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Research Article

# Development of biofertilizers for sustainable agriculture over four decades (1980–2022)

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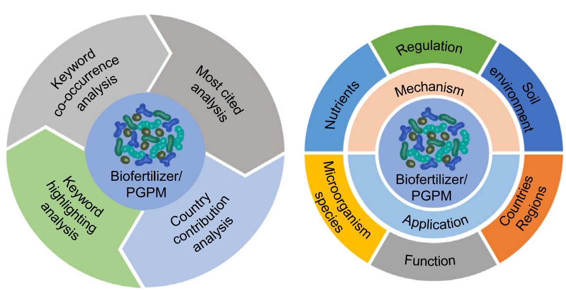
## HIGHLIGHTS

- We mined 12,880 articles related to biofertilizers in this study.
- Biofertilizer research can be categorized into three phases.
- Developing countries are keenly interested in the research of biofertilizers.
- Biofertilizers provide nutrients, regulate crop growth, and improve soil conditions.
- Pseudomonas, Azotobacter and Bacillus are the major microorganisms for biofertilizer.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The application of biofertilizers is becoming an inevitable trend to substitute chemical fertilizers for sustainable agriculture. To better understand the development of biofertilizers from 1980 to 2022, we used bibliometric mining to analyze 12,880 journal articles related to biofertilizer. The network cooccurrence analysis suggested that the biofertilizers research can be separated into three stages. The first stage (1980–2005) focused on nitrogen fixation. The second stage (2006–2015) concentrated on the mechanisms for increasing plant yield. The third stage (2016–2022) was the application of biofertilizers to improve the soil environment. The keyword analysis revealed the mechanisms of biofertilizers to improve plant-growth: biofertilizers can impact the nutritional status of plants, regulate plant hormones, and improve soil environments and the microbiome. The bacteria use as biofertilizers, included *Pseudomonas, Azospirillum*, and *Bacillus*, were also identified through bibliometric mining. These findings provide critical discernment to aid further study of biofertilizers for sustainable agriculture.

## 1. Introduction

Chemical fertilizers are the main product for soil nutrient supplementation and have been widely used in agricultural production since the middle of the last century (Cleland, 2013; Godfray et al., 2010). Chemical fertilizers can quickly and efficiently increase food production (Brown, 1981; Velimirovic et al., 2021). However, with the increasing input of these fertilizers, the rate of response is decreasing grad-

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ually (Chen et al., 2021; Tilman et al., 2002). In addition, chemical fertilization cause many environmental and health problems, such as soil and food pollution due to heavy metals and radioactive substances (Cheraghi et al., 2013; Latifi and Jalali, 2018; Savci, 2012a), air pollution produced by NO, $N_2O$, $NO_2$ and other gasses, groundwater pollution caused by nitrates (Goss et al., 1998; Rivers et al., 2012; Zhao et al., 2019), and changes in the soil pH and structure (Savci, 2012b; Xie et al., 2019).

Environmentally-friendly biofertilizers are a suitable alternative to chemical fertilizers and promote sustainable agriculture (Olanrewaju et al., 2017). Biofertilizer was defined as "a substance which contains living microorganisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant" (Vessey, 2003). These microorganisms are generally named plant-growth-promoting microbes (PGPM), plant-growth-promoting bacteria (PGPB), or plant-growth promoting rhizobacteria (PGPR). The commercial history of biofertilizers began in 1895 with "Nitragin" a preparation containing nitrogen-fixing rhizobium strains (Soumare et al., 2020). In the 1950s, phosphorus-dissolving bacteria began to be used as biofertilizers to convert phosphorus in the soil into a form that can be used by plants (Wang et al., 2019). Until now, various fungi, algae, and bacteria have been reported to show a growth-promoting effect on plants via diverse mechanisms (Azizoglu, 2019; Barin et al., 2022; Gezgin et al., 2020; Ismail et al., 2021; Naeem et al., 2021; Sun et al., 2020).

Application of biofertilizers in agriculture can effectively increase crop yields and reduce the use of chemical fertilizers. Studies have shown that biofertilizers, when used together with chemical fertilizers, can increase crop yields by 10%–40% and replace nearly 25%–30% of the chemical fertilizers (Pal et al., 2015). A study by the Brazilian Agricultural Research Corporation showed that the use of biofertilizers for biological nitrogen fixation in soybean cultivation can completely replace chemical nitrogen fertilizers without reducing yields and save approximately USD 15 billion annually (Bomfim et al., 2021). Additionally, the application of rhizobia biofertilizers in Zambia and the Republic of Congo increased soybean yields by approximately 48% and 500 kg/ha (Raimi et al., 2021). The results suggest that the application of biofertilizers is an effective approach to increase production in various countries.

Considering the economically and environmentally-friendly application of biofertilizers, it is necessary to make a time-span literature review to provide researchers with more objective and accurate guidance. Bibliometric analysis is an analytical method that uses computer tools to quantitatively measure and evaluate the research impact of a certain topic. It can reveal past literature characteristics and current research hotspots by evaluating and quantifying the number and growth trends of a particular academic subject (Becerra et al., 2020; Du et al., 2014; Mkhongi and Musakwa, 2022). This study aims to conduct quantitative and qualitative analysis on the number of articles published over the past few decades with the objective to assess the growth trends in biofertilizer-related research, uncover emerging topics and research directions within the field, and provide insights into the most influential and highly-cited papers, thereby aiding researchers in leveraging seminal works for future research.

