant protection against fungal pathogen. Nonetheless, the wider agricultural usage influence abiotic stress tolerance (drought, salinity, cold stress) and on a number of quality traits related to primary and secondary metabolism.

Seaweed polysaccharides are one type of biologically derived poly- and oligomer that is increasingly exploited in agriculture as an elicitor of plant defence. Laminarin, a storage glucan of brown algae of which refined preparations are used in agriculture applications is a good example. Despite the need to distinguish between biocontrol and bio stimulation (such as by increasing abiotic stress), signalling pathways may be coupled and both effects may theoretically be achieved by using the same inducers (Anbarasi *et al.,* 2020).

5. Inorganic compounds

Some chemical compounds act as an essential substance to most of the plant taxa, while these may be of no specific use to some other. The main five beneficial elements which are present in the soils and in plants as different inorganic compounds and in insoluble forms like amorphous silica seen in graminaceous species. The main five beneficial elements are Al, Co, Na, Se and Si. These elements functions can be fundamental functions such as cell wall strengthening by silica deposition or can be noticed in a defined environmental condition such as pathogen attack for selenium and osmotic stress for sodium (Koskey *et al.,* 2023). The definition for beneficial elements cannot be thus limited to its chemical nature, but also must be refer to its special contexts where the positive effects on the plant growth and stress response may be vividly observed. It may be seen that the bioactivity of some complex bio stimulants such as extracts of seaweeds, crop residue or animal wastes, involves the physiological functions of the contained beneficial elements. Many effects of beneficial elements are reported which promote plant growth, tolerance to abiotic stress and quality of plant products. This comprises of cell wall rigidification, osmoregulation enzyme activity by co factor, reduction of transpiration by crystal deposits, thermal regulations via radiation reflection, plant nutrition via interaction with other elements (Chitra *et al.,* 2023). Chlorides, phosphates, phosphite's, silicates and carbonates which are inorganic salts of beneficial and elements have been used as fungicides. Although the mode of action is yet to fully recognised, these organic compounds interact with the pH, osmotic and redox homeostasis, hormone signalling and enzymes involved in stress response.

6. Beneficial bacteria

Interaction of bacteria with plants can be seen in all possible ways, in regards of fungi there is a continuum between mutualism and parasitism , associations may be temporary or permanent, and some bacteria may even be vertically transmitted through the seed , bacterial niches extend from the soil to the interior of cells, functions influencing plant life include participation in the biogeochemical cycles, supply of nutrients, improvement in nutrient use efficiency, induction of disease resistance, improvement in abiotic stress tolerance, and so on. Regarding the taxonomic, functional, and ecological diversity of bio stimulants used in agriculture, two primary categories should be taken into account: (i) mutualistic endosymbionts of the type Rhizobium, and (ii) mutualistic, rhizosphere PGPRs ('plant growth-promoting rhizobacteria'). Rhizobium and related taxa are marketed as biofertilizers, which are microbial inoculants that make it easier for plants to absorb nutrients mentioned in table 1. Scientists have explored the biology and agricultural applications of the Rhizobium-based symbioses in great detail. PGPRs are multifunctional and have an impact on all facets of plant life, including nutrition, growth, morphogenesis, reaction to biotic and abiotic stress, and interactions with other organisms in agroecosystems (Awwad *et al.*, 2022). The use of PGPRs in agriculture are constrained and complex depending on the variable responses of the plant cultivar and also the receiving environment. In addition to this the technical difficulties associated with the formulations give rise to inconsistent results. Despite these setbacks, the world market of bacterial bio stimulants is growing in a rapid rate and is now regarded as some kind of probiotics.

