



REVIEW ARTICLE

Plant biostimulants in sustainable crop production: A review

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Received: 14 May 2026; Accepted: 30 June 2026; Available online: Version 1.0: 01 August 2026

Cite this article: Srinivasan P, Deepa N, Selvanayagi S, Senthilnathan S, Vasanthi R. Plant biostimulants in sustainable crop production: A review. *Plant Science Today*. 2026; 13(sp5): 1-11. <https://doi.org/10.14719/pst.15542>

Abstract

Plant biostimulants have shown significant potential as environmentally benign agricultural inputs that can improve soil health, crop yield, nutrient use efficiency and resistance to abiotic stress conditions under changing climatic conditions. With a focus on mechanisms of action, abiotic stress tolerance and economic potential, this study provides a thorough literature review and bibliometric analysis of studies on plant biostimulants in sustainable agricultural production. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework was used to ensure a transparent and systematic selection process. The Scopus database was the only source of scientific papers that were retrieved between 2015 and 2026. To identify relevant research related to plant biostimulants, sustainable agriculture, climate resilience, stress management and commercialization factors, a thorough keyword-based search method was used. About 1341 peer-reviewed journal and review papers that satisfied the inclusion criteria were chosen for in-depth analysis out of the 2593 publications that were found in the initial search. According to the bibliometric study, the most common research topics in the subject include soil health, microbial interactions, biofertilisers, abiotic stress tolerance and sustainable agriculture. Strong worldwide scientific cooperation was shown by co-authorship and bibliometric coupling analyses, especially amongst nations like China, Italy, Spain and India. The results also show that increasing plant physiological and biochemical responses under environmental stress circumstances is greatly aided by microbial inoculants, seaweed extracts, humic compounds and protein hydrolysates. Broader adoption is still delayed by issues with product standardization, field-level uniformity, regulatory frameworks and commercialisation despite significant research progress. Overall, plant biostimulants hold significant promise for promoting environmentally conscious agricultural production methods, climate resilience and sustainable agriculture.

Keywords: abiotic stress tolerance; agribusiness potential; climate-smart agriculture; microbial biostimulants; plant biostimulants; sustainable agriculture

Introduction

Agriculture is presently experiencing major challenges due to climate change, environmental degradation, decreased soil fertility and rising global food demand. Abiotic stressors that restrict agricultural yield and sustainability globally include drought, salt, severe temperatures, floods and nutrient deficits. Crop development, production and quality are eventually decreased as a result of these environmental stressors' detrimental effects on plant physiological, biochemical and metabolic processes. Simultaneously, the excessive dependence on synthetic fertilisers and chemical agro-inputs in conventional farming systems has contributed to soil degradation, greenhouse gas emissions, biodiversity loss and environmental pollution. Consequently, there is an urgent need to develop sustainable agricultural strategies capable of improving crop productivity while minimising ecological impacts and ensuring long-term environmental sustainability (1-3).

Plant biostimulants have recently become innovative and environmentally friendly agricultural products that can significantly contribute to sustainable agriculture (4, 5). Plant biostimulants have been described as substances or microorganisms that promote biological responses in plants, which increase the uptake of

nutrients, utilisation efficiency of nutrients, resistance to abiotic stresses, quality of crops and general plant vigour independent of their nutritional properties (4). Unlike chemical fertilisers, plant biostimulants mainly operate through physiological and biochemical control mechanisms instead of direct nutrient addition. These mechanisms include stimulation of root growth and development, enhancement of nutrient uptake and nutrient-use efficiency, activation of antioxidant defence enzymes, regulation of phytohormone activity, accumulation of osmoprotectants and improvement of plant tolerance to environmental stresses such as drought, salinity and heat stress (1, 3). Plant biostimulants encompass a variety of products, including seaweed extracts, humic/fulvic substances, amino acids, protein hydrolysates, beneficial fungi, arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR). Because of their versatile and environmentally sustainable features, plant biostimulants have attracted more attention from research organisations, policymakers and agricultural industries around the world (4, 6).

The relevance of plant biostimulants to agriculture is closely connected with their capability to boost the stress resistance of plants. Due to climate change, environmental stresses have become more frequent and severe, which is why they are a serious challenge

for agriculture. Numerous studies have demonstrated that the mechanisms that help plants become more resistant to abiotic stresses due to the usage of plant biostimulants are different: from boosting root development to activating antioxidant systems in plants. Furthermore, the application of biostimulants allows for adjusting the osmotic balance of plants and the activity of genes and metabolites responsible for coping with adverse conditions. Biostimulants allow crops to increase water use efficiency, nutrient assimilation and homeostasis. Consequently, crops can achieve higher yields even under unfavourable environmental conditions for growth (7, 8).

Among the various types of plant biostimulants for plants, microbial biostimulants have been extensively studied for their positive influences on plant development and soil properties. The beneficial microorganisms like *Bacillus* spp., *Pseudomonas* spp. and arbuscular mycorrhizal fungi increase nutrient mobilisation, root growth, soil microbial population and plant stress tolerance due to their ability to produce phytohormones, nutrient solubilisation, regulation of antioxidant enzymes and stress-responsive signal pathways activation (9, 10). Likewise, the role of non-microbial biostimulants like extracts of seaweed and humic substances has been recognised in stimulating plant metabolism and adaptation to adverse conditions. Seaweed extracts consist of bioactive molecules, including polysaccharides such as alginates, laminarins and fucoidans, amino acids, vitamins and phytohormones such as auxins, cytokinins and gibberellins, which are responsible for enhancing plant physiological activity, growth and stress adaptation (11). Humic substances can contribute to soil structure improvement, nutrient immobilisation, soil microbial population and root structure modification (12).

Technological advancements in biotechnology, molecular biology and nanotechnology have made plant biostimulants even more effective and applicable to sustainable agriculture. Biostimulants based on nanotechnology, along with advanced bioformulations, have been shown to be highly efficient in delivering nutrients, absorbing nutrients, mitigating stress and enhancing crop growth in challenging environments (13, 14). Moreover, the combination of plant biostimulants with precision agriculture techniques, digital agriculture technologies and climate-smart agriculture has opened up new possibilities for sustainable agriculture and improved resource use efficiency. It is anticipated that these technological breakthroughs will be instrumental in achieving Sustainable Development Goal (SDG) 2 (Zero Hunger) through enhanced agricultural productivity and food security, SDG 12 (Responsible Consumption and Production) through efficient resource utilisation, SDG 13 (Climate Action) through improved climate resilience and adaptation and SDG 15 (Life on Land) through the promotion of sustainable land management and soil health (15, 16).

