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Şanlıurfa, Türkiye

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8. Uluslararası Harran Bilimsel Araştırmalarda Yenilikçi Yaklaşımlar Kongresi, 16-18 Ocak 2023 tarihleri arasında Şanlıurfa'da 43 farklı ülkenin (Türkiye 106 bildiri- Diğer ülkeler 111 bildiri) akademisyen/araştırmacılarının katılımıyla gerçekleşmiştir

Kongre 16 Ocak 2020 Akademik Teşvik Ödeneği Yönetmeliğine getirilen "Tebliğlerin sunulduğu yurt içinde veya yurt dışındaki etkinliğin uluslararası olarak nitelendirilebilmesi için Türkiye dışında en az beş farklı ülkeden sözlü tebliğ sunan konuşmacının katılım sağlaması ve tebliğlerin yarından fazlasının Türkiye dışından katılımcılar tarafından sunulması esastır." değişikliğine uygun düzenlenmiştir.

Bilgilerinize arz edilir,

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ABSTRACT

Modern agriculture faces the challenge of increasing productivity while preserving natural resources and reducing environmental impacts. Biostimulants have attracted increasing attention as environmentally friendly tools for improving crop productivity, nutrient use efficiency, stress tolerance, and the sustainability of agricultural systems. The aim of this paper is to review the potential applications of biostimulants in modern agriculture, with particular emphasis on beneficial microorganisms and their role in stimulating plant growth, improving nutrient uptake, increasing tolerance to adverse environmental conditions, and supporting sustainable crop production.

A review of the relevant scientific literature on biostimulants was conducted, with particular emphasis on microbial biostimulants, plant growth-promoting microorganisms, plant growth-promoting rhizobacteria (PGPR), plant growth-promoting fungi (PGPF), and arbuscular mycorrhizal fungi (AMF), as well as the major groups of non-microbial biostimulants. Data collected from relevant scientific sources were analyzed and synthesized to present the role of beneficial microorganisms in promoting plant growth and sustainable agricultural production.

Particular attention was given to the mechanisms of action of biostimulants, including nutrient uptake, phytohormone regulation, stimulation of plant growth, and activation of plant defense mechanisms. Their potential to enhance plant tolerance to abiotic stresses is particularly important, as adverse environmental conditions can significantly reduce crop productivity and are expected to become more frequent and intense under climate change.

Further research should focus on advancing scientific knowledge of the mechanisms of action of biostimulants and improving their formulations based on findings from relevant scientific and experimental studies.

Keywords: Biostimulants, PGPR, PGPF, AMF, Sustainable Agriculture.

INTRODUCTION

Sustainable intensification of agricultural production, while simultaneously limiting its environmental footprint, represents one of the major challenges that humanity will face in the future (De Palma et al., 2022). Due to the continuous growth of the global population, modern agriculture is facing the need to increase productivity and production efficiency while simultaneously preserving natural resources and reducing negative impacts on the environment.

In recent years, increasing attention has been directed towards the application of environmentally friendly strategies that contribute to improving crop productivity while simultaneously maintaining economic sustainability and enabling their integration into existing crop production management systems (Jaros-Tsoj et al., 2026).

The specific properties of microorganisms and their significant role in maintaining the functionality of agroecosystems have made them potentially important components of modern agriculture based on environmentally friendly principles (Hossain & Sultana, 2020). In this regard, the application of biostimulants in agricultural production represents an important approach to improving productivity and yield quality, while simultaneously promoting more efficient use of natural resources and contributing to the sustainability of agricultural systems. The application of certain microbial biostimulants together with seeds can promote the formation of beneficial microorganism hotspots within the root zone (Bošković et al., 2023). Biostimulants are formulated to stimulate natural physiological and biochemical processes in plants, thereby contributing to their growth, development, and productivity.

The industrial sector plays a significant role in the development and promotion of the biostimulant concept, including microorganism-based products, through the establishment of professional associations such as the European Biostimulant Industry Council (EBIC) and the Biostimulant Coalition in the United States, which operate through collaboration with regulatory institutions, the scientific community, and other relevant stakeholders (Du Jardin, 2015).