Table1: Action of bio stimulants in the different functions of plant metabolism

	Humic acid	Seaweed extract	Protein hydrolysate	Glycine betamine	PGR rhizobacteria
Cellular mechanism	Promote cell wall loosening and cell elongation in roots of maize Activate plasma membrane	Stimulate expression of genes encoding transporters of micro nutrients	Stimulate phenylalanine ammonia-lyase (PAL) enzyme and gene expression, protects the flavonoids under salt stress	Protects the photosystem II against salt induced photodamage in quinoa	*Azospirillium brasilense* releases auxins and in addition activates auxin signalling pathways
Physiological function	Increases root biomass and the linear growth of the roots	Increasement in the tissue concentration and root to shoot transport of micro nutrients	Flavonoid protection against UV and oxidative damage	Maintenance of leaf photosynthetic activity during salt stress	There is an increase in lateral root density and surface of root hairs
Agricultural and horticultural function	Enhancement in the nutrient use efficiency and increased root foraging capacity	Improvement of mineral composition	Improves and increases crop tolerance to abiotic stress	Increasement in tolerance towards abiotic stress	High root foraging capacity as well as enhanced nutrient use efficiency
Economic and environmental benefits	Savings in fertilizers and results to a higher crop yield	Biofortification of plant tissues	Higher crop yield under stress condition	Higher crop yield under stress condition	Fertilizer savings and reduce losses to the environment, higher crop yield

7. Beneficial fungi

Fungi, being a diverse group of microorganisms that play vital roles in countless ecosystems, agriculture, medicine, and industry. Similar to the two sides of a coin, fungi have both good and bad in them, some of them are unsafe while some are beneficial in all sorts of way for the environment. In contrast to plants, animals and microbes, fungi are a separate kingdom of creatures offering a wide range of useful application that aid human kind in more ways than one and are essential for the preservation of the ecological equilibrium, for enhancing the soil health to manufacturing lifesaving medications (Alabi *et al.*, 2012). Beneficial fungi provide a wide range of functions. Mycorrhizal fungi are a diverse group of fungi which form interaction with 90% of all the plant species. Among the different interactions and taxonomic group involved, the Arbuscule forming mycorrhiza are the most widespread endomycorrhizal association with crop and horticultural plants, where fungal hyphae of Glomeromycotan species gore root cortical cells and thus forms branched structures called arbuscules. Fungal-based products applied to plants to promote nutrition efficiency, tolerance to stress, crop yield and product quality should fall under the concept of bio stimulants. Major limitations on their use are the technical difficulty to propagate AMF on a large scale, due to their biotrophic character and more fundamentally, the absence of understanding of the determinants of the host specificities and population dynamics of mycorrhizal communities in agroecosystems.

Biotrophic character – These characters are shown by organisms especially by those under fungi. Biotrophs derive energy from living cells, they are found on or in living plants with a complex nutrient requirement and do not kill the plants rapidly. Some of these fungi, mainly *Trichoderma spp.*, have been broadly studied and used for their bio-pesticidal (myco-parasitic) and biocontrol abilities, and have been exploited as sources of enzymes by biotechnological industries
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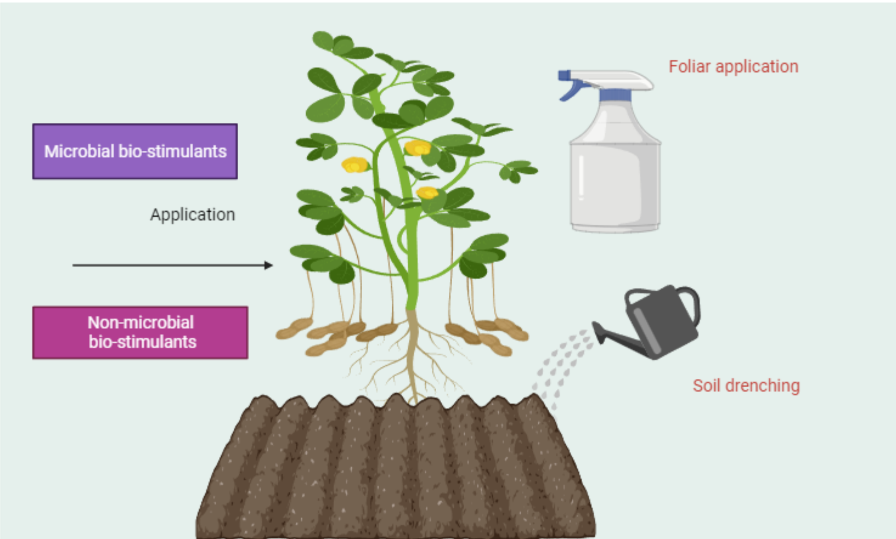