Apart from being agriculturally and environmentally beneficial, there is also great commercial and business potential for plant biostimulants. There has been a rise in consumer interest towards organic agricultural produce that is sustainable, free of residues and is eco-friendly. This is driving the global demand for inputs that are environment friendly in agriculture. Hence, there has been a rapid growth in the plant biostimulant industry because of increasing adoption, advances in product formulation and government policies promoting sustainable agricultural practices (17). Agribusiness companies are investing in research and development (R&D) work on microbial inoculants, marine plants,

bioactive substances and biostimulants technology. Moreover, there have been opportunities created by the commercialisation of plant biostimulants in various sectors of agriculture such as production, marketing, exports, consultancy and precision agriculture industries (14, 18).

Problem focus

Although plant biostimulants are increasingly becoming indispensable in the practice of sustainable agriculture, various scientific, technological and commercial hurdles persistently hinder their full-scale application and use within crop cultivation systems (19, 20). Traditional farming relies heavily on synthetic fertilisers and chemical farm inputs, leading to soil erosion, environmental contamination, biodiversity loss and the unsustainability of agriculture (21, 22). In parallel, the adverse impacts of abiotic stresses brought about by climate change-drought, salinity, heat stress and water - pose an increasing risk to global food security and crop yields (22, 23). While plant biostimulants have shown great promise in promoting plant development, nutrient absorption, stress resistance and soil quality, the physiological, biochemical and molecular mechanisms underlying their efficacy remain insufficiently understood (20, 24).

Furthermore, the efficacy of plant biostimulants largely depends on the type of crop, environmental factors, soil properties and mode of application (24, 25). Limited awareness among farmers, lack of extensive field testing, ambiguous regulations and expensive commercialisation processes further hinder the use of biostimulant products, especially in developing countries (20, 26, 27). Moreover, the rapid growth in the biostimulant sector requires reliable scientific evidence, comprehensive regulation and sustainable agricultural business approaches to promote their development and acceptance (19, 20, 27).

Despite many studies having been conducted on various aspects of biostimulants used in plants, there continues to be limited knowledge available across several disciplines, including plant physiology, microbiology, soil science, biotechnology and the agrifood industry (19, 24, 26). It is necessary to undertake a systematic literature review of biostimulant studies in order to analyse research trends, modes of action, biostimulants' potential in abiotic stress tolerance, collaborative research activities, opportunities for the agrifood industry, regulatory challenges, commercialisation prospects and sustainable agricultural applications.

Methodology

This systematic literature review on plant biostimulants used a methodology that is well-defined and clear for the comprehensive evaluation of available scientific literature. In this regard, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodological framework has been used in this study, which allows for the identification, screening, eligibility and inclusion of pertinent studies. Scopus was the primary database used for gathering literature for this systematic review since it contains several high-quality scientific articles in multidisciplinary fields. The literature search was conducted through the Tamil Nadu Agricultural University (TNAU) Library Gateway, which provided access to the Scopus database. Table 1 present the inclusion and exclusion criteria of literature in this systematic literature review (SLR).

Since 2015, there has been a lot of interest in research on plant biostimulants due to the growing concerns regarding climate change, environmental sustainability, reduced soil fertility and adoption of environmentally friendly farming practices. There has been a lot of research conducted in the past few years that has emphasised the importance of plant biostimulants for enhancing nutrient use efficiency, crop yield, growth of plants, abiotic stress resistance and sustainable agriculture. The research carried out in the last few years lays a solid foundation for the advancement of biostimulant technology in sustainable agriculture.

The search strategy was designed to capture relevant scientific studies using a combination of keywords related to plant biostimulants, sustainable agriculture, abiotic stress tolerance, mechanisms of action and agribusiness dimensions. The search query included terms such as “Plant Biostimulants,” “Microbial Biostimulants,” “Seaweed Extracts,” “Humic Substances,” “Protein Hydrolysates,” “Sustainable Agriculture,” “Abiotic Stress,” “Drought Stress,” “Salinity Stress,” “Mechanisms,” “Phytohormones,” “Agribusiness,” and “Commercialisation.” Boolean operators such as AND and OR were applied to broaden the scope of literature retrieval and ensure the inclusion of studies relevant to the objectives of the review. This approach ensured the identification of studies addressing both the scientific and commercial dimensions of plant biostimulants in sustainable crop production. The complete list of keywords employed during the database literature search is presented in (Table 2).

Bibliometric mapping and network visualisation analyses were performed using VOSviewer version 1.6.20. For author keyword co-occurrence analysis, a minimum occurrence threshold of 5 was applied. For co-authorship analyses, a minimum threshold of 5 publications per author and 5 publications per country was used. Only items meeting the specified thresholds were included in the final bibliometric visualisations.

A preliminary search conducted in the Scopus database yielded 2593 research papers. After this, there was a systematic screening process to filter the identified papers, as depicted in the PRISMA flow diagram presented in Fig. 1. During the identification stage, 2593 research papers were found using the Scopus database according to predetermined search terms.

After the identification process, the literature pool was filtered in the screening process by using the inclusion and exclusion criteria specified previously. The search focused on scholarly publications within the period between 2015 and 2026. Only English-language journal and review articles were included. Also, only open access final stages scholarly publications that are indexed in the category of journals source types have been considered in the analysis of this research. The decision to include only open-access publications was made to ensure transparency, accessibility and reproducibility of the review process, enabling all selected studies to be freely accessed and independently verified by researchers. Open-access articles also facilitate comprehensive data extraction without institutional subscription barriers. However, this criterion may introduce selection bias by excluding relevant subscription-based publications, including potentially high-impact studies. Consequently, some valuable scientific contributions may not have been captured in the present review, which may influence the overall comprehensiveness of the literature coverage. This limitation should therefore be considered when interpreting the findings of the study. Conference papers, conference reviews, editorials, books, book chapters, trade journals, proceedings, books series, in press articles and publications not written in English language were eliminated from this research.

In the subsequent screening phase, the articles that remained were critically evaluated based on their titles, abstracts and keywords in order to establish whether they met the purpose of the study. The scientific relevance and high quality of research related to plant biostimulants, sustainable agricultural practices, mechanisms of action, abiotic stress and commercial prospects of biostimulants were some of the key criteria used to filter out articles deemed inappropriate for inclusion in the review process. After the screening and selection process, a total of 1341 articles were selected for bibliometric analysis. These articles were used to generate bibliometric indicators and network visualisations, including author keyword co-occurrence, co-authorship, bibliometric coupling and co-citation analyses. Relevant studies from this dataset were also examined qualitatively to support the interpretation of bibliometric findings and discussion of plant biostimulant research trends, mechanisms of action and agricultural applications. Table 3 summarises the major categories of microbial and non-microbial plant biostimulants, their sources, mechanisms of action and agricultural applications.