## 2. Materials and methods

### 2.1. Data collection

Data retrieval and collection were conducted in the Web of Science Core Collection database. The specific retrieval formula was: Topic Search (TS) = ("bio*fertiliz*" OR "bio-fertiliz*" OR "bio*fertilis*" OR "bio-fertilis*" OR "biologi* fertiliz*" OR "biotic fertiliz*" OR "bio* organic fertiliz*" OR "bioorganic fertiliz*" OR "fungus fertilizer*" OR "fungal fertilizer*" OR "bacterial fertiliz*" OR "bacteria fertiliz*" OR "microbial fertiliz*" OR "microbiological fertiliz*" OR "microorganism fertiliz*" OR "bacterial manure" OR "microbial manure" OR "microorganism-manure") OR TS = ("bio*inoculant*" OR "bio-inoculant*" OR "biological inoculant*" OR "microb* inoculant*" OR "microbiological inoculant*" OR "bacteri* inoculant*" OR "fung* inoculant*" OR PGPR OR PGPB OR PGPF OR PGPM OR "Plant* growth* promot* rhizob*" OR "Plant-growth promoting bacteria*" OR "plant-growth promoting fung*" OR "plant-growth promoting microb*" OR "plant-growth promoting microorganisms" OR "plant-growth promoting actinomyce*") AND TS = ("plant" OR "grow*" OR "agric*" OR "agrono*" OR "soil") NOT TS = ("silag*" OR "ensilage" OR "ensiling").

### 2.2. Data analysis

In agricultural production, microbial inoculants are also used in the silage process to accelerate the fermentation process, which is not related to the research content of this study; therefore, it was excluded. We used Excel, Origin, and Tableau to organize data, and VOSviewer and Gephi to perform a visual collinear analysis of countries and keywords (Xu et al., 2022a, 2022b).

## 3. Results

### 3.1. Number of articles related to biofertilizers

Since the articles retrieved before 1980 appeared sporadically, the articles from 1980 to 2022 (43 years) were selected as the main object for analysis. As of January 2023, 15,451 articles were retrieved from the Web of Science Core Collection database according to the search formula mentioned above, including 12,880 journal articles, accounting for 83% of the total (Table S1). Articles can best represent the development trend of related research; therefore, in the following analysis, we analyzed and evaluated the articles from 1980 to 2022. The most used language was English (97.48%), followed by Spanish (1.21%), Portuguese (0.89%), and Polish (0.19%) (Fig. S1). English corresponds to the largest proportion, indicating that the main language of communication in this field is English. The number of published papers increased exponentially from 1980 to 2022 (Fig. 1) and can be divided into three stages: (1) early *q*-exponential growth (1980–2005); (2) intermediate linear growth (2006–2015); and (3) *p*-exponential growth (2016–2022). In the last six years, the number of annual publications has grown from 668 in 2016 to 1,775 in 2022. The publications in 2022 is 20 times the number of publications in 2000, suggesting that the research on biofertilizers was of great interest in recent years.

### 3.2. Several countries contributed to publication and cooperation

Statistical analysis of the top 10 countries in terms of the number of journal paper contributions was conducted (Table S2). India was the country that published the most articles related to biofertilizers, and reached 2,797, followed by China (2,013) and Brazil (989). The United States ranked fourth (979). The following countries were Pakistan, Iran, Spain, Canada, Egypt, and Mexico. Among the top-five and top 10 countries in terms of the number of articles, the proportion of developed countries accounted for 20% and 30%, respectively. The ratio of published papers from developed countries was much lower than that of developing countries, which contradicts the fact that the developed countries publish more articles in all scientific areas.

Developed countries generally conduct agricultural production in an industrialized manner, and the per capita consumption of chemical fertilizers is higher than that of developing countries (Heaton et al., 2013). Developed countries can provide sufficient chemical fertilizers for agricultural production (Table S3). However, the production of chemical fertilizers in most developing countries is far below the demand, especially in India and Brazil, which have large populations and scarce arable land, and cannot meet their normal agricultural needs. The agricultural model for most developing countries is still dominated by small-scale farming