Fig. 2 Effect of bio-stimulants and non microbial bio-stimulants on plant growth

Sustainability and environmental aspects

The current era, an era which is burdened with environmental challenges and a growing population, the role that bio stimulants put up towards ensuring food safety and sustainability cannot be overstated. Out of 100 kg of the applied fertilizer to the plant only about 30- 50 % is made available to the crops. The excess amount of fertilizers are lost by leaching or runoff, these excess losses of these additions therefore give rise to both financial setbacks as well as ecological harm. Nutrients such as nitrogen, phosphorous, potassium are subjected to runoff or leaching from the field and get accumulated into water bodies resulting in widespread contamination. These contaminations in water bodies like lakes, river, ocean can in turn trigger harmful algal blooms, disruption in the aquatic eco system and degrade the quality of water posing a high risk to both humans and animals in terms of health and basic need aspect (Suriya *et al.*, 2023). A healthy crop needs all its nutrients, in order for this farmer invest a lot of their investment in purchasing fertilizers only to see considerable amount of these investments literally flowing away. Additional to this causing direct financial, the wastage requires more frequent reapplication of fertilizers further escalating the cost of cultivation

Adopting bio stimulants as an integral part of the strategy devised to safeguard the environment, encourage sustainable crop production and ensuring food security. Any of the developed countries of the world such as Japan, China, European union, USA increasingly focus on addressing nutrient runoff, day by day the role of bio stimulants in sustainability and environmental aspects are becoming relevant. The dependency on synthetic inputs like fertilizers and pesticides, modifying environmental issues related to conventional farming and on parallelly improving crop productivity, quality and flexibility, thus supporting food security efforts (Saha *et al.*, 2020). The way to achieving and promoting sustainability are paved way by bio stimulants.