Table 1. Inclusion and exclusion criteria

Databases	Inclusion	Exclusion
Time span	2015 – 2026	< 2015
Document type	Articles, Review	Conference papers, Book chapters, Books, Editorials, Conference reviews
Languages	English	Non- English And others all Trade journal
Source type	Journal	Book series Book Conference proceeding Article in press
Publication stage	Final	Others
Open access	All open access	

Table 2. The list of keywords employed during the database literature searches

Databases	Keywords	Total number of articles
Scopus	"Plant Biostimulants" OR Biostimulants OR "Microbial Biostimulants" OR "Biological Stimulants" OR "Plant Growth Promoters" OR "Seaweed Extracts" OR "Humic Substances" OR "Protein Hydrolysates" AND "Sustainable Crop Production" OR "Sustainable Agriculture" OR "Climate-Smart Agriculture" OR "Green Agriculture" OR "Eco-friendly Agriculture" AND "Abiotic Stress" OR "Abiotic Stress Tolerance" OR "Drought Stress" OR "Salinity Stress" OR "Heat Stress" OR "Water Stress" AND Mechanisms OR "Mode of Action" OR Physiological OR Biochemical OR Molecular OR "Nutrient Uptake" OR Phytohormones OR "Plant Growth" AND Agribusiness OR Commercialisation OR "Market Potential" OR "Value Chain" OR Bioeconomy OR "Farmer Adoption" OR "Agricultural Innovation"	2593

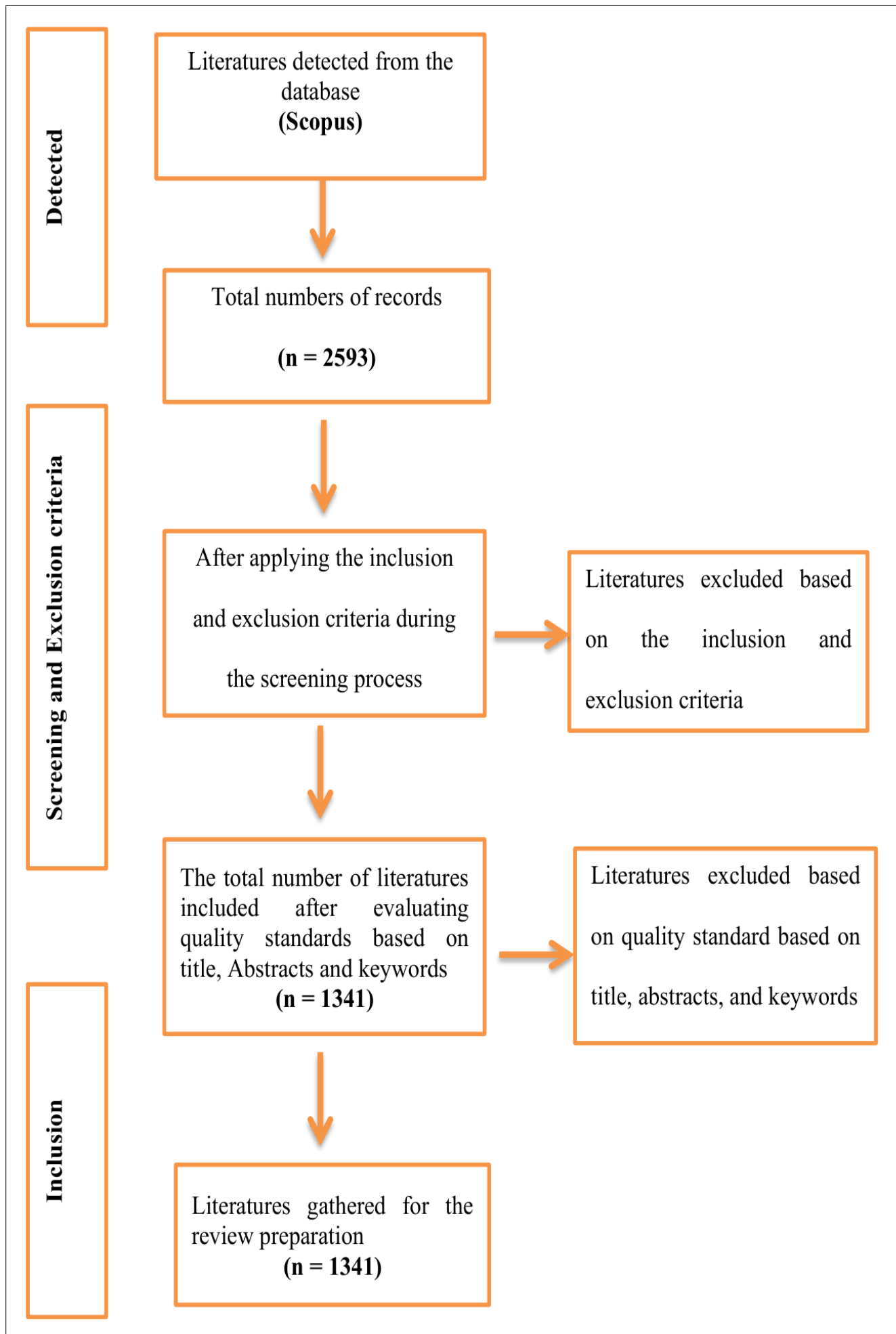


Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram.

Table 3. Classification, sources, mechanisms of action and agricultural applications of microbial and non-microbial plant biostimulants

Category	Source	Mechanism of action	Agricultural applications
Plant growth-promoting rhizobacteria (PGPR)	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Azospirillum</i>	Nitrogen fixation, phytohormone production, nutrient solubilisation	Plant growth promotion and stress tolerance
Arbuscular mycorrhizal fungi (AMF)	<i>Glomus spp.</i> , <i>Rhizophagus spp.</i>	Enhanced nutrient and water uptake	Drought and salinity tolerance
Seaweed extracts	<i>Ascomyllum nodosum</i> , <i>Ecklonia maxima</i>	Hormonal stimulation, antioxidant activation	Yield enhancement and stress mitigation
Humic and fulvic substances	Organic matter decomposition products	Improved nutrient availability and root growth	Soil fertility improvement
Protein hydrolysates	Plant and animal-derived proteins	Amino acid supply and enzyme activation	Growth promotion and nutrient-use efficiency
Amino acid-based biostimulants	Free amino acid formulations	Osmoregulation and metabolic enhancement	Abiotic stress management
Microalgae extracts	<i>Chlorella spp.</i> , <i>Spirulina spp.</i>	Bioactive compounds and nutrient supplementation	Crop productivity and quality improvement

Justification for inclusion criteria

Peer-reviewed journal articles and review articles were used as search results for this systematic literature review to ensure the quality, rigour and reliability of the selected studies. Peer-reviewed publications undergo rigorous editing and reviewing processes that improve the credibility of research works. The Scopus database was chosen due to its rich resources comprising high-quality multidisciplinary articles suitable for bibliometric analysis. This review took into consideration only those English-language publications that have been written from 2015 to 2026 since this period is the most relevant when it comes to plant biostimulants, sustainable agriculture and abiotic stress management. In addition, this study only utilised final-stage open-access journal publications. Other types of publications such as conference papers, conference reviews, editorials, books, book chapters, trade magazines, conference proceedings and article-in-presses were not taken into account due to their possible variations in peer-reviewing processes and accessibility.

