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Cultivating Tomorrow: A Review on Biostimulants and Their Transformative Role in Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. Author SS critical literature reviews and drafted the manuscript, author SK provided valuable guidance, critical suggestions and supervision, author BM made significant corrections, author VKR offered helpful suggestions during investigation, author JR Made substantial corrections, author NS provided critical inputs and helped in refining the manuscript, author SK provided expertise and critical feedback, author SP contributed to the literature review and provided essential feedback. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The need to feed a world population that is expanding, soil deterioration, and climate change are all serious difficulties for agriculture. Seaweed extracts, humic materials, and microbial cultures are among the natural sources of biostimulants, a family of compounds that provide a revolutionary means of augmenting plant growth and resistance. Biostimulants, as opposed to conventional fertilizers and insecticides, enhance nutrient uptake, promote stress tolerance, and stimulate natural processes to improve plant health. The various forms of biostimulants, such as amino acids, protein hydrolysates, seaweed extracts, and advantageous microbes and fungi, are examined in this review. It explores various modes of action, including enhanced interactions with the soil microbiome, hormone modulation, and antioxidant activities. Biostimulants provide a wide range of potential advantages, including higher crop yields, better resilience to environmental stresses, and a decreased need for chemical inputs, all of which support more environmentally friendly farming methods. The need for environmentally sustainable agricultural solutions is driving a sharp increase in the usage of biostimulants, according to market trends. Sales are expected to exceed 2 billion globally by 2018, thus farmers will likely embrace them more widely as they look for more affordable and ecologically friendly options. Standardizing biostimulant chemicals and comprehending their intricate interactions across many agricultural systems, however, continue to provide difficulties. This review attempts to give a thorough summary of the state of biostimulant research as it stands today, emphasizing significant discoveries, innovations in technology, and potential paths forward. This study highlights the potential of biostimulants to transform contemporary agriculture and make it more robust, sustainable, and able to meet the demands of global food security by promoting a deeper understanding of them.

Keywords: Biostimulant; seaweed extract; agriculture.

1. INTRODUCTION

The probability of hunger is likely to increase by 30% by 2050 as a result of climate change and anticipated population growth [26]. Given the state of agricultural productivity today, biostimulants show promise as a tool. The most important factor that has a major impact on agricultural yield and production, endangering both global food security and crop production systems sustainability, is the environmental condition [76]. A substance or combination of several naturally occurring organic compounds known as "biostimulants" can stimulate plant growth in a variety of environmental stresses [10]. Over the last few decades, the application of biostimulants in agriculture has increased dramatically, and by 2018, sales of these products are expected to reach 2 billion. This is mostly because there are many different sources for these components and the final product is complicated and typically contains a large number of poorly characterized compounds. Given that biostimulants come from an extensive selection of both inorganic and biological sources [15] and unreasonable to assume that there is a single mode of action for a variety of substances, 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 wastes prepared using widely divergent industrial manufacturing processes [17,29]. Oceans and seas are often referred to as the "source of life" due to their crucial role in sustaining and supporting a wide range of ecological and biological processes [9,12]. Oceans and seas are essential for sustaining life on Earth, influencing weather and climate, supporting biodiversity and providing resources and economic benefits. The current view is that newly developed synthetic fertilizers endanger both local and global ecosystems [48]. Among agriculture's main difficulties, today is developing ecologically friendly and sustainable solutions to meet the issue of feeding the world's rising population [34,57]. The only way to meet this goal, given the steadily declining amount of arable land, is to boost crop yields while safeguarding future harvests. Plant biostimulants

(PBs) are potentially a tool to mitigate climate change-induced stress and reduce the dependency on chemical fertilizers [37,38]. Applying Plant Biostimulants is an environmentally friendly technique for farmers to maintain crop productivity while using less fertilizer [37]. The biostimulants increase the yields of crops by lowering yield losses during stressful situations. This strategy can contribute to enhancing food security for a growing global population in the context of rising climate change risks [54].