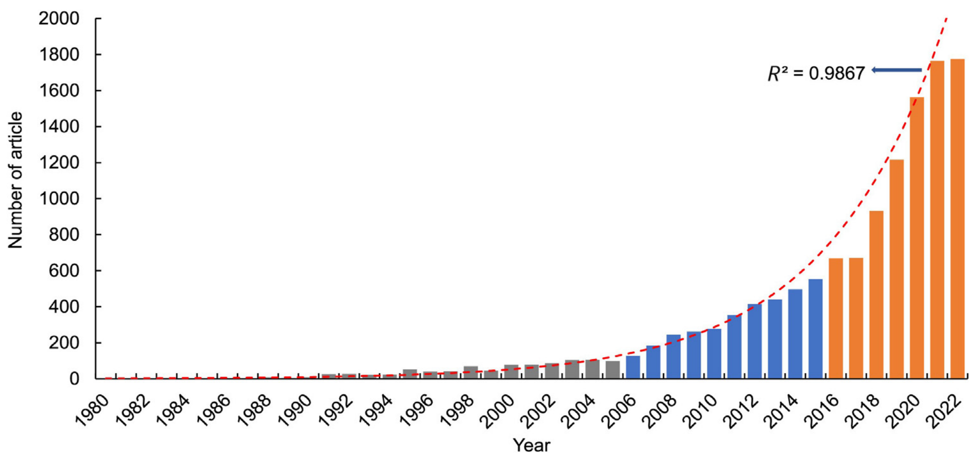


**Fig. 1.** Annual number of articles and growth rate of publications in the field of biofertilizers from 1980 to 2022.

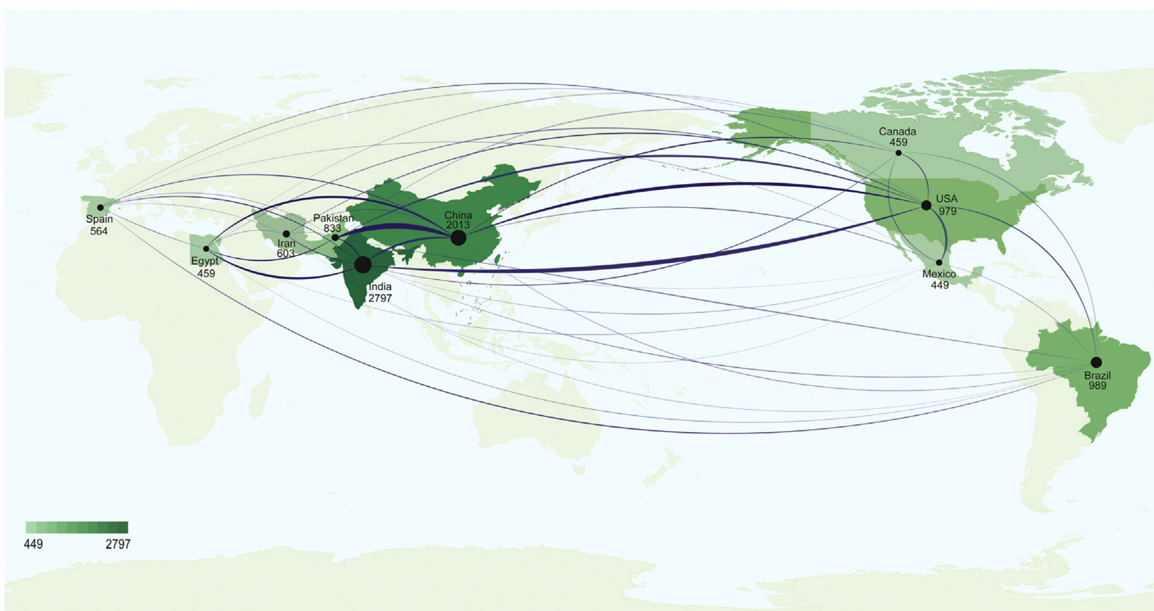


**Fig. 2.** Distribution and co-plot of cooperation network of the top 10 countries that published articles in the field of biofertilizers. The size of the circle indicates the number of publications in a country. The width and color of the line between two circles indicate the degree of cooperation between countries.

(Motesharezadeh et al., 2017). Under the dual constraints of output and cost, farmers tend to use relatively cheap compost, green manure, and plant-beneficial bacteria to fill the gap caused by insufficient chemical fertilizers. We predict that developing countries (especially countries with insufficient supply of chemical fertilizers) will invest more in biofertilizer research, which can explain that India and China are in the leading position in annual publication of journal articles.

A study is recognized as international collaboration if coauthors are from different countries. Interestingly, China showed the highest number of collaborative publications (651), the United States (636) followed by, India (472), and Pakistan (400). The United States, China, and India have relatively intensive cooperation with the other nine countries (Fig. 2). Among them, China and Pakistan have the closest cooperation, followed by the United States and China, the United States and India, and the United States and Mexico.

We further analyzed the publications from the top-five countries: India, China, Brazil, USA, and Pakistan. The number of publications grew rapidly, especially in the two developing countries, India and China, which have a large population and are agricultural-focused countries (Fig. 3). We also examined the top 15 institutions that publish biofertilizer-related literature (Table S4), including four institutions from India and four from China. The Indian Council of Agricultural Research published the most papers (595), followed by the Egyptian Knowledge Bank (446) and the Nanjing Agricultural University from China (260). The annual number of papers from India has been in a leading position and maintained a rapid growth trend. In 2004, India implemented the "Second Green Revolution" to promote an agricultural development model dominated by biotechnology including biofertilizers and biopesticides (Patel, 2013; Sinha, 1997), which may have contributed to the significant increase in the number of articles published in 2007. Since 2003, China has promulgated a series of similar policies (Zhang et al., 2011). In 2015, the China government announced the policies "Action Plan Zero Growth of Fertilizer Use by 2020" and "Action Plan for Zero Growth of Pesticide Use by 2020" (Jin and Zhou, 2018). These policies may be an important reason for the exponential growth in publications by Chinese scientists, suggesting that government policies are one of the main drivers in biofertilizer research.

### 3.3. Journals that publish papers related to biofertilizers

We further investigated the journals that publish papers in the field from 1980 to 2022 (Table S5). *Frontiers in Microbiology* was the journal with most published articles accounting for 313 papers, followed by *Plant and Soil* (242 papers) and *Applied Soil Ecology* (233 papers). Com-

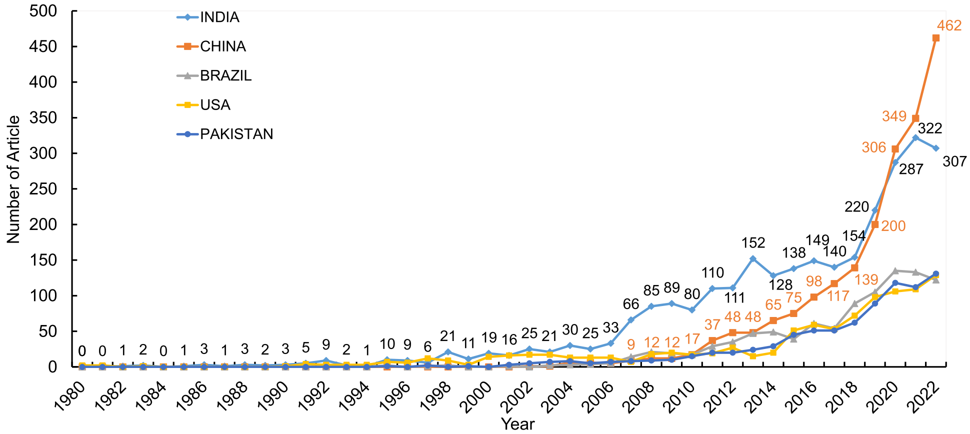


**Fig. 3.** Annual growth curve of the top-five countries in the total number of articles on biofertilizers during 1980–2022.

pared with the other journals, *Agronomy* (Basel) is a novel and open access journal launched in 2011. However, the publication in the journal increased fast, from 1 in 2017 to 86 in 2022 in just six years, which surpasses by far the other journals (Fig. S2).