Result and Discussion

Author keywords

The author keyword network visualised in Fig. 2 depicts the main research areas and theoretical links related to plant biostimulants in sustainable crop production. According to Fig. 2, “sustainable agriculture” is the primary and most dominant keyword, indicating that the main area of research into plant biostimulants today revolves around sustainability. In addition, the connections between sustainable agriculture, biostimulants, biofertilisers, soil quality and abiotic stresses show how environmentally friendly products have become increasingly important in increasing crop yields and resource-use efficiency under sustainable farming systems (19, 24).

The network also shows that terms like “biostimulants,” “biofertilisers,” “microalgae,” and “soil health” are highly related to sustainable agriculture, which means that biological and microbial inputs are used widely in agriculture to improve soil fertility and efficient nutrient uptake in crop cultivation systems (21, 26). Furthermore, the term “circular economy” included in the network highlights the growing interest in agricultural research to develop sustainable and environment-friendly approaches to minimise waste by recycling resources.

An additional essential cluster is based on the concepts of abiotic stress mitigation and climate resilience. Terms like “abiotic stress,” “drought,” “salinity,” “climate change,” and “plant growth-promoting rhizobacteria” are all interrelated in a very tight manner, which signifies the significance of plant biostimulants in alleviating

the effects of stress in the environment. The interrelationship also shows that current research focuses more on the use of microbial and biological agents to increase the resistance of plants to environmental stresses caused by drought, salinity and climate change. Previous studies have reported that biostimulants can enhance stress tolerance through improved antioxidant defence systems, osmotic adjustment and regulation of stress-responsive physiological processes (5, 7, 15).

Keywords within the blue cluster focus more on microbial interactions and research topics associated with the rhizosphere. The use of keywords such as “PGPR,” “rhizosphere,” “rhizobacteria,” “biofertiliser,” and “biocontrol” shows significant research work done to explore beneficial microorganisms that help in promoting plant growth and suppressing diseases. The association between all of these keywords points towards the increasing role of microbial biostimulants as efficient substitutes for chemicals-based agricultural inputs in sustainable agriculture due to their ability to improve nutrient acquisition, plant growth and stress resilience (10, 12, 26). It can be seen from the network of keywords that the study of plant biostimulants is highly interdisciplinary and encompasses several research topics, such as sustainable agriculture, plant tolerance to abiotic stress, microbial interactions, soil quality and climate resiliency. The interconnection between these keywords implies that plant biostimulants are increasingly becoming an essential approach to improve agricultural sustainability and productivity.

Network of co-authorship

Visualisation of co-authorship among authors depicted in Fig. 3 represents the connections and collaboration networks of scientists who have contributed in the field of plant biostimulants and sustainable agriculture. It has been revealed from the figure that there exist several clusters of authors that signify scientific collaboration by the scientists conducting researches on the fields of plant biostimulants and abiotic stress tolerance. The presence of many author clusters signifies an interdisciplinary nature of the field.

The red cluster represents one of the most prominent collaborative groups in the network. The list of members in this group includes authors like Babalola, Olubukola Oluranti, Santoyo, Gustavo, Fadji, Ayomide Emmanuel, Kumar and Ajay. It can be noticed that there exists a strong connection between these authors and this is due to their collaboration with each other. These collaborations are associated with topics such as microbial biostimulants, plant growth promoting rhizobacteria, sustainable agriculture and abiotic stress management, which have been widely recognised as important research areas for improving crop productivity and environmental sustainability (2, 10, 17).