2. BIO STIMULANT AND ITS IMPORTANCE IN SUSTAINABLE AGRICULTURE

Extracts obtained from organic raw materials with bioactive compounds are known as biostimulants. The term "plant biostimulant" clearly defines components, apart from fertilizers and insecticides, which, when exposed to seeds, plants, or exact formulations of growth substrates can alter the biological processes of plants in a way that provides for potential edge to development, growth, and/or the stress reaction [28]. The stress-response-feedback continuum in plants is an important physiological process that influences plant plasticity. Abiotic and biotic stressors are the two primary categories of stress in plants. Herbivory, pest assault, and disease-causing pathogens are examples of biotic stressors, while drought, salt, heavy metals, floods, and severe temperatures are examples of abiotic stressors. [36]. To increase crop production, quality, and productivity biostimulants provide biologically active chemicals that may enhance plant metabolic activity. [67]. They seem to be a general term for anything that is good for plants but isn't a fertilizer, insecticide, or soil enhancer. They possess the ability to alter a plant's physiological processes in a way that may be advantageous to the plant's growth, development, and/or stress response [28]. By interfering with plant signalling pathways, biostimulants increase plant output by lowering the unfavorable plant reaction to stress [13]. In both outdoor and greenhouse crop production, the significance of biostimulants has grown significantly in recent years. While pesticides promote plant growth by lessening the negative effects of pathogens and pests on plant integrity and functionality, nutrients provide the chemical elements needed by metabolic processes for the synthesis of biomolecules and the production of biomass. Nutrients and pesticides are specifically aside in the classification of Biostimulants to create the greatest possible clarity on this distinction [28,85]. The morphological, physiological, and yield attributes of tomato (*Solanum lycopersicum*) plants treated with biostimulants are much better than those of control plants [50]. Because they function as a chemical catalyst in plants and enhance attributes like plant height, number of branches per plant, number of leaves, number of pods per plant, length of pod, number of grains per pod, yield, grain quality, plant growth regulators and biostimulants can raise yield in fenugreek [4,74]. The morphological parameters of Tuberose (*Polianthes tuberosa* L.) cv. Prajwal can be improved, along with the flower yield and quality, by applying biostimulants externally on the leaves and biofertilizers drenching with the soil. Crop regulation makes use of biostimulants. The mutually beneficial relationship between nutrients and biostimulants [5].

3. FORMULATIONS OF BIOSTIMULANTS

The utilisation of cold cellular-burst technology is responsible for the elevated concentrations of these two biomolecules that promote plant development in the Kelpak® samples. To find the ideal concentrations of eckol and phloroglucinol for plant growth in various liquid seaweed fertilisers, more research is needed [68]. The impact of foliar and soil drench applications of liquid seaweed extracts (LSEs) derived from *Ulva lactuca, Caulerpa sertularioides, Padina gymnospora,* and *Sargassum liebmannii* as biostimulants on tomato (*Solanum lycopersicum*) germination and growth under laboratory and greenhouse conditions. Liquid seaweed extracts (LSE) increase fruit development and maintain plant growth [39].

4. CLASSIFICATION AND VARIOUS TYPES OF BS

There are various kinds of biostimulants, including inorganic chemicals, microbial biostimulants, plant and algae extracts, and acid-based biostimulants. Based on the source of raw material it is classified as including microbes, protein hydrolysates, seaweed extracts, humic and fulvic acid compounds [6]. These several kinds of biostimulants each have advantages in terms of improved fertility, enhanced vigour, benefits to plant health, and improved crop quality [63]. Biostimulants include a wide range of compounds, including extracts from seaweed, humic substances, complex organic materials, beneficial chemical components, inorganic salts, chitin, and chitosan derivatives, Antitranspirants, free amino acids, and other compounds containing nitrogen [28]. A foliar spray containing different biostimulant components, including as phytohormones, humic acid, and seaweed extract, was used. It promotes natural processes that improve crop quality, tolerance to abiotic stress, and nutrient uptake. Biostimulants are an efficient way of influencing physiological and biochemical features that lead to increased yield and growth [45].

5. ROLE OF SEAWEED EXTRACT-BASED BIOSTIMULANT

As a result of their advantageous effects on soil, both macro- and microalgae have long been employed to increase plant productivity and food production in different parts of the world. Algae and the soil ecosystem surely interact in complex ways, and the benefits that result vary depending on the crop and the local environmental factors. This has led to a great deal of conjecture on the mechanisms at play and the veracity of the results that have been published. It has been 60 years since the first seaweed extract was produced commercially for use in agriculture. For the first time, these aqueous extracts made it possible to directly apply soluble seaweed components to certain plant organs like leaves and roots. Seaweed extracts have opened up new and interesting possibilities for use in both plant and animal applications [23].

