Biostimulants: Emerging Role in Sustainable Agriculture for Crop Adaptation and Mitigation Against Abiotic Stress and Food Security

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Abstract

Biostimulants potentially improve crop growth, yield, and food production through efficient nutrient utilization and support of existing plant defense mechanisms under biotic and abiotic stress conditions. These substances also known as "plant conditioners" or "bioeffectors" offer a simplified and practical approach for addressing challenges posed by climate change through the ever-changing environmental conditions. Currently, applications involving biostimulants for agricultural sustainability have increased in nearly every dimension, bolstering crops' resilience and increased performance of the plant's vital morphological, physiological, and reproductive processes, achieving high and good quality

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yields. Biostimulants have been applied to crops enhancing nutritional efficiency regardless of the genotype and cultivation methods. Therefore, this chapter evaluated the role of biostimulants in improving crop growth, development, and response under abiotic stresses such as drought, extreme temperatures and salinity by examining the various raw materials in their compositions like proteins, humic acids, microbial extracts, algal extracts, and plant-based products explored for adaptation and mitigation, including food security. Subsequently, the contribution of biostimulants in improving the quality of crops produced for human consumption and their impact on the environment are also discussed and some preliminary conclusion drawn regarding their overall application and safety regulations.

Keywords

Abiotic stress · Biostimulants · Biotic stress · Climate change · Crops · Safety regulations

Introduction

The role of biostimulants in agriculture serves as one of the most important and eco-friendly advancements in the history of agricultural research in this sector, agro-economy, food production systems, and for human consumption and survival (du Jardin 2015). Although, the agricultural sector has changed dramatically over the centuries, especially during the past decades, the introduction of biostimulants guarantees the sector's main objective of remaining the primary source of food production, ensuring stable and consistent food supply for billions of people worldwide. Efficient agriculture is also key to enabling industrial transformation of economies in both developed and developing countries. It serves as a reliable source of better livelihoods for families directly dependent on it, and a guardian of the earth's fertile environment through carbon and mineral recycling (Delgado and Follet 2002; Davis et al. 2023; Schunko et al. 2024). However, for many years, human populations have regularly contributed to increasing atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other harmful gases that play a key role in the gas fluctuations observed in the atmosphere (Lynch et al. 2021). These emissions occur as human beings endeavor to sustainably reconstruct their subsistence niches to achieve high levels of food production, whereby their actions lead to massive climatic and environmental instabilities, particularly driven by the increase in global human population and their various anthropogenic activities, including unsustainable agricultural practices (Rowley-Conwy and Layton 2011). Lynch et al. (2021) suggested that agriculture serves as a significant contributor of man-made global warming, which precedes another issue called climate change.

Climate change caused by global warming poses serious threats to humans and agriculture in the form of widespread flooding, drought, and extreme temperatures. These are commonly known as abiotic stress factors, including depletion in soil mineral nutrient compositions, that dramatically reduce crop growth and development, as well as yield quantity and quality, thus negatively affecting global food security (Sanchez-Bermudez et al. 2022). Amongst the abiotic stresses, drought (also referred to as water-deficit) causes major reduction in crop growth and yield, indiscriminately for rainfed and irrigated cultivation of crops. The most important staple crops such as maize (*Zea mays*), wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), rice (*Oryza sativa*), and barley (*Hordeum vulgare*) experience drought which causes serious morphological, physiological, biochemical, and molecular defects in both below ground and above ground parts of the plants as reported by Ray et al. (2018) and Toulette et al. (2022). Severe drought effects are still suffered by these crop species even though they are grasses (Poaceae) possessing a Hatch and Slack pathway (C_4) taking place between the mesophyll and bundle sheaths of the leaf mesophyll to avoid photorespiration that leads to water loss (Furbank 2016). Other abiotic constraints include salinity and chilling stress that also have adverse effects on agricultural food production.

The current effects of climate change are widely receiving attention and encouraging everyone working in the sector, particularly, farmers, breeders, and agricultural researchers, to make food systems more sustainable. All food producers are now encouraged to produce food without using agricultural practices that have damaging effects on the environment and health of humans, as well as animals. But as per recent assumptions, climate change-induced abiotic stresses will continue negatively influencing crop yield losses up to 70% for cereals (Francini and Sebastiani 2019) and 60% for pulses (Kopecka et al. 2023) if more environmentally friendly and climate-smart strategies are not adopted and successfully implemented. Furthermore, considering the major concerns being raised against the adoption of modern agricultural technologies such as the production of genetically modified organisms (GMOs), particularly, GM crops, and the excessive use of agrochemicals, the new alternatives must at least be eco-friendly, biodegradable, and free of harmful chemical byproducts. Like many other recently adopted technologies, the production of GM crops, and use of agrochemicals for controlling pests, pathogens, and supplying nutrients to the soil still do not proceed without policy conflicts and strict regulations (Karalis et al. 2020; Demi and Sicchia 2021). However, these concerns regarding their environmental and human health associated risks are never ignored by authorities, and also professionals in the research fraternity and the general public.