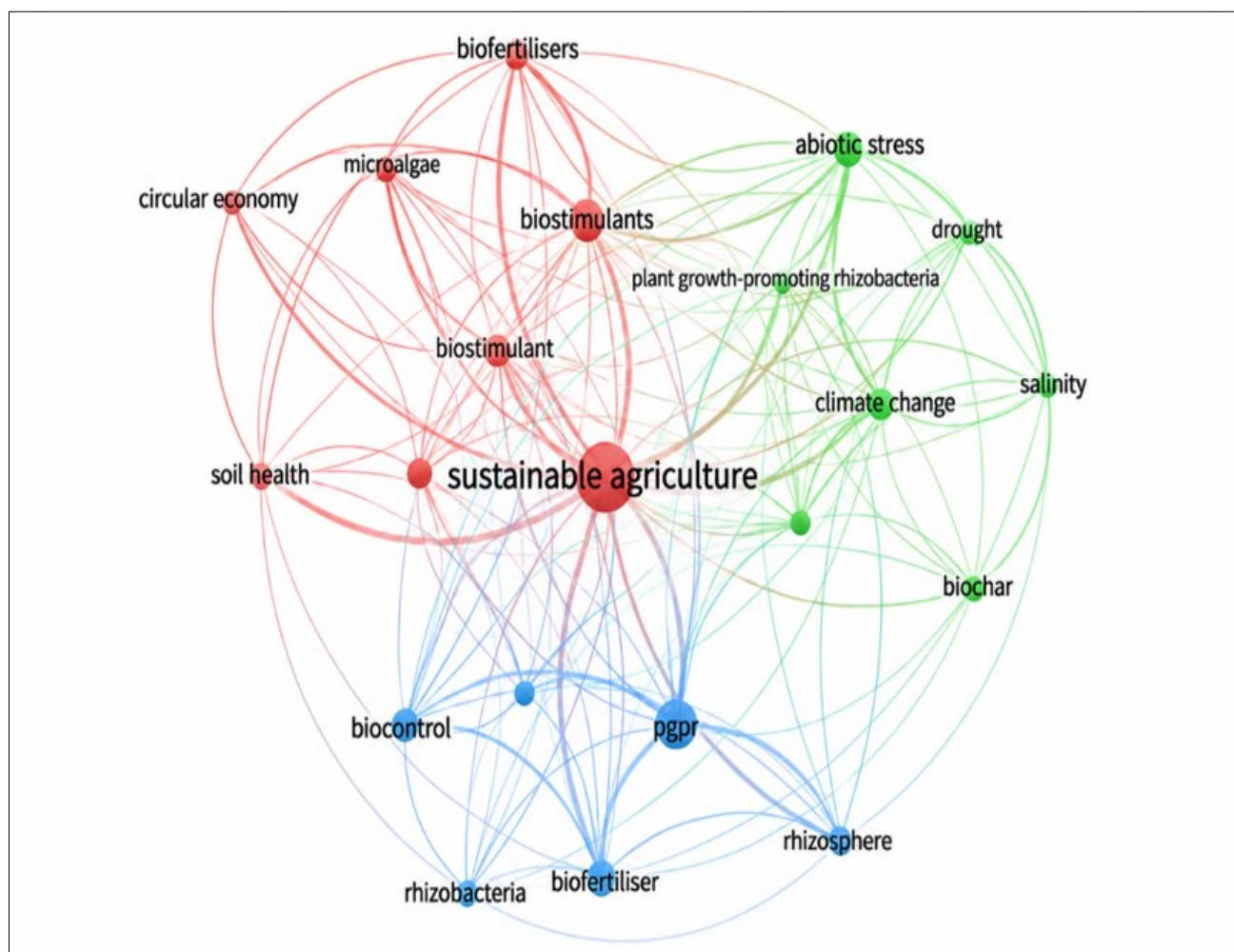


Fig. 2. Author keywords.

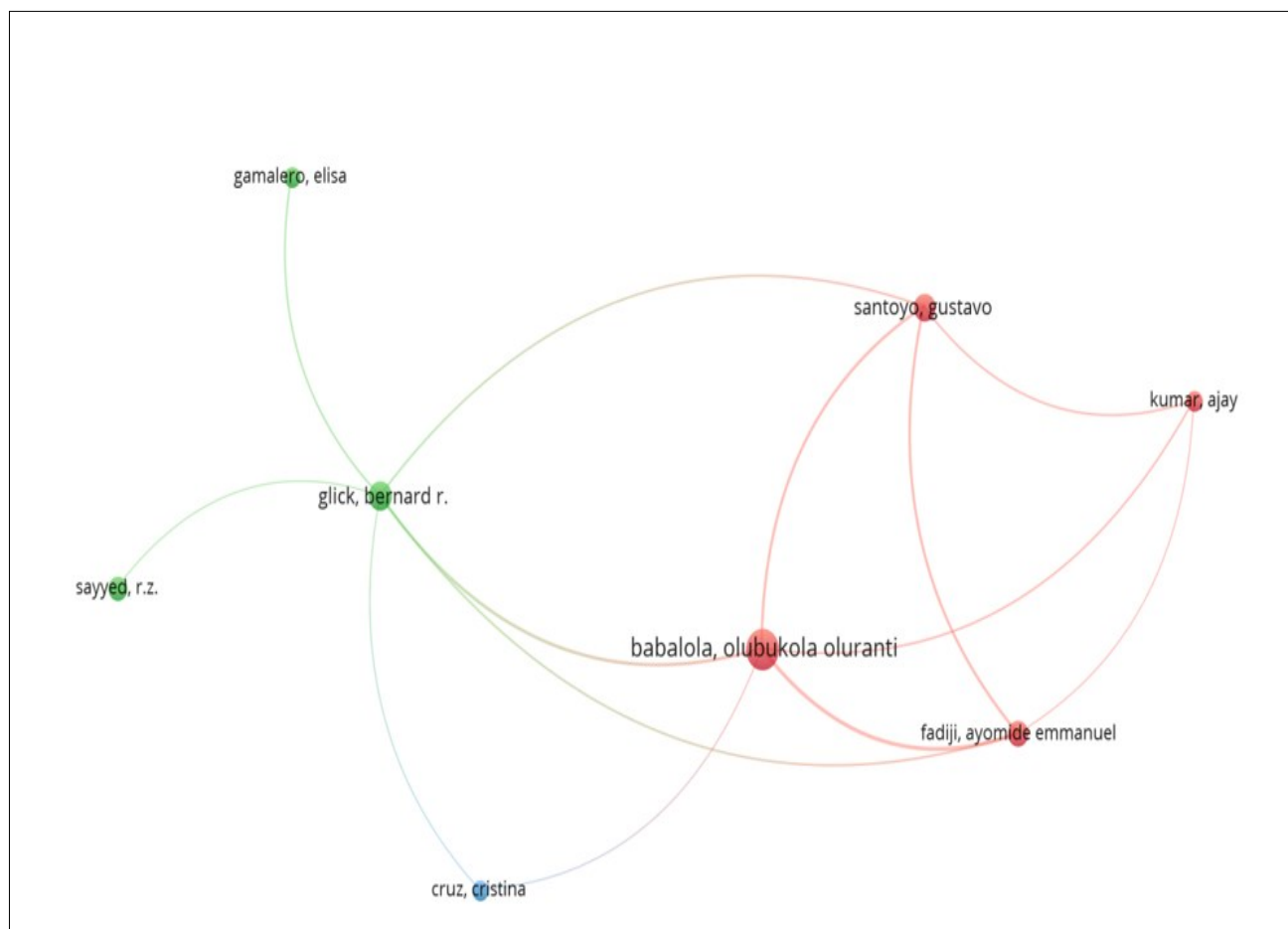


Fig. 3. Network of co-authorship author.

Other important authors in another cluster are Glick, Bernard R, Sayyed, R Z and Gamalero, Elisa. This particular cluster emphasises research collaborations involving studies in plant microbe interaction, use of biofertilisers, rhizobacteria and stress tolerance. Glick, Bernard R. in particular, is one of the central connecting authors who link different research collaborations, thus facilitating integration of knowledge among various fields of research. Connecting links among clusters show cooperation in research between interdisciplinary scientists specialising in sustainable agriculture and plant biostimulants.

Furthermore, the network suggests that the links formed between scientists who wrote together are highly focused on certain key individuals who serve as influencers. It can be argued that top-ranking authors play an important part in contributing to scientific developments in this particular discipline. As such, the collaborative aspect of the network highlights the increasing attention of the international community to plant biostimulants and the importance of conducting studies together to deal with problems linked to climate change, sustainable farming and crop stress. Overall, the co-authorship analysis demonstrates close collaboration among researchers across multiple disciplines.

Network of co-authorship countries

The network analysis of co-authorship between countries shown in Fig. 4 demonstrates global research collaborations and international scientific collaborations in the domain of plant biostimulants and sustainable agriculture. As seen from the figure, there exist numerous collaborative networks between countries conducting research on issues connected to plant biostimulants, abiotic stress resistance, sustainable agriculture and climate-smart agriculture. The existence of multiple clusters implies that research in this domain is very collaborative in nature and conducted globally.

Among the countries participating in the network, India, China, Italy and Spain have been found to be highly influential and well-connected partners contributing to the field. India has been seen to form one of the hub nodes of the network and has collaborated well with various countries, showing the important role it plays in contributing to plant biostimulant research through international collaboration. Likewise, China has shown itself to collaborate well with countries like Pakistan, Bangladesh, Malaysia and Indonesia.