One of the important characteristics of biostimulants is their multi-level mode of action, which can affect different levels of plant organization, from the early stages of development to the formation of final yield and quality. Their application can positively influence germination, biomass accumulation, and the quality of plant products through coordinated effects at the molecular, biochemical, and physiological levels (Jaros-Tsoj et al., 2026). Plant biostimulants promote plant growth and development throughout the entire life cycle, from seed germination to full maturity, by acting through various physiological and biochemical mechanisms. In addition, their application can contribute to improved metabolic efficiency, nutrient uptake and utilization, plant tolerance to abiotic stress and recovery following stressful conditions, as well as improved quality of agricultural products, more efficient water use, enhancement of certain physicochemical properties of soil, and stimulation of beneficial soil microorganisms (EBIC, 2012). Today, microbial biostimulants based on pure or mixed cultures of microorganisms are available on the market and are intended to improve plant productivity, alongside non-microbial biostimulants based on various substances, such as mineral elements, seaweed extracts, protein hydrolysates, and others.

The aim of this paper is to examine the potential applications of biostimulants in modern agricultural production, with particular emphasis on the role of beneficial microorganisms and other biostimulant substances in stimulating plant growth and development, improving nutrient uptake, increasing tolerance to adverse environmental conditions, and promoting more efficient use of natural resources, while highlighting their importance for the development of more sustainable agricultural production systems.

LITERATURE REVIEW

The results of previous studies indicate broad possibilities for the application of biostimulants in crop production. Based on the nature of their active components and mechanisms of action, biostimulants can be broadly classified into microbial and non-microbial groups. Microbial biostimulants include various beneficial microorganisms, including bacteria, fungi, and other microbial inoculants, whereas

non-microbial biostimulants comprise a range of organic and inorganic substances, such as seaweed extracts, protein hydrolysates, humic and fulvic acids, silicon, and other mineral elements.

Microbial biostimulants comprise plant growth-promoting microorganisms (PGPM), including plant growth-promoting rhizobacteria (PGPR), plant growth-promoting fungi (PGPF), and arbuscular mycorrhizal fungi (AMF) (Castiglione et al., 2021). Microbial biostimulants can provide various benefits within modern crop production systems. In this regard, many microbial biostimulants are capable of synthesizing physiologically active compounds, auxins, and vitamins, supplying plants with these substances and thereby improving plant nutrition. In addition, microbial biostimulants can act as antagonists against certain phytopathogenic microorganisms and play a protective role in plants (Bošković et al., 2023).

Plant growth-promoting bacteria (PGPB) are beneficial, free-living bacteria associated with the root surface (rhizoplane), rhizosphere, and phyllosphere, which play an important role in plant growth and development. They include microorganisms belonging to genera such as *Bacillus*, *Pseudomonas*, *Azotobacter*, *Enterobacter*, *Azospirillum*, and others (Sridhar, 2012). They can increase the availability of nutrients in the rhizosphere soil and synthesize or modulate the activity of various phytohormones, including auxins, gibberellins, and cytokinins, thereby positively affecting plant growth and development. The rhizosphere represents a dynamic zone of intensive interactions between plants and diverse microorganisms, with the microbial community playing an important role in the ability of plants to protect themselves against various pathogens. Rhizosphere microorganisms can exert direct protective effects through different forms of competitive and antagonistic interactions (Beneduzi et al., 2012; Sood et al., 2020). PGPB can contribute to increasing phosphorus availability in soil through its solubilization. By producing phosphatases and phytases, they can transform poorly soluble organic forms of phosphorus into forms that are more readily available to plants. This ability is exhibited by bacteria belonging to various genera, including *Burkholderia*, *Pseudomonas*, *Bacillus*, *Rhizobium*, *Agrobacterium*, *Achromobacter*, *Streptomyces*, *Micrococcus*, and *Erwinia* (Richardson et al., 2009). Most rhizosphere-associated PGPM are closely associated with plant root systems and exert phytostimulatory effects through both direct and indirect mechanisms (Thakur et al., 2021).

Microbial preparations based on pure or mixed cultures of these microorganisms can be applied to soils in which phosphorus is present in poorly available forms, thereby contributing to its mobilization and increasing its availability to plants.