Such concerns ultimately also lead to the consideration and application of new agricultural strategies such as the use of biostimulants to enhance crop productivity and resilience to environmental stress. Biostimulants refers to biological substances and microorganisms or microbial inoculants that can be used as alternatives to agrochemicals like chemical fertilizers and pesticides to promote growth and yield of crops (Rouphael and Colla 2020). These substances recently became more desirable due to their ability to concomitantly raise crop productivity needed to feed the growing human population while reducing the negative impact of agriculture on the environment. With this background, this chapter focusses on discussing the following: (1) role of biostimulants in supporting, strengthening, and driving sustainable agriculture by improving morphological, physiological, and biochemical development of crops with or without abiotic stress, (2) examine the mitigative and adaptative effects of biomaterials such as humic acid, protein concentrates, and extracts from microbial, algal, and plant-based sources for use as biostimulants, and then (3) outline the pros and cons of these growth-stimulating substances—juxtaposed with agrochemicals—considering their raw materials and compositions, as well as their effect on human health, environment, and regulatory policy trajectory, globally.

Biostimulants Types and Their Biogenic Synthesis

As previously highlighted, biostimulants (also known as plant conditioners or bioeffectors) refers to the substances forming a group of biological materials or microorganisms applied to plants, particularly crop species with the intention to improve nutrition efficiency, growth, yield, and tolerance to biotic and abiotic stresses (du Jardin 2015). Biostimulants are primarily comprised of organic or biological substances such as amino acid and protein hydrolysates, humic acid, seaweed extract, beneficial fungi, botanical extracts, and microbial extracts that are summarized in Table 1. By extension, these also include commercially available mixtures of highly concentrated mineral nutrients combined with various growth stimulants like vitamins and plant growth regulators (PGRs).

Table 1 Summary of the most common types of biostimulants, source material, and application in the improvement of crop growth, yield, and responses to abiotic stress

Biostimulants	Source/species	Application	References
Amino acids and protein hydrolysates	Animal or plant origin	Root system, foliar application	Sun et al. (2024)
Antitranspirants: abscisic acid (ABA), calcium carbonate (CaCO3), fulvic acid (FA), salicylic acid (SA)	Chemical extraction/ synthesis	Applied directly on the plant as comprised films forming (physical barrier), metabolic (stomatal closure) and reflective (kaolin) types	Kociecka et al. (2023)
Botanic extracts	Plants; examples include Hypericum perforatum (St John's-wort), Taraxacum officinale (common Dandelion), Trifolium pratense (red clover), Urtica spp. (nettle), Valeriana officinalis (valerian), and Solidago gigantea (giant goldenrod)	Direct plant application in liquid or dried formulations	Godlewska et al. (2021)
Humic substances (humic acids, humins, and fulvic acids)	Microbial and chemical degradation of organic matter	Applied directly to soil	Sutton and Sposito (2005), Trevisan et al. (2010)

(continued)

Table 1 (continued)

Biostimulants	Source/species	Application	References
Microbial inoculants	Bacterial: Azotobacter spp., Bacillus spp., Enterobacter spp., Pseudomonas spp., Fungal: Arbuscular mycorrhizal fungi (Glomeromycota)	Direct application to soils or rhizosphere	Vessey (2003), Berruti et al. (2015)
Seaweed extracts	Freshwater and marine ecosystems. Species include brown algae such as Ralfsia, Ascophyllum, Padina, Sargassum, Laminaria spp.	Formulated in liquid or dried form for field application or directly on the plant	Calvo et al. (2014)