In relation to Europe, where the cluster includes countries like Italy, Spain, Germany, Portugal, Greece and France, significant collaborations in sustainable agriculture, biofertilisers and microbial biostimulant science have been identified. In particular, Italy emerges as a significant collaboration node in the European research landscape, implying that Italy is likely playing a key role in promoting scientific research into biostimulants and sustainable farming methods. Spain also demonstrates important international collaborations with nations from Latin America, including Brazil, Mexico, Argentina, Colombia, Chile and Peru.

Another significant cluster includes countries such as Morocco, Tunisia, Algeria and France, which are closely interconnected, suggesting regional collaborations focusing on sustainable farming systems, soil health and climate adaptation strategies. Similarly, African countries including Nigeria, Ghana, Ethiopia, Kenya and Cameroon also appear within the collaboration network, indicating increasing research participation from developing regions in the field of sustainable agriculture and plant biostimulant technologies.

The high level of interconnections among the countries shows strong international collaboration, interdisciplinary exchange of knowledge and joint scientific efforts to address global agricultural

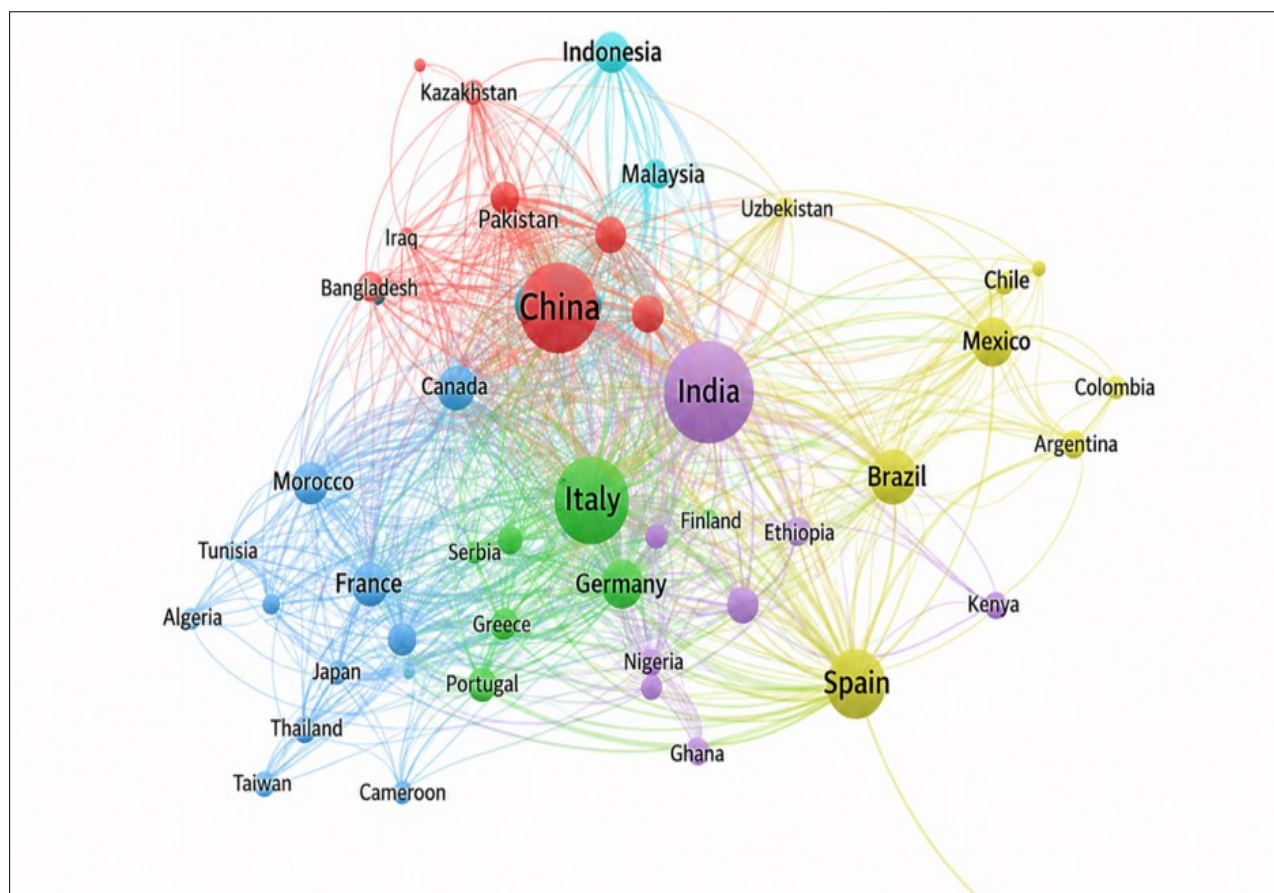


Fig. 4. Network of co-authorship countries.

challenges, including climate change, abiotic stress, soil degradation and food security (22, 23). The network also indicates that there has been increased scientific activity in the field of research on biostimulants of plants in all parts of the world, including both the developed and the developing countries. In general, it can be seen from the co-authorship country network that there has been increased global collaboration and scientific integration in the study of plant biostimulants..

Documents of bibliometric coupling (Country wise)

The network analysis of bibliometric coupling between countries in Fig. 5 shows how much similar are the interests, research outputs and references of the scientific publications from different countries related to plant biostimulants and sustainable agriculture. Bibliometric coupling occurs when countries have similar references in their scientific works, indicating thematic and citation-based relationships among studies. The figure clearly demonstrates the connectivity of the countries, showing the development of the research of plant biostimulants, abiotic stress resistance and sustainable crop production throughout the world.

The network is primarily segregated into two main clusters that reflect the existence of distinct yet connected research collaboration as well as themes among nations. The first or green cluster consists mainly of nations like India, China, the US, Saudi Arabia, South Korea, Pakistan, Australia, Canada, Egypt and Malaysia. Among these countries, India emerges as the most influential node, reflecting its significant contribution to research in plant biostimulants, sustainable agriculture, microbial techniques and abiotic stress. China and the US have also shown strong bibliometric linkages, which depict their active participation in highly impactful research activities within this field.

The group of red countries consists of nations like Italy, Spain, Germany, France, the United Kingdom, Brazil, Poland, Mexico, South Africa and the Russian Federation. The nation of Italy stands out in terms of being one of the important nations belonging to this group, thus representing the research importance and common scientific interest shared among other countries both European and non-European. Spain and Germany also form an important part of this group with respect to their research collaboration and thematic similarities.