The seaweeds are photoautotrophic marine algae with a variety of traits. These multicellular organisms are largely derived from water-based environments and provide a wealth of possible applications as well as being economically viable, renewable, and harmless to the environment resources [75]. The proportionate effectiveness of SWE use in the agricultural sector demonstrates the beneficial effects on plant development, yield, nutritional quality, and bioactive content. Application of Seaweed Extract (SWE) is therefore linked to a greater capacity of plants to withstand both abiotic and biotic stresses. [35]. Many macroalgae are employed in the synthesis of biostimulants; however, in the past few years, *Ascophyllum nodosum, Ecklonia maxima,* and *Kappaphycus alvarez*ii, together with the genera *Gracilaria* spp., got particular interest. [71,72]. Red seaweeds include *Kappaphycus alvarezii, Gracilaria edulis, Acanthophora spicifera, Gelidium robustum*, and *Gracilaria parvispora,* and brown seaweeds include *Ascophyllum nodosum, Fucus* spp., *Laminaria setchellii, Sargassum hildebrandtii, Turbinaria* spp*., Macrocystis pyrifera, Sargassum horridum, Ecklonia arborea, Durvillaea antarctica*, and *Sargassum horridum* [2]. One of the most popular biostimulants made from different seaweed species is seaweed extract (SWE). The main component of commercially marketed SWEs is polysaccharides, which make up between 30 and 40 percent of their fractions [7].

The Ascophyllum nodosum extract (ANE), application of ANE (SealicitTM) to soybean in Brazil and Canada indicates the favorable benefits of anti-shattering, pod dehiscence, firmness, seed weight, and eventually seed yield in soybean (Glycine max) [52]. Spraying seaweed extract at seedling, stem elongation, and early mature stage improves enzyme activity to increase sucrose % on sugarcane stems [20]. Ascophyllum nodosum extract (ANE) influences the mechanism of nitrogen (N) uptake in plants, assimilated in plant parts. In a better way, it allowed to reduce the N fertilization and simultaneously increase the yield of barley. It maintains Nutrient Use Efficiency (NUE), and reduces Nitrogen (N) fertilizer application by up to 27%, In another way it leads to sustainable, profitable, and eco-friendly agriculture [33].

6. ROLE OF HUMIC ACID AS BIOSTIMULANT

Humic acid primarily contributes to increased root growth, as well as morphological and physiological alterations in roots and shoots associated with nutrient intake, distribution, and assimilation. It may additionally trigger modifications in primary and secondary plant metabolism associated with resistance to abiotic stress. It was formed by non-renewable resources such as peat and coal [16]. These proteins were analyzed further using bioinformatic techniques, and their biological functions protein synthesis, folding and elongation, and energy and metabolism were organized into three primary categories. Additionally, these scientists were able to connect the found proteins to several biological processes, including respiration, the metabolism of energy and cell walls, protein synthesis, folding, and degradation, as well as responses to heat, inorganic chemicals, and cell transport and division. These findings might clear the way for a deeper comprehension of the molecular pathways that Humic Acid (HA) favorably affects. The quantity of carbohydrates and the majority of free amino acids in the roots were significantly reduced in a metabolomic investigation that also used *A. thaliana* and treatments with Humic Acid (HA) as a biostimulant [22]. A rise in protein content in the roots and leaves, most likely as a result of increased protein synthesis and metabolic activity, may be contributing to the plants treated with Humic Acid growing at a faster rate [14]. Humic acid, when used as a biostimulant in cucumber crops, boosts crop growth parameters such as plant height, stem diameter, and biomass content, as well as ammonia and potassium storage capacity and availability of P status. He concludes that 1% Humic Acid applied to substrates (cocopeat) improves plant development. [82]. Advantages of Humic Acid on growth indices, carotenoid content, antioxidant activity, and nutritional value of yarrow in field and greenhouse conditions. In alkaline soils with low pH, yarrow can grow and become more antioxidant-active by applying HA [8]. In maize roots, humic compounds have been shown to encourage cell wall elongation and loosening [42].

7. ROLE OF FULVIC ACID AS BIOSTIMULANT

The FA are characterized by high concentrations of carboxylic groups (COOH), low concentrations of aromatic structures, and high concentrations of phenolic substances [16]. In spring wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sugar beetroot (*Beta vulgaris*), Fulvic Acid (FA) biostimulants were found to enhance germination while also increasing shoots and increasing the dry weight of shoots and roots. Through faster cellular water potential restoration, osmotic adjustment, increased stomatal conductance, photosynthetic activity, and photoassimilate production, higher efficiency in energy dissipating mechanisms, which reduced Reactive Oxygen Species (ROS) generation, and higher activity of antioxidant enzymes, fulvic acids induced soybean plants to recover from water deficits more effectively [69]. When given at various phenological stages, fulvic acid may mitigate the harmful effects salt stress causes to the photosynthetic system in soybean plants. The benefits of Fulvic Acid (FA) on yarrow's growth indices, carotenoid content, antioxidant activity, and nutritional content in both greenhouse and field settings. Applying Fulvic Acid (FA) to yarrow can help it grow and become more antioxidant-active, especially in alkaline soils with low [8].