Generally, biostimulants are biogenically synthesized from agro-industrial wastes, microbial cells, and marine and botanical organisms (Table 1). For instance, valorization of agricultural wastes and plant-based extracts are used to produce cost-effective growth-stimulating compounds such as antitranspirants (chemically extracted as indicated in Table 1) required for efficient water management in drought-stricken plants. Wax extracted from cauliflower (*Brassica oleracea*) leaves was formulated using supercritical CO_2 to improve water-use efficiency and stomatal conductance in rapeseed (*Brassica napus*) (Faralli et al. 2022). Seaweed extract containing bioactive compounds that include essential minerals, proteins, lipids, polysaccharides, vitamins, and polyphenols were obtained using different biorefinery approaches depending on the desired final product. Recently, Mattoso et al. (2024) mentioned dewatering, filtration, drying, and grinding following by aqueous extraction through different solvents (water, ethanol, chloroform, or methanol) to produce high-value seaweed extract products with reduced wastes and water loss. In microbial extracts, the methods include hydrolyzing bacteria into a hydrolysate and then formulating it as a plant biostimulants for foliar or soil applications (Kumari et al. 2023). Seaweed and botanical extracts are often formulated as liquid or dried extracts for use as biofertilizers. The development of these novel biomaterials based on the type of biostimulants summarized in Table 1 exhibited the potential to boost crop growth and yield without adversely affecting environmental, biological, organismal, or species diversity (Szparaga et al. 2021).

Although, their potential impact in agriculture have been widely reported to be beneficial for early seedling development, improved plant growth, higher crop yield, and also preventing environmental stress imposed on cultivated plants following direct foliar applications, Karthik and Jayasri (2023) used seaweed extracts prepared using *Turbinaria ornate*, *Ulva intestinalis,* and *Portieria hornemannii* as biofertilizer formulations in *Vigna radiata* (L.) R. Wilczek pot culture. The plants were treated with various individual and combinations of these formulations yielding maximum germination and an upsurge in plant performance with overall increases in morphological, physiological, and biochemical crop attributes.

Role of Biostimulants in Crop-Stress Interactions

Biostimulants are essentially required to improve the growth of plants during fluctuating environmental conditions for enhancing the quality and quantity of crops produced, either applied directly on the plant or used as soil conditioners. The effects of these substances on plant growth and development also vary depending on the compound or mixture composition used, and the crop, both of which play a critical role in improving the morphological and physiological characteristics of the plants (Shahrajabian et al. 2021). When directly or indirectly applied to plants (Fig. 1), biostimulants effectively act as the source of nutrition as well as signaling molecule that promote growth and stress management. Currently, many studies showed that biostimulants improve food production through sustainable cultivation of crops under adverse environmental conditions.

Humic acid (HA) sourced from coal, lignite, and organic matter, including soil was reported to increase yield by positively affecting soil physical, chemical, and biological properties (Fig. 1). HA influenced the texture, structure, water holding capacity, cation exchange, pH, soil carbon, enzymes, nitrogen cycling, and nutrient availability as reported by Ampong et al. (2022). In maize, HA also improved grain yield and nitrogen use efficiency by 99.1% and 11.6%, respectively, in addition to 29% decrease in annual cumulative N_2O emission when added to controlled-release fertilizer (Guo et al. 2022). Seaweed extract alone or extract mixtures applied as biofertilizer made from *T. ornate*, *U. intestinalis,* and P. *hornemannii* as previously highlighted also stimulated maximum seed germination and increased shoot length, root length, fresh

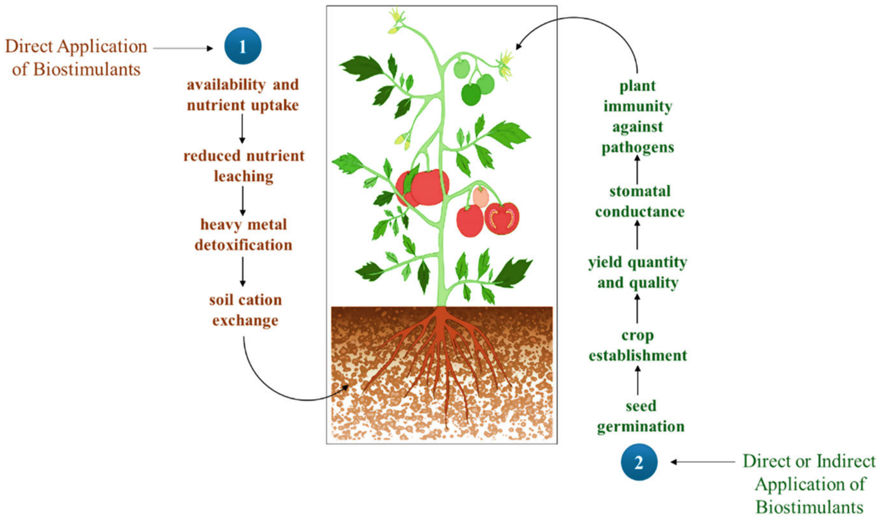

Fig. 1 Summary of important effects of biostimulants on crop growth and development based on direct and/or indirect application (du Jardin 2015; Ali et al. 2021; Shahrajabian et al. 2021; Guo et al. 2022; Karthik and Jayasri 2023)