In addition to the above, PGPB produce various low-molecular-weight volatile organic compounds (VOCs), including ketones, alcohols, hydrocarbons, and aldehydes, which can contribute to microorganism–plant interactions, including the stimulation of plant growth. This has been confirmed by the effects of VOCs produced by PGPB strains on the growth of *Arabidopsis thaliana* (Ortiz-Castro et al., 2009; Ryu et al., 2003).

Among the numerous microorganisms inhabiting the rhizosphere, particular attention has been devoted to plant growth-promoting fungi, known as PGPF (Plant Growth-Promoting Fungi). Over the past several decades, research has focused on various representatives of this functional group, with particular attention given to selected representatives of the genera *Trichoderma*, *Penicillium*, *Phoma*, and *Fusarium* (Hyakumachi, 1994).

Previous studies indicate that PGPF can positively influence plant growth and development, as well as stimulate plant defense mechanisms against phytopathogenic microorganisms, highlighting their potential for the development of more environmentally friendly approaches to crop production (Hossain et al., 2017). Owing to these properties, PGPF can be considered a potentially important component of sustainable agriculture, given their ability to influence plant physiological processes through various interactions in the rhizosphere and contribute to more efficient utilization of available resources within the agroecosystem. PGPF formulations represent a promising approach to their commercialization and application for enhancing plant growth and development in agricultural production.

In recent years, arbuscular mycorrhizal fungi belonging to the class *Glomeromycetes* have attracted considerable attention due to their ability to promote plant growth and nutrition. Their particular importance stems from their potential to mitigate various challenges faced by modern agricultural production, especially those associated with climate change. In this context, arbuscular mycorrhizal

fungi can contribute to increasing plant tolerance to various forms of abiotic stress, including water, temperature, salinity, osmotic, and light stress, as well as stress caused by the presence of pollutants or insufficient availability and imbalance of nutrients (Israel et al., 2022).

Non-microbial biostimulants represent an important group of commercially available biostimulants and comprise non-living substances of organic or inorganic origin, whose efficacy primarily depends on their chemical composition and the concentration of bioactive compounds, such as humic acids and amino acids, protein hydrolysates, seaweed extracts, and similar substances. Their non-living nature provides greater stability during storage but precludes the ability to reproduce and colonize the plant or its environment (Ciriello et al., 2024).

Protein hydrolysates are obtained through the breakdown of plant and animal proteins, and their application can affect several physiological processes, including photosynthetic activity, nutrient uptake and transport, root development, biomass accumulation, and increased plant tolerance to abiotic stress. These effects are associated with the stimulation of antioxidant mechanisms and the regulation of the osmotic status of plant cells. Studies have shown that foliar and/or root application of protein hydrolysates can induce changes in the primary and secondary metabolism of treated plants (Lucini et al., 2015).

Humic substances constitute an important component of soil organic matter and are formed as a result of complex transformation processes involving plant and animal residues, in which microorganisms also participate. Their presence plays an important role in the functioning of the soil ecosystem, as they are involved in carbon and nitrogen cycling, influence the behavior and mobility of various compounds in the soil, and contribute to the formation and maintenance of stable soil structure. Based on their color and solubility in alkaline and acidic solutions, humic substances are classified into humic and fulvic acids. Humic acids have a medium molecular weight, are darker in color, and are soluble in alkaline solutions but insoluble in acids. Fulvic acids have a lower molecular weight, are lighter in color, and are soluble in both alkaline and acidic solutions. The importance of these acids lies in their ability to increase the proportion of water-stable soil aggregates, thereby promoting good water permeability, more efficient water use, improved aeration, and a favorable biological regime in structurally stable soils (Bošković et al., 2023). Biostimulants based on seaweed extracts can promote plant nutrition, enhance the growth of the aboveground parts and roots, and stimulate the microbiological activity of the soil in the plant rhizosphere, among other effects. As reported by Ciriello et al. (2024), the particular importance of seaweed extracts lies in their ability to increase plant tolerance to abiotic stress, such as high temperatures, water deficiency, drought, and salinity.

The preventive application of seaweed extracts may enhance plant resistance to subsequent stress, as demonstrated in *Arabidopsis thaliana*, where pre-treatment with the extract alleviated the oxidative effects of herbicide exposure and induced changes at multiple levels of the plant response (Sujeeth et al., 2022).