8. ROLE OF MICROORGANISMS-BASED BIOSTIMULANT

It's possible that biostimulants based on bacteria and fungi can help ameliorate the negative environmental effects of agriculture [61]. Additionally, microbes are essential to the phyllosphere, rhizosphere, and endosphere of plants because they increase the availability of certain nutrients and make them easier for plants to absorb. The symbiotic relationship between the two has been vital for the evolution of both [81]. Many microorganisms, including *Arthrobacter* spp, *Pseudomonas* spp, *Rhodococcus* spp, *Enterobacter* spp, *Ochrobactrum* spp, *Acinetobacte*r spp, *Bacillus* spp, *Rhizobium* spp, and *Streptomyces* spp, have been thoroughly investigated to explore their possible function as biostimulants; some of these species have even been commercialized [81].

Several soils were used to extract *Bacillus* spp and *Pseudomonas* spp, and this not only serves as bio fungicides to support the health of plants and soil [18]. The use of Enterobacter strain 15S may have solubilized calcium phosphate ($Ca_3(PO_4)_2$) to assist plants in overcoming P shortage, whereas the association of maize activated plant metabolism. Based on nutritional status, this mechanism enhances plant growth and P nutrition. The amount of chlorophyll was assessed using the chlorophyll meter (SPAD) [3].

9. ROLE OF PEPTONE AND PROTEIN BIOSTIMULANT ON CROPS

Fruit qualities such as sugar deposits, overall acidity, carotenoid levels, and vitamins C and E were preserved when peptone was utilized as a biostimulant. Peptone promotes vegetative growth and fruit yield by increasing cytokinin accumulation and photosynthetic pigments in plants. Peptone treatment effectively increases tomato yield in greenhouse conditions when N priming is used [59]. Protein-based biostimulants derived from enzymatic hydrolysis may be a suitable strategy for enhancing productivity and improve the utilization of specific nutrients, including nitrogen [21]. Through the application of Protein hydrolysates, it improves in photosynthetic rate, root growth, and upregulation of genes linked to antioxidant activity, photosynthesis, nutrient uptake, and primary metabolisms; increased biomass, concentration of soluble sugars, and levels of chlorophyll and phenolic content in plants.

Elevated levels of terpenes, alkaloids, phenylpropanoids, and chemicals containing nitrogen [30]. Enhanced stomatal conductance and photosynthetic rate during drought stress; lessening the adverse impacts of stress on transpiration rates and gas exchange. Enhance the drought tolerance and increase the chlorophyll content in broccoli [43]. Increased the amount of plant biomass and leaf chlorophyll by stimulating the proliferation of microorganisms that promote plant growth [56].

Table 1. Cumulative potential benefits of biostimulants in agricultural sector

Biostimulant	Plant Species	Plant Response	References
Humic acids	*Arabidopsis thaliana*	Increased heat stress tolerance through activation of heat-shock protein genes; elevated amounts of proteins involved in energy metabolism and cell walls; respiration, folding, protein synthesis, degradation, reaction to heat and inorganic chemicals, cell trafficking and division, and a drop in the concentration of amino acids and carbohydrates.	[19]
	Brassica napus	Reduction in soluble carbohydrates, linolenic and erucic acid; increase in yield and chlorophyll percentage; enhanced oil quality, plant net the processes of photosynthesis gas exchange rate, and electron transport flux.	[65]
	Capsicum annuum L.	Enhanced chlorophyll content resulted in enhanced net photosynthesis; enhanced root development and increased plant biomass under drought stress while quickly decreasing leaf stomatal conductance and transpiration rates.	[14]
	Phaseolus vulgaris L	It alters the stress-related gene expression	[77]
	Solanum tuberosum	Improved plant growth, nutrient transport, and photosynthetic indices under drought stress; increased tuber production and plant biomass.	[58]
	Zea mays	Enhanced efficiency in using water and nitrogen; increased expression of genes involved in water transport, nutrient absorption, and nitrate transporters	[24]
Fulvic acid	*Arabidopsis thaliana*	Reduced production of reactive oxygen species (ROS), oxidative as well as induce drought stress tolerance, and downregulation of genes associated with growth impairment under stress	[66]
	Beta vulgaris	Enhanced germination parameters, including soluble sugar content, root size, and yield	[11]
Seaweed extracts (*Ascophyllum nodosum*)	*Glycine max* L.	Enhanced stomatal conductance, photosynthetic efficiency and activity, chlorophyll content, and antioxidant activity under drought stress and root growth	[27]
	Allium cepa	Yield growth and a decrease in downy mildew severity, Improving the onion's chlorophyll and carotenoid concentrations, as well as its plant height, leaf count, bulb diameter, protein content, and sulfur content.	[40]
	Lycopersicon esculentum	Improve photosynthetic indices, pollen viability, and thermo tolerance at both normal and high	[25]