weight, dry weight, carotenoids, chlorophyll (a and b), carbohydrates, and proteins among some of the critical characteristics by 28, 120, 41, 54, 80, 41, 18, and 21%, consecutively in *V. radiata* (Karthik and Jayasri 2023). The improvement of all of the abovementioned growth characteristics generally play an important role in enhancing plant's fitness, immunity, and recovery against both biotic and abiotic stresses.

Pigments like carotenoids and proteins are similarly involved in the defense of plants against abiotic stress. For instance, the protective role of carotenoids against stresses such as drought, temperature variations, and nutrient scarcity, include the regulation of photoprotective, antioxidant, and stress signaling mechanisms, together with synthesis of vitamin precursors necessary for normal cell function, growth, and development. Moreover, carotenoids were also found to accumulate in aging seeds, and during germination at higher temperatures as antioxidants protecting the seeds against oxidative stress (Smolikova et al. 2011). Besides the abovementioned characteristics, biostimulants are extensively utilized in the adaptation and mitigation of abiotic stress, including biotic factors above-surface and those below the ground which are considered as source of various microbial pathogens (Ma et al. 2022; Monteiro et al. 2022).

Potential Role of Biostimulants on Mitigation and Adaptation of Abiotic Stress

Biostimulants as fertilizers can increase soil organic matter while retaining soil physical and chemical properties that assist in maintaining water holding capacity of the soil. High water retention capacity of the soil in the long-term after biostimulant application is caused by increased soil physicochemical properties that lead to decreased bulk density, increased porosity, and alternation in aggregate stability as reported by Wadduwage et al. (2023). The findings further indicated that biostimulants stimulated microbial activity by 40%, soil enzyme activity related to carbon and nitrogen cycling by over 20%, and substrate-induced respiration by 10%, as a result of increased soil moisture content. As advancing food security and agricultural sustainability remains a global priority, the use of appropriate plant protectants such as fulvic acid and other antitranspirant could counteract effects of abiotic constraints with maximum food production, and without causing any negative effects on food quality, soil stability, and environmental health. A handful of researchers have also demonstrated that increased soil moisture content as a result of biostimulants application will alleviate the effects of water deficit in crop production. Garcia-Garcia et al. (2020) reported decreased negative effects of drought stress by improving nutrient uptake and osmotic adjustment efficiencies through mixtures such as lixiviates from proteins and algal extracts.

Abiotic stress induced by high temperatures also causes serious problems in crop growth and development. For instance, reports show that heat stress impairs cell membrane and protein stability, including many other biological processes involving both primary and secondary metabolism (Francini and Sebastiani 2019; Garcia-Garcia et al. 2020; Cocetta et al. 2022; Kopecka et al. 2023). Cocetta et al. (2022) also reported the successful application of two biostimulants based on *Ascophyllum nodosum* extracts and animal L-2 amino acids as primary treatments to protect *Arabidopsis thaliana* plants against heat stress (37 ± 1 °C). These findings indicated that both treatments were capable of reducing oxidative damage in leaves and cell membranes by activating specific heat shock proteins, antioxidant systems, and reactive oxygen species (ROS) scavengers. Even under salinity stress, biostimulants aided in the recovery from salt stress induced using 150 mM sodium chloride (NaCl) in lettuce (*Lactuca sativa* L.) (Zuzunaga-Rosas et al. 2024). As indicated previously, biostimulants used as antitranspirants were also reported by Faralli et al. (2022) to mitigate and adapt plants against drought stress by reducing transpiration in rapeseed. Therefore, a full exploitation of the abovementioned biostimulants, as well as others, could mark the end of overreliance on conventional agricultural practices such as tillage, fallow periods, and excessive use of chemical fertilize inputs (Wadduwage et al. 2023) to achieve sufficient and sustainable food production for the ever-increasing human population globally.