MATERIALS AND METHODS

A review of the relevant scientific literature on biostimulants was conducted, with particular emphasis on microbial biostimulants, plant growth-promoting microorganisms, plant growth-promoting rhizobacteria (PGPR), plant growth-promoting fungi (PGPF), and arbuscular mycorrhizal fungi (AMF), as well as the major groups of non-microbial biostimulants. Particular attention was given to their mechanisms of action, including nutrient uptake, phytohormone regulation, stimulation of plant growth, and the development of plant defense mechanisms. Data collected from relevant scientific sources were analyzed and synthesized to present the role of beneficial microorganisms in promoting plant growth and sustainable agricultural production.

RESULTS AND DISCUSSION

Biostimulants are becoming increasingly important in modern agriculture, primarily due to the need to develop environmentally sustainable production systems, as well as their growing economic potential.

Their development and application have been further supported by the establishment of the European Union regulatory framework, including EU Regulation (2019/1009), under which biostimulants are covered by regulations governing fertilising products. Particular importance is attributed to microbial biostimulants, which represent a promising approach to sustainable agriculture aimed at increasing the yield and quality of agricultural products while simultaneously reducing the negative environmental impacts of agrochemicals (Castiglione et al., 2021).

Various mechanisms of their action have been studied, including plant colonization, interactions with host plants, and the potential for developing appropriate formulations to enable more effective application in agricultural production. Plant growth-promoting fungi (PGPF) can contribute to mitigating the adverse effects of abiotic stress, including drought, elevated temperatures, and other unfavorable environmental conditions. These findings indicate the potential of PGPF in the development of more sustainable agricultural production systems and in reducing dependence on conventional agrochemical inputs (Hossain & Sultana, 2020). Yakhin et al. (2017) emphasize that mitigating the effects of abiotic stress represents one of the most significant potential effects of biostimulant application, as adverse environmental conditions can substantially reduce plant productivity, while the frequency and intensity of certain stress factors are expected to increase further as a result of climate change. The particular importance of biostimulants stems from their potential application under increasingly pronounced climate change conditions, including temperature fluctuations, uneven precipitation patterns, more frequent periods of water scarcity, soil salinization, and other related stresses. Therefore, the application of biostimulants is considered one of the potential approaches for enabling plants to maintain better functioning under changing environmental conditions. Particular attention is being devoted to their potential to increase water and nutrient use efficiency and to maintain plant physiological activity during periods of stress. In this context, biostimulants may represent one component of the broader concept of sustainable agriculture. Their application can contribute to more rational use of water and mineral nutrients, as well as to reducing the need for intensive use of certain agrochemical inputs. Of particular importance are systems in which biostimulants are combined with appropriate agronomic practices, as their effects depend on the overall conditions under which plants develop. Therefore, biostimulants should not be regarded as universal substitutes for fertilizers or plant protection products, but rather as tools that can support natural physiological and microbial processes important for plant productivity.

CONCLUSION

Biostimulants represent an important approach in modern crop production, particularly in the context of the need for more rational use of natural resources and the reduction of the negative environmental impacts associated with intensive agricultural production. Based on a review of the available literature, it can be concluded that microbial and non-microbial biostimulants can influence plant growth and development, nutrient uptake and utilization, the quality of plant-derived products, and plant tolerance to abiotic stress conditions through various mechanisms of action.

Particular importance is attributed to plant growth-promoting microorganisms, including PGPR, PGPF, and arbuscular mycorrhizal fungi (AMF), which, through various interactions with plants, can contribute to plant nutrition and growth, as well as their ability to adapt to adverse environmental conditions. In addition, protein hydrolysates, humic and fulvic acids, and seaweed extracts represent important groups of non-microbial biostimulants with diverse potential applications in crop production. Their application may be particularly relevant within integrated production systems, in which they are combined with appropriate agronomic practices.

Further research should focus on gaining a better understanding of the mechanisms of action of different biostimulants, as well as on the development and improvement of their formulations and application methods, in order to enable a more reliable assessment of their efficacy under different agricultural production conditions.

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