Biostimulant	Plant Species	Plant Response	References
		temperatures; higher fruit yield and chlorophyll content. Increase fruit yield components in both salinity-stressed and normal circumstances	
	Malus domestica	It minimises the alternate bearing habit	[73]
	Solanum melongena	Greater productivity and growth of vegetation	[15]
	Triticum aestivum L.	Enhanced germination circumstances and produced better grain quality and yield.	[11]
	Vitis vinifera L	Increased berry number, anthocyanin, phenolic content, plant biomass, yield, Nitrogen (N), and soluble sugar concentration all without adversely affecting the quality of the berries.	[32]
Seaweed extracts (*Ecklonia maxima*)	*Oryza sativa*	Improved germination, seedling vigour, and root growth; increased yield parameters, grain number, protein, and nutritional content in the grain, plant biomass, and chlorophyll content.	[53]
	Phaseolus vulgaris L.	Improve better nutritional quality, higher yield, and antioxidant activity in the seeds	[47]
	Saccharum officinarum	Improve brix content in the juice	[44]
	Zea mays	Increased yield, photosynthetic pigments, antioxidants, grain quality, and protein content under drought stress Improve plant growth, antioxidant activity, and nutrient uptake, under ideal conditions	[78]
Kappaphycus alvarezii	*Solanum esculentum*	Fruit production, length, diameter, and nutritional quality also increased	Zodape et al. (2008)
	Solanum tuberosum L	Enhanced plant growth indices; higher yield, higher quality yield; higher concentration of nutrients; higher ascorbic acid and soluble sugar content.	[64]
	Saccharum officinarum	Enhanced plant growth and juice brix content; increased plant production.	[44]
		Improved plant stress tolerance; increased root development, photosynthetic pigment concentration, RWC, amino acid content, proline, and soluble sugar content	[64]
	Zea mays	Reduced photosystem damage and lipid peroxidation; improved yield parameters, photosynthetic pigments, antioxidants, grain quality, and protein content; under drought stress.	[79]
		Unfavorable circumstances, increased yield characteristics and quality, enhanced nutrient uptake, enhanced plant growth, reduced lipid peroxidation, and ROS production.	

10. PHYSIOLOGY AND METABOLISM

Seaweed extracts and their chemical constituents have a special effect on plants' metabolic regulatory pathways, which are being illuminated by recent developments in seaweed extract research that involve gene expression analysis. In spinach treated with a commercial brown algal extract, there was an increase in total soluble protein, antioxidant properties, content of phenolics and flavonoids, and transcript abundance of regulatory enzymes involved in nitrogen metabolism (cytosolic glutamine synthetase, glutathione reductase, and betaine aldehyde dehydrogenase and choline monooxygenase) [31]. The synthesis of chloroplasts increased, chlorophyll degradation decreased, and senescence was delayed, all of which contributed to the rise in chlorophyll concentration. It enhances maize productivity despite its low phosphorus uptake [41]. The problem of alternating bearing under nutrient-deprived conditions was resolved by applying a commercial seaweed extract to apple trees (variety Fuji), but not under normal nutrient management conditions. Furthermore, the biostimulant minimized fruit production oscillations in alternate-bearing trees by improving plant growth, fruit production, and fruit quality [73]. It seems that the presence of a hormone or signaling component in a commercial seaweed extract derived from *A. nodosum* may contribute to its effect on alternate bearing under nutrient-deprived situations.