Effect of Biostimulants on Soil Fertility

Presently, soil fertility has worsened globally due to land degradation, soil erosion, application of chemical fertilizers, and other unsustainable agronomic practices such as land usage without crop rotation, tillage, and excessive use of plant disease protection chemicals. Loss of soil fertility adversely affects agricultural outputs by reducing the ecosystem's viability, ability for crop cultivation, and causing food scarcity (Mani et al. 2021). These do not only impede crop production but also overly hinders progress toward achieving sustainable land rehabilitation and combatting the effects of climate change, including alleviating poverty, hunger, and malnutrition. Soil fertility will continue to deteriorate across the world if the role of advancements such as biostimulants as an eco-friendly strategy and contribution to improved agricultural practices is not intensified. Particularly, because the production of biostimulants is cheaper than chemical fertilizers and could therefore, be used to curb the excessive use of chemicals mostly in developed countries, while reducing the scarcity of fertilizers that is leading to below average crop productivity in developing underprivileged regions (Karthik and Jayasri 2023).

Due to the major problems associated with the use of inorganic fertilizers like the alteration of soil pH, negative impact on microbial diversity, and decreased variation as well as balance in soil mineral nutrient compositions. These underutilized biofertilizers will increase manure supplements provided from abundant sources such as seaweed, botanicals, and microbial sources without delays or shortage to enhance food production. Predominantly, farmers across the world depend on inorganic fertilizers to improve crop productivity while causing pollutions and threats to biodiversity, negatively affecting animal and human lives. Some reports show that inorganic fertilizers are highly soluble, with higher potential for leaching into groundwater systems posing a serious risk to water quality compared to biofertilizers (Kakar et al. 2020). Therefore, the application of biostimulants such as protein hydrolysates, amino acids, HA substances, and others (Table 1) can serve as valuable alternative options in reducing excessive use of inorganic fertilizers.

Crop Yield and Quality Improvements

The nutritional and functional profile of biostimulants is reported to be a remarkable development in agriculture, although, their potential has not been adequately explored, especially through evaluation of crop products fortified with these biogenic compounds. Recent research revealed the potential for these compounds to reduce yield losses and improve the quality of harvested grains, particularly in response to environmental stresses (Faralli et al. 2022; Sanchez-Bermudez et al. 2022; Karthik and Jayasri 2023; Wadduwage et al. 2023; Zuzunaga-Rosas et al. 2024), and without any extension to pre- and post-harvest assessments of the crops. As they have now emerged as alternative primary source of essential nutrients in crop production, a clear understanding of their influence on the quality and quantity of yields is also important. Current evidence revealed phytostimulatory properties on yield quantity and quality as a result of biostimulant application.

Majkowska-Gadomska et al. (2021) reported increased total harvest of *Capsicum annuum* fruits, cultivar Cyklon (0.2–3.8 $kg.m^{-2}$), using commercial stimulants Biocin F, Multical, and BB soil containing a mixture of lactic acid bacteria (*Lactobacillus casei*, *L. plantarum*), photosynthetic bacteria (*Rhodopseudomonas palustris*), and yeasts (*Saccharomyces cerevisiae*). Other studies also discovered that sole and combined application of biostimulants significantly improved yield quantity in many crops, such as maize, ranging from 1–5 tonnes per hectare ($t.ha^{-1}$) to 16–20 $t.ha^{-1}$ (Ocwa et al. 2024). In general, some of these yield quality characteristics enhanced by biostimulants are essential in promoting harvests' feeding standards or product quality and are briefly summarized in Fig. 1 and Table 2. Furthermore, crops fortified with these compounds should contain sufficient amounts of nutrients that are easily converted into dietary materials that can be consumed by humans and animals. As such, current evidence gathered from the use of biostimulants indicate that adequate levels of nutrients may be provided by crops fortified with biostimulants and such findings will be discussed in subsequent section of this chapter.

Nutritive Value of Foods Produced Using Biostimulants

Even though biostimulants directly or indirectly deliver essential nutrients into propagules such as seeds for plant growth and development, some trigger transition from vegetative to reproductive growth, playing a critical role in the development of flowers and fruits, while helping plants to overcome the various habitat challenges. Millions of hectares of crop field are now treated with biostimulants, with some like Indigo Ag-bioinstrinsic W10 enhancing drought protection during critical crop filling stages, optimizing root growth and improving water-use efficiency (Calvo et al. 2014). Overall, the improvement of plant growth and yield by biostimulants has

Table 2 Composition of nutrients and mineral elements significantly enhanced by the application of biostimulants during crop cultivation