These strong associations between the two clusters reveal the presence of common scientific backgrounds and common research interests among countries in different geographical locations concerning sustainable agricultural production and use of plant biostimulants. In addition, the strong interrelationships between the countries also indicate substantial knowledge sharing, similar citation patterns and an ever-growing globalisation of research in the agricultural and environmental sciences. Furthermore, the bibliometric network shows an increased involvement of both developed and developing countries in plant biostimulants research. For instance, countries like Pakistan, Egypt, South Africa and Malaysia have been involved in more and more scientific publications regarding resilient agriculture and sustainable technology in agriculture. It reveals the global relevance of biostimulants in addressing challenges associated with climate change, abiotic stresses and food insecurity. Recent studies have demonstrated that biostimulants contribute to improved crop resilience, nutrient-use efficiency and sustainable agricultural productivity under adverse environmental conditions (5, 7, 24). Thus, the coupled bibliometric network clearly shows that there exist many thematic similarities between biostimulants research and sustainable agricultural.

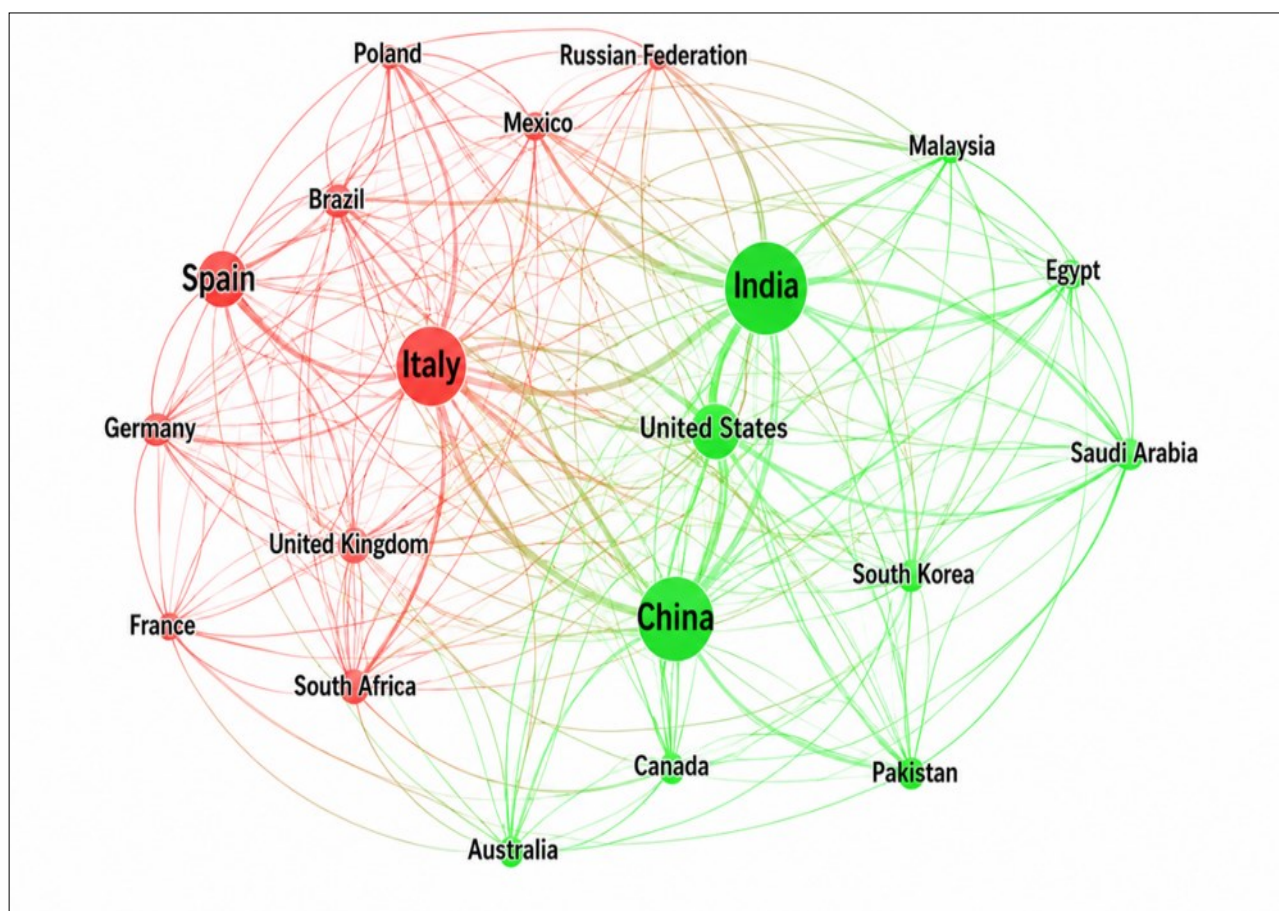


Fig. 5. Documents of bibliometric coupling (Country wise).

Co-citation of cited references

The network graph of co-citation of cited references shown in Fig. 6 provides an insight into the intellectual structure and the body of literature at the core of the area of plant biostimulants and sustainable agriculture. Co-citation analysis is a technique that detects references that are often cited together in scholarly publications, thus showing impactful studies, themes and knowledge clusters in the area of study. The network graph shows close ties between high-impact publications, implying the presence of solid research bases regarding plant growth-promoting microorganisms (PGPMs) and biostimulants.

In the graph, Smith D L appears as one of the highly cited authors in the co-citation network. The high connectivity of this citation reveals its important contributions in the field of PGPMs, microbial biostimulants and sustainable agriculture. Likewise, citations related to “Ricci E,” “Sessitsch A,” and “De Los Santos-Villalobos S” are tightly connected, meaning that these citations play an important role in studies relating to microbial biostimulants and plant stress resistance mechanisms.

Another important cluster includes references related to “Du Jardin P” and “Kloepper J W,” which are strongly interconnected with studies on plant biostimulants and agricultural sustainability. “Du Jardin P.” appears as a major foundational reference in the field, particularly in defining the concept, classification and mechanisms of plant biostimulants. Likewise, “Kloepper J W” is strongly associated with research on PGPR and microbial interactions that enhance crop productivity and stress resilience. The green cluster further highlights references related to microalgal biostimulants and sustainable agricultural applications, indicating growing scientific interest in biological alternatives to synthetic agricultural inputs. The close connections among these references suggest increasing research integration between microbial technologies, biostimulants and climate-resilient agricultural systems.

Plant biostimulants enhance abiotic stress tolerance through multiple physiological and molecular mechanisms. Several studies have reported that biostimulants stimulate antioxidant defence systems by increasing the activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX), thereby reducing oxidative damage caused by reactive oxygen species (ROS) under stress conditions (5,7,16). Biostimulants also promote the accumulation of osmoprotectants such as proline, glycine betaine and soluble sugars, which help maintain cellular osmotic balance during drought and salinity stress (3, 5). Furthermore, biostimulants influence hormonal signaling pathways by modulating the biosynthesis and activity of auxins, cytokinins, gibberellins, abscisic acid and jasmonates, resulting in improved root architecture, nutrient acquisition and stress adaptation (2, 4, 15). At the molecular level, biostimulants can regulate the expression of stress-responsive genes involved in antioxidant metabolism, ion transport, osmotic regulation and defense signaling pathways, thereby enhancing plant resilience under adverse environmental conditions (7, 13, 14).