11. UPTAKE OF NUTRIENTS

It is also known that different seaweed extracts have an impact on the regulation of genes that are crucial for nutrient uptake. For instance, *A. nodosum* extract enhanced auxin transport and nitrogen sensing by upregulating the expression of the nitrate transporter gene NRT1 [49]. Furthermore, it is known that certain chemical components of brown seaweed extract stimulate the growth and root colonization of helpful soil fungi. suggest that in addition to having Arbuscular Mycorrhiza (AM) stimulatory chemicals, red and green algae aid in the growth of mycorrhizal fungi in higher plants [51]. It has been found that applying brown seaweed extract topically increases grapevine copper uptake. Water stress tolerance, a rapid recovery in rehydrated plants, and the maintenance of a greater leaf water potential and stomatal conductance during the stress period were all induced by the extract with remarkable efficacy [80]. Seaweed extracts include nutrients that are easily absorbed by leaves via their hydrophilic cuticle pores and stomata. Environmental factors that impact stomata opening, cuticle and cell wall permeability, and temperature, humidity, or light intensity also impact the absorption of these mineral nutrients from the leaf surface. It was demonstrated that foliar application of seaweed extract products, including those of a commercial *A. nodosum* extract, enhanced the Copper (Cu) uptake in grapevine under conditions of nutrient deficiency. This was likely due to increased cell membrane permeability.

12. ABIOTIC STRESS TOLERANCE

Additionally, the effects of intensive agricultural methods are a major factor in the frequent occurrence of unfavorable conditions for crop plant growth and development. Globally, abiotic stressors are responsible for significant losses in crop productivity. Salinity alone has the potential to severely reduce the productivity of important food-producing crops [84]. Applying an *A. nodosum* extract formulation, for instance, reduced the leaves' osmotic potential, a crucial marker of osmotic tolerance, and enhanced grapes' ability to withstand freezing temperatures. In greenhouse experiments, a commercial extract of *A. nodosum*-treated vegetables, bedding plants, and turf crops significantly reduced water use (better water use efficiency), increased leaf water content, and improved drought-wilted plant recovery when compared to controls. Two weeks apart, root treatments of a commercial Ascophyllum extract to almonds increased the treated plots' negative mid-day stem-water potential [55].

Abiotic stress has become more common in recent years, mostly as a result of climate change, which has led to an extraordinary rise in extreme weather events and patterns. Additionally, the effects of intensive agricultural methods are causing unfavorable conditions for crop plant growth and development to spread widely. Abiotic stress is responsible for significant global crop output losses. [46] reported that abiotic stresses such as salinity, drought, waterlogging, and high temperatures are some of the primary factors that influence the quantity and quality of horticultural crops. [83] proposed that an increase in Potassium (K^+) uptake and the presence of "cytokinin-like" molecules in the extract were responsible for of this uptake.

Applying seaweed extracts to creeping bentgrass increased its heat tolerance. These abiotic stresses are predicted to have a greater adverse impact by the real climate change scenario, raising major concerns about crop productivity and, consequently, global food security [70]. The biostimulant based Glycine betaine (GB)-enhances the crop abiotic stress tolerance (drought), and treated plants get higher photosynthetic activity, through the accumulation of lipids and thickening of leaf resulting in ass increase Water Use Efficiency (WUE). Generalized Additive Mixed Modeling (GAMM) was used to evaluate the photosynthetic efficiency [36]. Among these, GAMMs have been implemented successfully in a wide range of applied science areas. [60; 62]. Similarly, the impacts of GB on water-use efficiency (WUE) have received less attention [1].

13. CONCLUSION

In conclusion, by improving plant growth, stress tolerance, and nutrient uptake, biostimulants outperform conventional fertilizers and pesticides in sustainable agriculture. They are essential for combating rising food prices, degraded soil, and climate change. The types, processes, and revolutionary potential of biostimulants in agriculture are reviewed in this paper. Growing worldwide sales of biostimulants are expected, reflecting a shift in farming practices toward more environmentally friendly options. For widespread application, nevertheless, issues like product standardization and comprehension of biostimulant interactions in diverse agricultural systems need to be resolved. Developing application guidelines and elucidating biostimulant mechanisms should be the main goals of future studies. Effective integration requires cooperation between industry, politicians, and researchers. To sum up, biostimulants have the potential to completely transform agriculture by improving plant health and yield while lowering the need for chemical inputs. Using biostimulants will result in robust, environmentally friendly farming systems that will improve both environmental sustainability and global food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts. – I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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