Nutrient(s)	Biostimulant	Crop	References
Carbohydrates	Humic acid	Maize, Pepper	Majkowska-Gadomska et al. (2021), Ocwa et al. (2024)
Oil	Humic acid	Maize	Ocwa et al. (2024), Trevisan et al. (2010)
Proteins	Humic acid	Maize	Ocwa et al. (2024)
Vitamin C (L-ascorbic acid)	Multical, MK5	Pepper	Majkowska-Gadomska et al. (2021)
Nitrate (NO_3)	Biocin F	Pepper	Majkowska-Gadomska et al. (2021)
Copper (Cu)	AA-Prim, AA-Hort	Wheat	Popko et al. (2018)
Sodium (Na)	AA-Prim, AA-Hort	Wheat	Popko et al. (2018), Jang and Kuk (2021)
Calcium (Ca)	AA-Prim, AA-Hort, Soy-leaf extract	Wheat, Lettuce	Jang and Kuk (2021)
Molybdenum (Mo)	AA-Prim, AA-Hort, Soy-leaf extract	Wheat	Jang and Kuk (2021)
Magnesium (Mg)	Soy-leaf extract	Lettuce	Jang and Kuk (2021)
Iron (Fe)	Chinese chive extract	Lettuce	Jang and Kuk (2021)
Free sugars (Gluc/Mal)	Chinese chive extract, Soy-leaf extract	Lettuce	Jang and Kuk (2021)
Nitrogen	Garlic extract, *Eucalyptus* extract	Quinoa plant	EI-Rokiek et al. (2019)
Phosphorus	*Eucalyptus* extract	Quinoa plant	EI-Rokiek et al. (2019)
Potassium	*Eucalyptus* extract	Quinoa plant	EI-Rokiek et al. (2019)

Note: AA-Prim, AA-Hort refer to commercial biostimulants Amino acid-Prim and Amino acid-Hort, and Soy-leaf extract refers to Soybean (*Glycine max* L.) leaf extract. Gluc- refers to glucose and Mal- to maltose

been linked to enhanced nutrient uptake and internal nutrient status of the plant. For example, fortified biostimulants of fish, seaweed, and humic acid improved the physiology and advanced development of tomato fruits, as well as marketable fruit yield at harvest by an overall 27% (Weisser et al. 2023). Marketable yield refers to the number of profitable fruits produced by a crop which is affected by many factors, including growth conditions, type of variety/cultivar and the level of stress or stress combinations. Willow bark extract, Bistep, and the combination of Willow + Bistep (W + B) highly influenced macronutrient composition and ionic ratios of lettuce cultivars grown under greenhouse conditions. The high levels of macronutrients accumulated in biostimulant fortified lettuce is expected to play an important dietary role in the body of consumers, as building blocks for carbohydrates, proteins, and fats, ensuring the supply of energy for optimal body functioning (Martiniakova et al. 2022). Furthermore, a balanced amount of macronutrient, micronutrients, and flavonoids help in boosting healthy growth and immunity in addition to bone mineral density, microstructural development, and positive contribution to gene-diet interactions required for a healthy lifestyle (Prentice 2001). However, there is no doubt that in order to stay healthier, the body requires adequate amounts of essential nutrients, carbohydrates, and vitamins obtained from different sources including crops fortified and grown with the help of biostimulants as indicated in Table 2.

Enabling Sustainable Agriculture with the Use of Biostimulants

Sustainable agriculture is one pillar that can be used to ensure sufficient and consistent supply of food to achieve food security. However, food insecurity and malnutrition continue to exist, in part, due to inefficient agricultural practices, inequality, and ineffective distribution of resources. Among some of the agronomic limitations to sustainability are nutrient deficiencies (e.g., N deficiency), stress (drought, heat, chilling, salinity, etc.), and pathogenic organisms that, as previously mentioned, adversely affect agricultural productivity. Currently, all efforts required to meet production efficiency seem to demand appropriate technology, resilient ecosystems, and stable maintenance of the environment (Afrous and Abdollahzadeh 2011). It is evident that this criterion will be met in events where the application of biostimulants is intensified. For instance, excessive application and continued dependence on inorganic N fertilizers that raise the cost of crop production and increased environmental degradation (Keikha et al. 2023) can be expunged if microbial inoculants composed of atmospheric (N_2) fixing bacteria (diazotrophs) are significantly used in agricultural systems. As the production of food must be increased in order to respond to increasing consumer demand, coupled with yield losses caused by climate change, measures such as the monitoring of soil health as a climate change adaptation and mitigation strategy must be encouraged.