### 3.4. Most highly cited articles in the field

Citation analysis provides insights into the research trends in the field. We searched the top 10 most cited articles for further analysis, which yielded a total of 7,574 citations (Table 1). Among the top 10 most cited papers, three papers were from Canada, three from the United States. The remaining four were from China, India, Israel, and Russia. The most cited was "Methods for isolating and characterizing ACC deaminase-containing plant-growth-promoting rhizobacteria" (958 citations) published in *Physiologia Plantarum*. The paper reported a method to isolate bacteria containing 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase to evaluate the effect of selected bacteria on plant growth (Penrose and Glick, 2003). The second most cited article was "Bacterial volatiles promote growth in *Arabidopsis*" published in the *Proceedings of the Natural Academy of Sciences*, USA, and describes the ability of some PGPRs to release a mixture of volatile organic compounds (VOC), especially 2,3-butanediol and acetoin that play an important role in promoting growth in *Arabidopsis* (Ryu et al., 2003). The third-ranked article was "A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria" which uses a model to explain how bacterial ACC deaminase interacts with ACC and reduce the concentration of ethylene by reducing the concentration of endogenous ethylene precursors in plants (Glick et al., 1998). In summary, the top cited articles mainly focus on the basic research on the mechanism, methods, and effects of microorganisms to promote plant-growth.

### 3.5. Keyword analysis of related literature from 1980 to 2022

Keyword analysis can light the research focus of biofertilizer throughout time. The cooccurrence of the keyword network from 1980 to 2022 (Fig. 4a) can be divided into six categories related to biofertilizers: microorganisms (mainly including different types of growth-promoting bacteria, *Pseudomonas, Azospirillum, Bacillus*, and rhizobia, which can be used as biofertilizers), mechanisms (nitrogen fixation, phosphorus solubilization, growth promotion, and biological control), nutrients (nitrogen and phosphorus), crops (wheat, corn, soybean, and tomato), environment (salt, drought, and heavy metal stresses), and location (soil and rhizosphere). The analysis suggested that the research in biofertilizer focused on bacterial function, mechanisms to increase crop growth, and the application of the biofertilizer.

We performed network cooccurrence analysis of keywords of three different periods (1980–2005, 2006–2015, and 2016–2022) to investigate the differences between the periods. The cooccurrence of the keyword network in the first stage (1980–2005, Fig. 4b) showed that "PGPR" accounted for the largest number of keywords including "*Azospirillum*", "Nitrogen-fixing bacteria", "Rhizobia", "Rhizosphere bacteria", "*Pseudomonas*", and other growth-promoting bacteria. Correspondingly, the most important keyword in the mechanism category was "Nitrogen fixation", followed by "Yield" and "Plant-growth promotion", implying that the main direction of research was the use of biofertilizers for nitrogen fixation, thereby promoting crop growth and increas-

**Table 1**
Top 10 most cited journal articles between 1980 and 2022.

| No. | Title | TC | TC/Y | Journal | Country | Reference |
|---|---|---|---|---|---|---|
| 1 | Methods for isolating and characterizing ACC deaminase-containing plant growth-promoting rhizobacteria | 958 | 45.62 | Physiol. Plant. | Canada | (Penrose and Glick, 2003) |
| 2 | Bacterial volatiles promote growth in Arabidopsis | 944 | 44.95 | Proc. Natl. Acad. Sci. U.S.A | USA | (Ryu et al., 2003) |
| 3 | A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria | 886 | 34.46 | J. Theor. Biol. | Canada | (Glick et al., 1998) |
| 4 | Enhanced plant-growth by siderophores produced by plant growth-promoting rhizobacteria | 868 | 19.73 | Nature | USA | (Kloepper et al., 1980) |
| 5 | Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities | 732 | 45.75 | Microbiol. Res. | India | (Ahmad et al., 2008) |
| 6 | Bacterial volatiles induce systemic resistance in Arabidopsis | 714 | 35.70 | Plant Physiol. | USA | (Ryu et al., 2004) |
| 7 | Plant growth-promoting bacteria confer resistance in tomato plants to salt stress | 706 | 35.30 | Plant Physiol. | Israel | (Mayak et al., 2004) |
| 8 | Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities | 690 | 38.33 | Appl. Soil Ecol. | China | (Chen et al., 2006) |
| 9 | Plant growth-promoting bacteria that decrease heavy metal toxicity in plants | 541 | 22.54 | Can. J. Microbiol. | Canada | (Burd et al., 2000) |
| 10 | Cadmium-tolerant plant growth-promoting bacteria associated with the roots of Indian mustard (*Brassica juncea* L. Czern.) | 535 | 28.16 | Soil Biol. Biochem. | Russia | (Belimov et al., 2005) |

TC: total citations; TC/Y: average annual citations.