The interconnectedness of the cited references clearly shows that the field of plant biostimulants has a strong scientific base, which is interconnected. Moreover, the co-citation graph shows that scientific research related to this topic is multidisciplinary in nature, covering microbiology, physiology of plants, soil sciences, sustainable agriculture and environmental management. Interconnected clusters of references indicate the continuous process of scientific development and growing relevance of this field for sustainable agriculture. In conclusion, the co-citation analysis clearly shows that scientific studies on the subject of biostimulants are founded on the basis of highly influential primary research, which greatly contributes to the development of plant biostimulants technologies and sustainable agriculture practices.

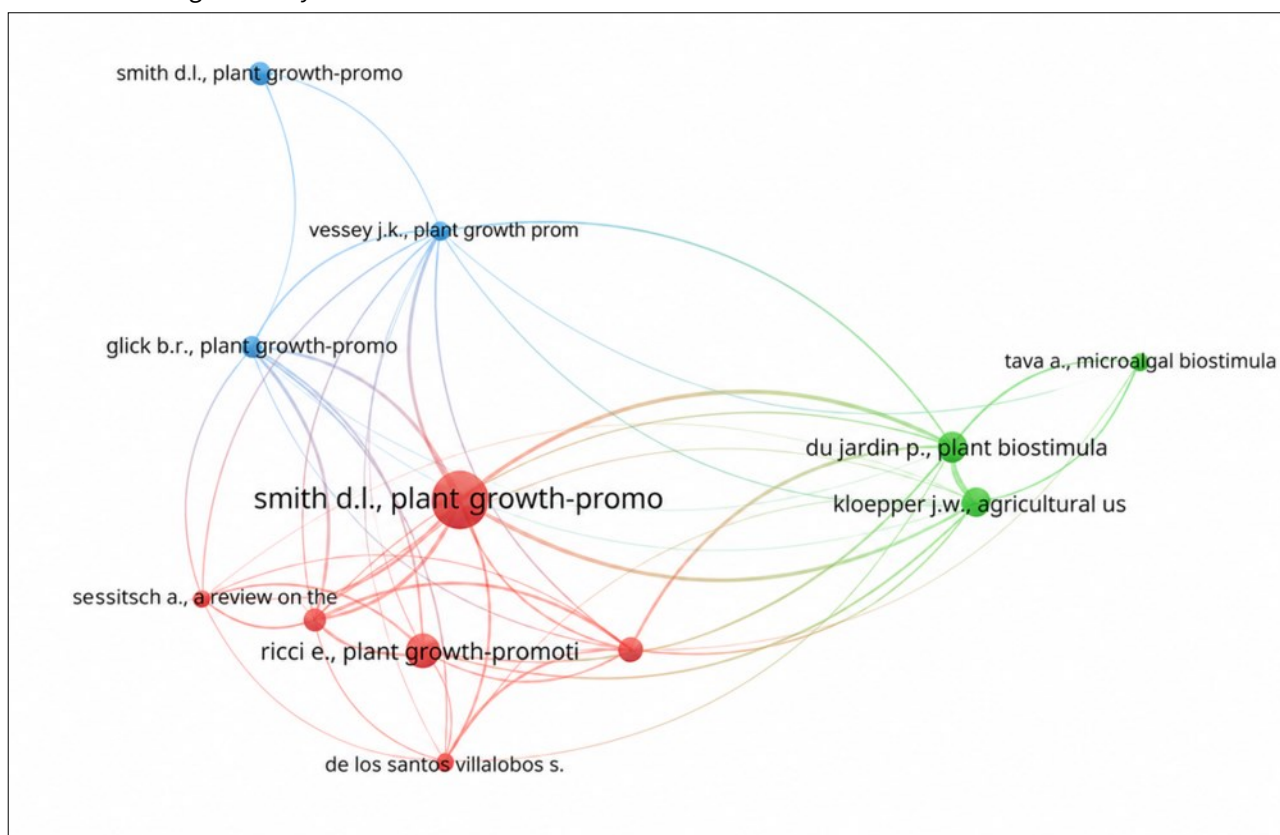


Fig. 6. Co-citation of cited references.

Conclusion

Plant biostimulants have emerged as promising tools for sustainable agriculture due to their ability to enhance crop productivity, nutrient-use efficiency, soil health and tolerance to abiotic stresses. The findings of this systematic literature review (SLR) and bibliometric analysis reveal a substantial increase in global research on plant biostimulants since 2015, highlighting their growing importance in addressing challenges related to climate change, sustainable crop production and food security. The analysis identified sustainable agriculture, abiotic stress management, microbial interactions, soil health and climate resilience as the major research themes, while international collaboration networks demonstrated the global relevance of this field. Despite their considerable potential, challenges related to variability in field performance, limited understanding of molecular mechanisms, regulatory inconsistencies and commercialisation barriers continue to hinder wider adoption. Therefore, future research should focus on elucidating the physiological and molecular mechanisms of biostimulant action, conducting long-term field validation studies across diverse agroecological conditions, developing standardised evaluation protocols and harmonised regulatory frameworks and integrating biostimulants with precision agriculture and climate-smart farming practices to enhance sustainable and resilient crop production systems.

Acknowledgements

The author sincerely acknowledges the invaluable guidance, constructive criticism and continuous encouragement provided by the Chairman and Advisory Committee members throughout the preparation of this review article. Their insightful suggestions made a significant contribution to the conceptualisation and completion of this work. The author also expresses sincere gratitude to the institutional library and research facilities for providing access to relevant databases, scholarly articles and reference materials essential for this review. Appreciation is extended to farmers, traders, processors and other stakeholders for sharing their practical knowledge and field-level insights. The author further thanks peers, colleagues and mentors for their continuous support, encouragement and valuable discussions, which greatly enhanced the quality and rigour of this review.

Authors' contributions

SP conceptualised the study, collected the relevant literature, performed the analysis and interpretation and prepared the manuscript. ND contributed to the development of ideas, validation and critical review of the manuscript. SS¹ contributed to drafting the manuscript. SS² contributed to reviewing the manuscript. RV contributed to validation. All authors read and approved the final manuscript [SS¹ - S Selvanayagi; SS² - S Senthilnathan].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used the Grammarly AI tool to improve grammar and increase the article's readability. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of publication.

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Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.