According to Feliciano (2022), good soil management and safeguarding sufficient soil fertility throughout can be defined as a great stewardship since a productive land remains part of our shared natural capital. As such, the intensive use of fertilizer inputs, soil degradation through tillage, and removal of crop residues reduces soil quality, causing nutrient deficit, soil erosion, and loss of organic matter. However, the use of humic acid, seaweed, and botanical substances have boosted such soils by restoring its compost content for sustained crop productivity. Humic acid and seaweed both improved soil properties by increasing cation exchange, neutralizing soil pH and increasing nutrient availability (Ampong et al. 2022). The effects of foliar and soil applications of humic acid substances on plants grown under induced salinity stress (20 and 60 mM NaCl) demonstrated increased nutrient uptake (N, P, K, Mg, Na, Ca, and Zn) in corn (*Zea mays* L.) (Khaled and Fawy 2011). Moreover, seaweed and plant extracts have been used as soil conditioners for centuries, particularly in coastal areas. Both biomaterials contain several essential plant nutrients, including a significant level of mineral nutrients such as phosphorus and nitrogen as reported by Monteiro et al. (2022), Ma et al. (2022), and Karthik and Jayasri (2023). The phycocolloids (non-crystalline seaweed gum) derived from brown macroalgae (Lomartire and

Goncalves 2023) helped to improve soil structure, increase water retention, and improve metal binding to soil organic matter (Izzati et al. 2019).

Furthermore, in line with this assertion, *Ascophyllum nodosum* seaweed extract (ANE) was reported to improve the growth of soybean plants under drought stress. The application of ANE also modulated the expression of stress-responsive genes that presumably amplified soybean's natural defense against drought stress (Shukla et al. 2018). Plant accessibility to sufficient water and nutrients in soil is a well-known limiting factor for sustainable crop production, but more eco-friendly strategies like the application of biostimulants must be fully explored to avoid intensive use of chemicals and environmental degradation.

Safety Regulations, Health, and Environmental Risks

So far, many scientific approaches to crop plant improvement have resulted in substantial changes in the genetic structure of many crops, from earlier selection through conventional breeding to the use of modern agricultural biotechnology to improve crop growth, yield, and resilience to stress. In genetically modified crop production (also known as GMO or biotech crops), many countries have developed legislation and compliance measures to assess their adoption and risks to public and environmental health. Among the concerns raised were the risks of outcrossing between GM crops, other cultivated crops, and wild plants, impact on insect populations, all leading to the loss of biodiversity (Bawa and Anilakumar 2013). Equally, regulatory attention must also be given to the use of biostimulants to understand their potential health and environmental risks. Parties that should be particularly interested in this debate could range from government authorities, interest groups, and consumers. The lack thereof, of such regulations for these stimulatory substances and microorganisms should be a major concern for regulators, stakeholders (especially environmental groups and researchers etc.), and consumers. Currently, many countries use different names for biostimulants, and the development of specific and harmonized frameworks still lags far behind those involving GMOs.

Du Jardin (2015) earlier attributed this lack of progress on policy development and alignment with international standards to the absence of formal biostimulants definition and consensus of the concept by regulatory bodies. Countries across Europe, and a few found in other regions globally are still embarked on developing harmonized product regulations, especially to avoid the differences in classification observed from one country to another. However, environmental sustainability, like the sustainability in agriculture, remains a fundamental concern in all aspects. Biostimulants need to be conveyed under a suitable classification in order to expand their successful long-term integration into plant production systems. As reported by Lynch et al. (2021), the use of chemical and synthetic growth regulators should be minimized due to environmental issues, and perhaps, replaced with biostimulants and bioprotectants. Moreover, as earlier indicated, inorganic fertilizers or chemical fertilizers, including N fertilizers have been evaluated for their potential contaminating effects of underground water, food crops, and contribution to global warming, as well as other detrimental effects on natural habitats (Aryal et al. 2021).

In addition, inorganic fertilizers are manufactured through an energy intensive process that requires fossil fuel which then contributes to the generation of greenhouse gases (Woods et al. 2010). The use of biostimulants will in turn boost and promote bio-intensification, as a key strategy for achieving sustainable biomass valorization without excessive carbon emissions and combating climate change (Boodhoo et al. 2022). All biostimulatory substances interact with the physiology of plants and should therefore, be regulated and assessed for their safety and impact both indirectly on the rhizosphere (Alari et al. 2013; Berruti et al. 2015) and/or directly on the plant, immediately as well as after treatment. The role of plant biostimulants has emerged as a beacon of hope in alleviating agricultural challenges since some studies have indicated that they have no major negative effects on the environment or human health (Kisvarga et al. 2022). This assertion is based on the fact that they contain low biological toxicity, get rapidly degraded in soil, have low mobility in food, low application rate, and have proved to restore soil fertility as well as sustainability (Ertani et al. 2015; Alori and Babalola 2018; Kisvarga et al. 2022; Kumari et al. 2023).