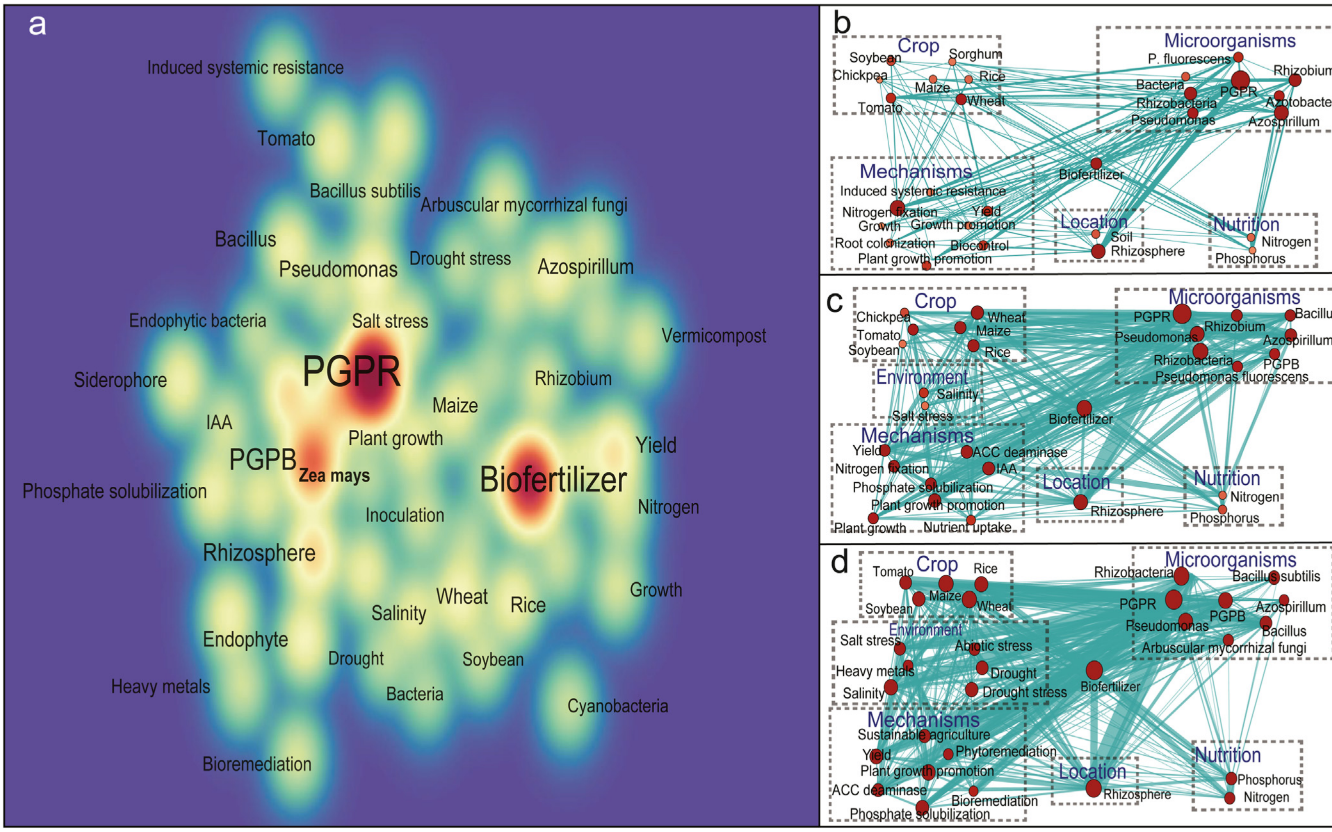


**Fig. 4.** Social network of author keywords in articles related to biofertilizers. (a) Social network of the top-50 author keywords with the highest occurrence from 1980 to 2022. The size of the circle indicates the frequency of publication in a country. The width and color of the line between two points indicate the degree of cooperation between countries. Author keyword cooccurrence information for (b) 1980–2005, (c) 2006–2015, and (d) 2016–2022.

ing crop yield at this stage. New environmental keywords, including “Salt”, “Salt stress”, and “Heavy metals”, appeared in the second stage (2006–2015, Fig. 4c), suggesting that scientists began to pay attention to study the function of biofertilizers on environmental stresses. Additionally, “Indole-3-acetic acid (IAA)” was another keyword that appeared frequently, suggesting that the studies related to the mechanism to increase plant-growth were the research focus at this stage. In the third stage (2016–2022, Fig. 4d), the occurrence of the keywords “Nitrogen-fixing microorganisms” decreased. In contrast, the proportion of keywords such as “Phytoremediation”, “Salt”, “Heavy metal stress”, and “Siderophore” increased. “Sustainable agriculture”, “Abiotic”, “Drought stress”, “Antioxidant”, and “Microbiome” have also been added to the top-keywords list. The increased proportion of salt and heavy metal stresses, imply a much broader application of biofertilizers to improve plant stress and increase plant-growth.

