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Biocontrol of Phytopathogens Using Plant Growth Promoting Rhizobacteria: Bibliometric Analysis and Systematic Review

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Abstract: Biocontrol has emerged as an effective strategy for managing plant pathogens and pests. The use of plant growth-promoting rhizobacteria (PGPR) as biocontrol agents offers a sustainable alternative, enhancing plant morphology, biochemistry, physiology, and secondary metabolism. This study conducts a bibliometric analysis and systematic review of PGPR-based biocontrol research from 2019 to 2023, using the Web of Science (WoS) database. A total of 2823 publications were identified, with a significant increase in scientific output since 2019. Original research articles dominated the field, with India, China, the USA, and Pakistan leading in publication volume. Key contributors included Babalola (North-West University, South Africa), Kloepper (Auburn University, USA), and Shen (Nanjing Agricultural University, China), each with at least 25 publications. Co-authorship analysis revealed four major research networks centered in India, China, Brazil, and Canada. *Bacillus* and *Pseudomonas* were the most studied PGPR genera, recognized for their roles as bioinoculants, bioremediators, and biostimulants, mitigating the negative impacts of synthetic fertilizers and pesticides. This analysis underscores the growing global focus on PGPR-based biocontrol and its potential for sustainable agriculture. Strengthening international collaboration and accelerating applied research on PGPR formulations will be critical for optimizing their efficacy and scalability in real-world agricultural systems.

Keywords: sustainable agriculture; bioinoculants; biological control; plant–microorganism interactions; plant growth-promoting bacteria; soil health

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1. Introduction

The ever-increasing human population is a concern for food security because agricultural production systems are affected by different biotic and abiotic factors that determine yield and quality. To improve plant productivity, humanity relies on the excessive supply of agrochemicals, mainly fertilizers and pesticides, which affect human health and the physical, chemical, and biological properties of the soil, as well as causing environmental pollution [1]. Plant diseases, caused by various phytopathogens such as fungi, bacteria, viruses, nematodes, and protozoa, are the biotic factors that affect agricultural production and cause losses in yield and quality. Between 20 and 40% of plant productivity losses are caused by phytopathogens, and one option to mitigate plant diseases is biocontrol, which is the use of beneficial microorganisms that reduce the negative effects of phytopathogens and promote plant growth [2]. In view of this situation, there is currently a growing interest in the search for sustainable alternatives to mitigate the adverse effects of both fertilizers used to nourish plants and pesticides applied to control phytopathogens in soil and in plants. Soil is a source of nutrients for plants and an ecosystem in which bacteria, fungi, protists, and animals co-exist in diverse and active/coordinated communities [3]. The nutrient-rich portion of soil surrounding plant roots is called the "rhizosphere", in which a diversity of bacteria, including PGPR, are found. They promote plant growth through (1) biological nitrogen fixation, (2) the solubilization of inorganic phosphorus and the mineralization of organic phosphorus, (3) the production of phytohormones, e.g., indole-3-acetic acid (IAA), cytokinins, and gibberellins, (4) the production of siderophores, 1-amino-cyclopropane-1-carboxylate (ACC) deaminase, and hydrocyanic acid (HCN), and (5) the biological control or biocontrol of phytopathogens and insects, synthesizing antibiotics or fungicidal compounds, or competing with harmful macro-organisms (Figure 1) [4]. Biocontrol is a promising approach that has demonstrated its efficacy on various plant pathogens and pests in plant species [5]. The use of microorganisms among PGPR as biocontrol agents is a recent and environmentally friendly strategy, as they improve the morphology, biochemistry, physiology, and secondary metabolisms of plants. They moreover cause ISR in plants and produce different toxins, antibiotics, enzymes, etc., to control the proliferation and damage of phytopathogens [6].