Conclusions and Future Perspectives

Plant biostimulants are currently evolving into a revolutionary tool used to improve crop growth and yield through sustainable nutrient utilization and strengthening plant defense mechanisms against environmental stresses. While embraced by many, including farmers, policy makers, and researchers, biostimulants offer a simplified and practical approach to address challenges posed by climate change and food insecurity. Used as biofertilizers and plant protectants, biostimulants are successfully applied to major staple crops as indicated in Table 2 which align with the United Nations Sustainable Development Goals (SDGs), particularly the goal focused on ending hunger by achieving food security and improve nutrition by promoting sustainable agriculture (Goal 2 of the SDGs). The continued use of biostimulants will also assist in promoting conservation of natural resources and sustainable development (Schunko et al. 2024). This implies that, apart from their effect on the cultivation of crops, they will bring into the system a direct meaningful impact and relations with other economic and socio-economic and social factors as illustrated in Fig. 2.

As Feliciano (2022) reported, there are socio-economic factors, such as crop production issues related to food security and alleviating poverty that encourage the adoption of biostimulants in agricultural systems. Furthermore, sustainable crop cultivation is strongly influenced by combined influence and interplay of environmental factors, economic issues, availability of natural resources, and the need for human survival. This suggests that farmers look for cost-effective and profitable measures to increase crop productivity like the adoption of biostimulants while indirectly contributing positively to environmental protection and innovative ways to combat climate change driven abiotic stress constraints (Tolisano and Del Bouno 2023). Ultimately, the inclusion of biostimulants in agricultural practices could

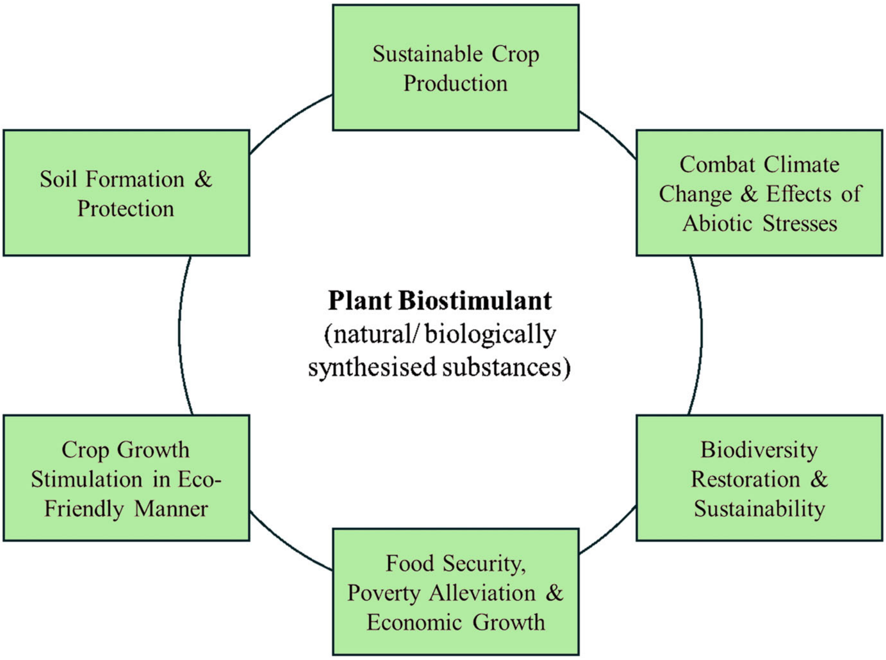

Fig. 2 Schematic representation of the beneficial factors influencing adoption of biostimulants for sustainable agricultural productivity

potentially guarantee higher yields through the improvement of morphological, physiological, and biochemical characteristics of crops, while sustainably contributing to the adaptive and mitigative responses to abiotic stresses. The main motivation for this adoption is the demand for food and food security necessary to be achieved, whereas effectively and accurately addressing potential safety concerns that may occur while harnessing these stimulative natural resources, such as seaweed, botanical extracts, and beneficial microbes to improve crop productivity in a suitable and sustainable manner.

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