### 3.6. Microorganisms that can be used as biofertilizers and their functions mined from bibliometric analysis

We mined the microorganisms that can be used as biofertilizers from the word cloud of keywords (Fig. 5a). It can be found that “Rhizobacteria” and “Endophyte” were the keywords that most frequently appeared. Although “Rhizobacteria” and “Endophyte” are not specific to the genus, the high frequency of appearance suggested that rhizosphere bacteria and endophytes are critical research topics. The high frequency of the two keywords also implied that the rhizosphere and the interior of plants are the main locations for the survival and function of biofertilizers. The genus “*Pseudomonas*” and the species “*Pseudomonas fluorescens*” are the keywords with highest frequency of appearance following “Rhizobacteria” and “Endophyte”, suggesting that *Pseudomonas* is the most widely studied microorganisms in biological fertilizers. *Pseudomonas* not only

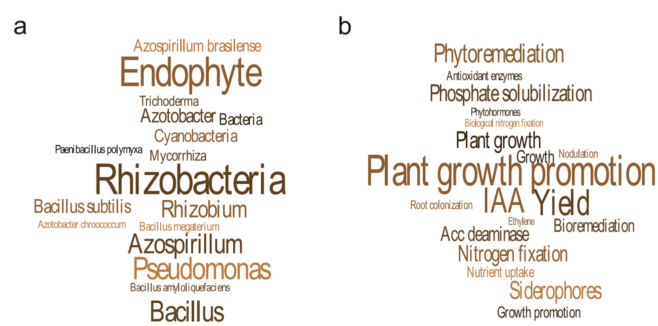


**Fig. 5.** Word cloud of author keywords of the top 20 most frequently occurring microorganisms and their functions in biofertilizers from 1980 to 2022. (a) Microorganisms that can be used as biofertilizers, and (b) their function. The size of the font indicates the number of times the keyword appeared.

can dissolve phosphorus, solubilize potassium, fix nitrogen, secrete ACC deaminase, IAA, and produce siderophores, but also has the ability to perform biological control, and is widely used in biological fertilizers (Kaur et al., 2022; Liu et al., 2019; Nascimento et al., 2021; Pham et al., 2017). The most frequent keywords after “*Pseudomonas*” were “*Bacillus*” “*Azospirillum*”, and “*Rhizobium*” (Table S6). *Rhizobium* are microorganisms used as biofertilizers since 1895. *Rhizobium* can symbiotically form root nodules with the roots of legume crops and fix nitrogen efficiently in root nodules (Yuan et al., 2020). Although the nitrogen fixation efficiency of *Azospirillum* is not as good as the symbiotic nitrogen fixation efficiency in legume nodules, it results in nitrogen fixation in crops, such as maize, rice, and wheat (Russo et al., 2005). Similar to *Pseudomonas, Bacillus* has the function of phosphate and potassium solubilization, nitrogen fixation, and secretion of ACC-deaminase, plant hormones, and siderophores (Delfim et al., 2018; Mehmood et al., 2021b; Misra and Chauhan, 2020). Additionally, *Bacillus thuringiensis, B. subtilis*, and *B. megaterium* can secrete antibacterial and insecticidal substances (crystal proteins, polypeptides, and some enzymes) to prevent and control a variety of plant pests and diseases (Kildea et al., 2008; Swain and Ray, 2009; Wang et al., 2020). Furthermore, *B. velezensis* SQR9 (formerly known as *B. amyloliquefaciens* SQR9) is an extensively researched PGPR that secretes a wide range of secondary metabolites. These include lipopeptides, polyketides, and bacillunoic acids, which are antibacterial branched-chain fatty acids (Huang et al., 2023; Xu et al., 2014). In addition to bacteria that can be used as biofertilizers, fungi (Trichoderma and Mycorrhizae) and microalgae (cyanobacteria) can also be used as biofertilizers to promote plant-growth (Liu et al., 2020; Pereira et al., 2008). Trichoderma-amended fertilizer significantly enhances Arabidopsis and cucumber growth by modulating the microbial community to promote plant performance (Hang et al., 2022). Mycorrhizal fungi supply essential mineral nutrients (typically phosphorus and nitrogen) and offer protective benefits to host plants against both biotic and abiotic stress factors. This highlights their potential as biofertilizers for sustainable agriculture (Shi et al., 2023). Microalgae, including cyanobacteria, exhibit nitrogen fixation under anaerobic conditions. Cyanobacteria not only meliorate soil quality and fertility but also produce polysaccharides, antimicrobial agents, plant growth hormones, and other metabolites that stimulate plant growth (Dineshkumar et al., 2018).

We further mined the function and mechanisms of biofertilizers from the keyword analysis (Fig. 5b). "Promoting plant-growth" and "yield" were the most frequent keywords, indicating that the increase in yield has received the highest attention regarding the effect of biofertilizers. The following keywords were IAA, phytoremediation, siderophores, phosphorus dissolution, and nitrogen fixation. IAAs are important plant hormones while phosphorus and nitrogen are substances that affect the growth and nutritional status of plant (Li et al., 2021; Strader and Bartel, 2011). Furthermore, phytoremediation is one of the effective methods for the treatment of heavy metal contaminated soils. *Bacillus, Pseudomonas*, and mycorrhizal fungi can promote plant-growth, improve phytoremediation efficiency, and improve plant tolerance via changing the valence state of heavy metals (oxidize, reduce, or acidify heavy metals) through the secretion of chelating agents, siderophores, metabolites, extracellular polymers, and ACC-deaminase (Liu et al., 2021; Riaz et al., 2021; Zainab et al., 2021). The findings imply that microorganisms can function as biofertilizers through various mechanisms.

## 4. Discussion

Based on keyword analysis, the main mechanism of action of biofertilizers include (1) improve and supply plant nutrients, (2) regulate plant-growth, and (3) improve soil condition and microbiome. We further explain the mechanisms in detail (Fig. 6).