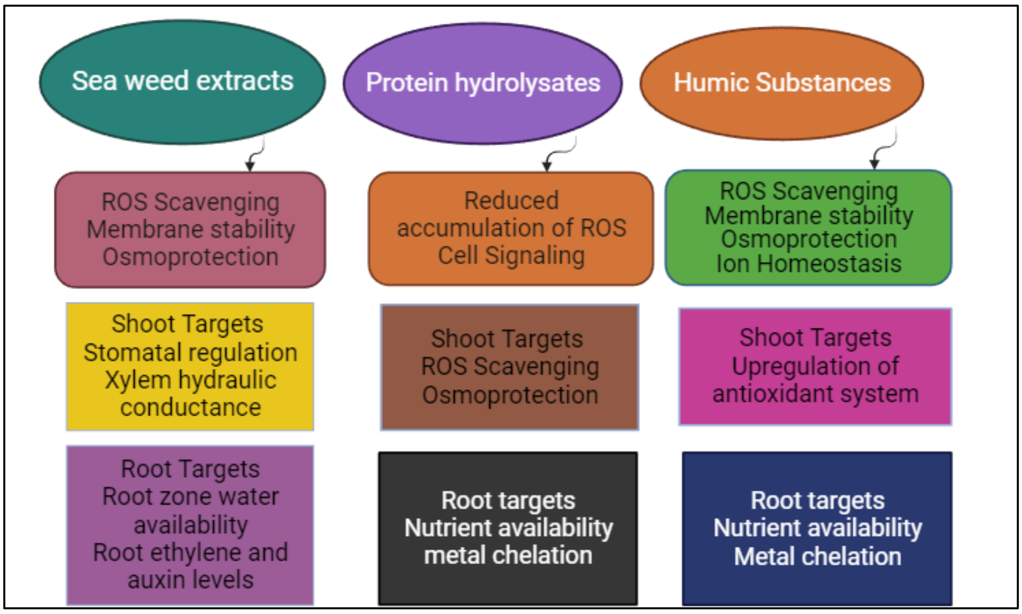

Figure 3 Key bio stimulants mechanism when non microbial bio stimulants interact with plants and their habitat

Future aspects

Growing in popularity as a sustainable source of plant bio stimulants that can increase agricultural yields and lessen reliance on synthetic fertilisers is cyanobacteria. They have demonstrated positive impacts on nutrient usage efficiency, blooming, photosynthetic activity, seed germination, seedling development, and resistance to abiotic stressors. The various physiologically active chemicals generated by cyanobacteria, including phytohormones, amino acids, proteins, antioxidants, carbohydrates, and polysaccharides, are thought to be responsible for these effects. To confirm the effects of distinct cyanobacterial strains on various plant species, however, consistent techniques are required. It is vital to comprehend the precise impact of various strains on plant physiology and to identify the pertinent chemicals engaged in the biostimulation process. Cyanobacteria can be used to produce standardised and secure bio stimulant products, although cost optimisation and more study of the conditions for growth, extraction, and application methods are required. The creation of cyanobacterial bio stimulants customised to certain crops and habitats requires a multidisciplinary approach, including the identification of novel bioactive strains, improvement of growth conditions, biochemical characterisation, and comprehensive agronomic trials.

Microalgal bio stimulants have been put into use, however there have been difficulties that need more attention. Finding the best conditions and commercial microalgal strains or microalgal/bacterial consortia should be the focus of research. Additionally, efforts should be made to expand the metabolome's coverage to find fresh bio stimulant precursors or bio actives. For the effective commercialization of microalgal bio stimulants, waste streams from microalgal production must be integrated, and the best extraction methods must be chosen. Finding new bio stimulant compounds or precursors can be aided by understanding the genetic and molecular biosynthetic processes in algae or algal-bacterial consortia. It is important to consider how the composition of microalgal extracts is affected by seasonal fluctuation and the time of harvest. In order to establish the best application kinds, concentrations, timing, and duration of bio stimulant effects, field studies should confirm laboratory-based results. It is important to carefully analyse how seasonal fluctuations, simultaneous application of many components, interactions with other components, crop kinds, soil characteristics, and microbiome makeup affect bio stimulant activity. Characterising and creating new bio stimulants as well as examining their mechanisms of action and interactions with microbiomes can be aided by high-throughput sequencing, phenotyping, and omics methods. To comprehend synergistic interactions, it is important to investigate the possible co-application or mixing of microalgal bio stimulants with other bio stimulants or fertilisers. Their effective commercialization depends on overcoming regulatory obstacles, following the law, and changing public opinions about bio stimulants.

The complexity of the physiological effects of bio stimulants presents a scientific challenge, as these substances induce physiological responses in plants that are subject to tight homeostatic regulations. The tripartite interactions between the bio stimulant, the plant, and the environment must be properly addressed for successful use. Technical challenges include formulating and blending bio stimulants with other fertilizing materials and optimizing combinations to improve nutrient use efficiency. Monitoring crops and determining when and how to apply bio stimulants is also challenging, as abiotic stressors are difficult to assess and quantify. Regulatory challenges involve categorizing and assessing bio stimulants, as well as ensuring regulatory certainty and market harmonization. Specific provisions for efficacy assessment may be necessary due to the unique mode of action and intended effects of bio stimulants. Supranational regulations could streamline the process and optimize data bridging with existing regulations.

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