### 4.1. Enhancing nutrient supply to plants through biofertilizers

Soluble nutrients, such as $NH_4^+$, $K^+$, and $PO_4^{3-}$, can be absorbed by plants directly; however, insoluble phosphate or potassium salts, phosphorus, or potassium in the soil cannot be absorbed (Omar, 1998; Shin et al., 2016). Additionally, nitrogen cannot be used by plants directly. Nitrogen-fixing microorganisms use the enzyme nitrogenase to convert nitrogen into $NH_4^+$ or $NO_3^-$, which can be absorbed and utilized by plants (Rees et al., 2005). Most of the phosphorus in soil, including organic phosphorus (phosphoinositide, phospholipid, and nucleic acid) and inorganic phosphorus (phosphate rock and insoluble phosphate), cannot be absorbed by plants (Turner and Blackwell, 2013). Phosphorus-solubilizing microorganisms, such as *Bacillus, Pseudomonas*, and fungi, can secrete phytase, nuclease, and phosphatase to hydrolyze organic phosphorus and convert it to phosphate that can be absorbed (Malboobi et al., 2009; Qiao et al., 2019; Singh et al., 2020). These microorganisms can also secrete organic acids and protons, which dissolve phosphate rock and insoluble phosphate by reducing the pH and increasing the available phosphorus in soil (Chen et al., 2006; Vyas and Gulati, 2009; Yin et al., 2021). Most of the potassium in the soil is bound in minerals (potassium feldspar, muscovite, illite, and vermiculite) and cannot be absorbed and utilized by plants. Potassium-solubilizing microorganisms can secrete substances such as protons, organic acids, enzymes, and extracellular polysaccharides, which can release potassium by reducing pH, chelating, and destroying the crystal structure of potassium feldspar (Muthuraja and Muthukuma, 2021; Xue et al., 2018).

### 4.2. Regulation of plant growth by biofertilizers

Biofertilizers can regulate plant growth by regulating plant hormones and producing siderophores, enzymes, small molecular peptides, lipids, polysaccharides, antioxidants, and VOC, thereby increasing yield (Glick et al., 2007; Mehmood et al., 2021a; Wang et al., 2022). Rhizosphere microorganisms can synthesize or degrade plant hormones, such as IAA, cytokinin (CTK), and gibberellin (GA), thereby regulating the level of plant hormones, stimulating the division and elongation of plant cells, and promoting plant growth (Tsukanova et al., 2017). Lima et al. (2020) inoculated palm seedlings with *Bacillus amyloliquefaciens* and observed altered phytohormone levels. IAA and abscisic acid increased by 66% and 44%, respectively, while ACC levels decreased by 24%, and plant stem dry matter, root dry matter, plant height, and stem diameter increased by 110%, 123%, 39% and 19%, respectively. The stress hormone ethylene is another important metabolite for the growth and development of plants. When plants are under stress, the ethylene content increases, thereby slowing down the growth rate of plants. Some microorganisms can secrete ACC deaminase to convert the ethylene precursor ACC into $\alpha$-ketobutyric acid and $NH_3$, thereby reducing ethylene content and promoting plant-growth (Win et al., 2018). *Bacillus* and *Pseudomonas* can secrete VOC (2, 3-butanediol, 3-hydroxy-2-butanone, esters, and hydrocarbons) to promote plant growth and induce resistance or tolerance in plant systems (Lee et al., 2012; Zhang et al., 2007). Remarkably, *Bacillus* exhibits the fascinating capability of secreting specific metabolites, such as tropine, citric acid, acetyl-L-carnitine, and levulinic acid. These compounds serve to attract plant-beneficial *Pseudomonas stutzeri*, leading to the formation of biofilms on plant roots consequently stimulating plant growth (Sun et al., 2022). Furthermore, *Bacillus* is known for its antibiotic production, featuring notable antibacterial and antifungal properties. These antibiotics, such as bacillomycin D, can also impact processes like iron acquisition, biofilm formation, and ecological competition (Xu et al., 2019). Additionally, siderophore-producing rhizosphere bacteria can increase the iron content in plants and improve the tolerance of plants to metals such as iron, promoting plant-growth on soils containing heavy metals (Huo et al., 2021). Biofertilizers can induce host defense mechanisms by secreting polysaccharide-degrading enzymes (Aoki et al., 2020), such as chitinase, protease, glucanase, and cellulase (Shi et al., 2013). Finally, biofertilizers can produce antibiotics (Kefi et al., 2015), improve soil chemical conditions, and modify the soil microbial community composition (Shen et al., 2015) to antagonize pathogens and pests, thereby protecting and promoting plant-growth.

### 4.3. Alteration of microbiota and soil structure by biofertilizers

The effectiveness of biofertilizers hinges on the successful colonization of microorganisms within the plant rhizosphere (Hassan et al., 2019). This rhizospheric colonization comprises three crucial steps: chemotaxis, adhesion, and biofilm formation. Bacterial motility and chemotactic responses allow them to selectively reach specific binding sites on plant surfaces. Adhesive factors bestow bacteria with the ability to adhere to surfaces, with some adhesive factors also having

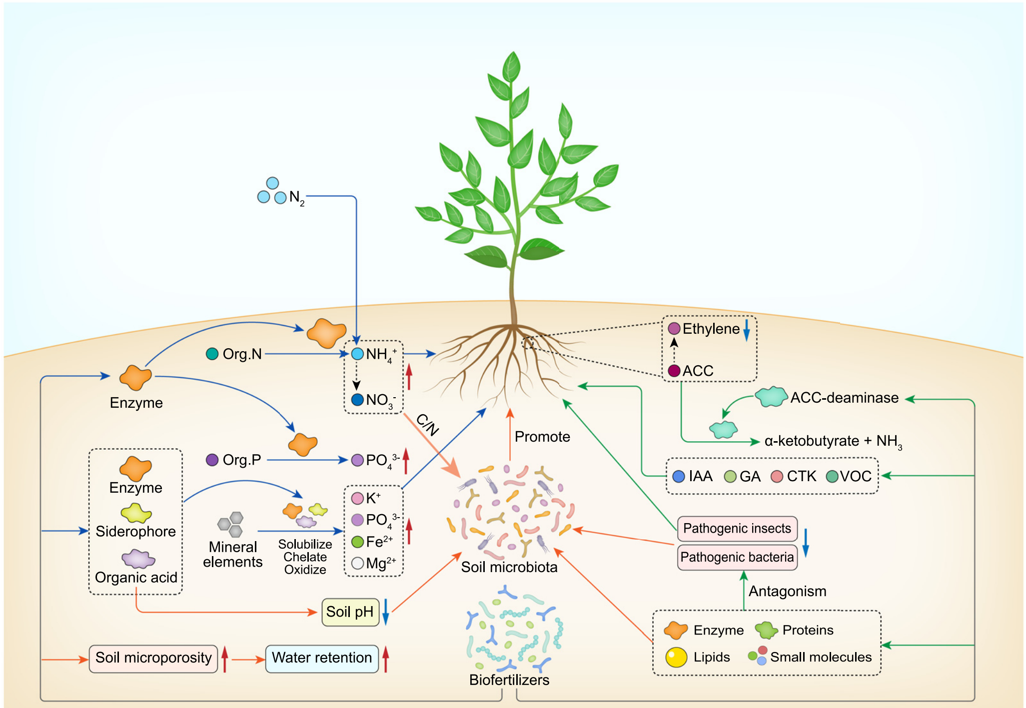


**Fig. 6.** Mechanism of plant-growth promotion by biofertilizers. (1) Biofertilizers can improve the nutritional status of plants. Bacteria in the biofertilizer can convert $N_2$ into inorganic nitrogen ($NH_4^+$, $NO_3^-$), and the organic phosphorus in the soil into inorganic phosphorus. The organic acids, siderophores, and enzymes secreted by bacteria can release $PO_4^+$, $K^+$, $Fe^{2+}$, and $Mg^{2+}$ from mineral elements by dissolution, chelation, and oxidization. (2) Biofertilizers can regulate plant-growth. The plant hormones (IAA, GA, and CTK) secreted by bacteria in biofertilizers can promote the proliferation and growth of plant cells. ACC deaminase secreted by bacteria can reduce the content of ACC, the precursor of ethylene synthesis in plants, thereby reducing ethylene content. Biofertilizers can secrete VOC (2, 3-butanediol and 3-hydroxy-2-butanone) to promote plant growth and induce resistance or tolerance in plant systems. Enzymes, lipids, and small molecular weight substances secreted by bacteria can inhibit or kill harmful bacteria and pests, and reduce the damage of harmful bacteria and pests to plants. (3) Biofertilizers can improve soil environmental conditions. Bacteria in biofertilizers can change the soil structure, improve soil microporosity, and improve water retention. The organic acids secreted by beneficial bacteria can reduce soil pH, increase N content, and inhibit harmful bacteria, thereby affecting microbiota community in the soil.

the capacity for specific binding to plants. The bacterial biofilm formation serves as an indispensable foundation for their stable colonization (Trivedi et al., 2020). The process of colonization implies that application of biofertilizer could affect the species or proportion of dominant microbes in the soil community through a small amount of or short-term life activities. For example, application of biofertilizers with *B. amyloliquefaciens* can increase the abundance of bacteria and decrease that of fungi with alteration of the bacterial composition and reduction of the abundance of harmful bacteria, which effectively inhibits banana fusarium wilt (Fu et al., 2017). The reshaping of the soil microbiome by biofertilizers has also been observed in sugarcane, alfalfa, apricot, and other crops (Baldi et al., 2021; Liu et al., 2022; Zhao et al., 2022). Furthermore, the application of biofertilizers in soil can improve the physical quality of the soil, especially retaining moisture due to increased microporosity (Alencar et al., 2015). *B. thuringiensis* change the carbon-nitrogen ratio by mineralizing organic matter, which affects the protists and microbiota structure in the soil (Zhao et al., 2022). Finally, *B. subtilis* secrete organic acids, which can reduce the pH of the surrounding soil and promote plant growth in saline-alkali land (Alakhdar et al., 2020).

### *4.4. Limitations of this study*

Although we reviewed and mined publications in biofertilizers from bibliometrics analysis, our study still suffers from several ineluctable limitations. First, we only selected articles published in English. While such publications account for more than 95% of the articles retrieved, language constraints remain. Second, to retrieve as many research-relevant literatures as possible, our search strategy included some terms related to biofertilizers and microbial inoculants for agricultural production, and tried to reduce irrelevant research-related literature by using the operator NOT. However, since there are no 100% accurate search results, a handful of publications that are not related to biofertilizers might have been included. Third, the difference between the classification of individual articles in the Web of Science and the actual content may affect some of the detailed data, but due to the very small number of articles, it does not affect the overall research. Despite these limitations, given the extensive documentation collected in this study, we believe that our findings provide a comprehensive summary and useful perspective for current research. Therefore, it provides important guidance for future research.

## 5. Conclusions

We used bibliometrics to characterize publications in the field of biofertilizers, including contributing countries and institutions, research directions, citations, and keywords. The study found that developing countries are far more enthusiastic about biofertilizer research than developed countries. Additionally, the various mechanisms that promote plant-growth by biofertilizers were summarized from the literature, and bacteria with the potential application for biofertilizers were also mined from the literature. The study showed the importance of biofertilizers and the research in the field may increase the application ratio of biofertilizers to replace chemical fertilizers in agriculture.

## Declaration of Competing Interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ziliang Dong reports a relationship with Chongqing Taiji Group Co., Ltd. that includes: employment.


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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2023.09.006.

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