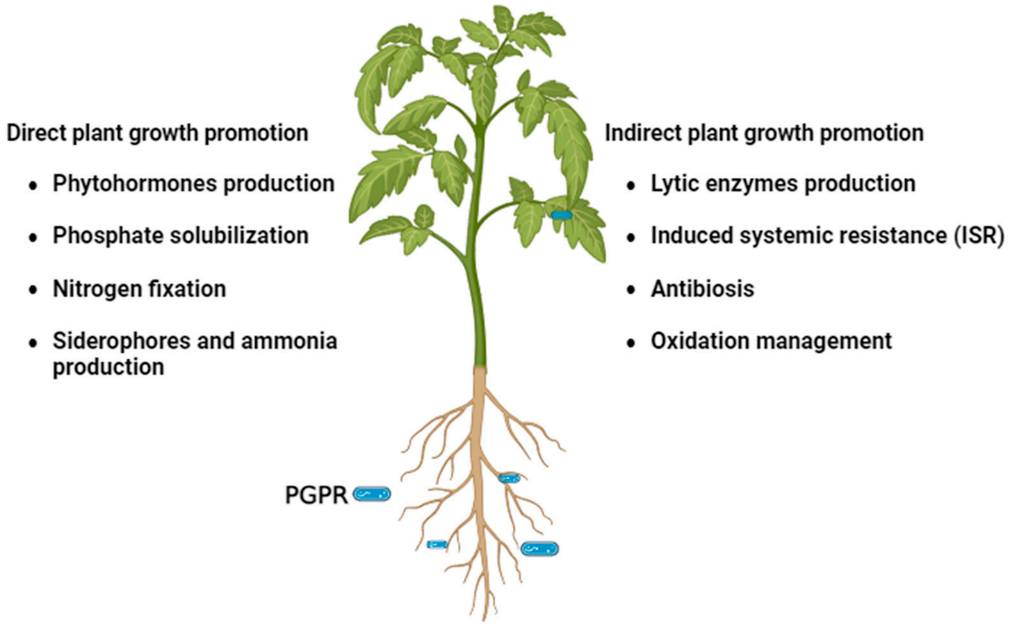

Figure 1. Direct and indirect mechanisms of PGPR, made in BioRender.

A sustainable alternative is the use of agricultural inputs such as bioinoculants based on soil-dwelling microorganisms that have the ability to promote growth and improve plant and soil health. The direct and indirect mechanisms of plant rhizosphere bacteria on the root system and plant shoot growth have been demonstrated. These types of bacteria are called plant growth-promoting rhizobacteria (PGPR) [7] and group together different genera, e.g., *Azospirillum*, *Pseudomonas*, *Azotobacter*, *Klebsiella*, *Enterobacter*, *Alcaligens*, *Arthrobacter*, *Burkholderia*, and *Bacillus*. Species of the genus *Bacillus*, such as *B. megaterium*, B. circulans, *B. coagulans*, *B. subtilis*, *B. azotofixans*, *B. macerans*, and *B. velezensis*, are reported as PGPR [8]. The mechanisms of PGPR that promote plant growth and health are biological nitrogen fixation, phosphate solubilization, production of phytohormones and hydrolytic enzymes that act as biocontrol or biological control, production of extracellular polysaccharides, and induced systemic resistance [9]. Biocontrol is an important component in integrated crop management systems. Its principle is based on the use of live microorganisms to reduce and/or maintain the population of phytopathogens below the economic threshold. The biological control method is efficient in the short, medium, and long term and is an environmentally sustainable alternative that harms neither humans nor animals. Beneficial bacteria such as PGPR show diverse antagonistic mechanisms against plant pathogens, in particular competition for space and nutrients, hydrolytic enzymes, induction of resistance, and synthesis of volatile compounds and biofilms [10]. The exploitation of PGPR for the biocontrol of fungal diseases is a novel field of research. The species studied are mainly antagonistic fungi, such as *Trichoderma* spp., and bacteria of the genera *Pseudomonas*, *Bacillus*, and *Streptomyces*. The various studies showing biocontrol efficacy for many isolates reveal the need to characterize the metabolic and molecular mechanisms underlying these activities [11].

For its part, bibliometrics is the application of mathematical and statistical methods to scientific literature (books and other media). It is an effective tool for understanding and analyzing research trends in various areas of study, allowing the identification of articles, authors, journals, countries, and their connections in published research addressing a particular topic [12]. Bibliometric indicators are tools that help to quantify scientific production and evaluate the impact on the community. For bibliometric analysis, bibliographic information is needed. In general, it can be divided into bibliometric indicators of journals and authors (individual and collaborative). Investigations into the role of PGPR in pest and disease biocontrol have increased significantly, as demonstrated by an increase in the number of studies conducted between 2000 and 2019 [11]. An analysis of 6056 publications extracted from the Web of Science Core Collection (WoSCC) between 2012 and 2021 highlights the prevalence of topics such as PGPR, biocontrol, and phytoremediation in agricultural research. These microorganisms, linked with concepts of “microbial interactions” and “sustainability”, are playing a crucial role in the adoption of ecological approaches to more sustainable agriculture [13]. In particular, *Bacillus*, *Pseudomonas,* and *Rhizobium* have established themselves as key genera in the development of biofertilizers and biocontrol agents. Bibliometric analysis of 875 and 3242 articles in WoSCC on how PGPR shows a pattern of sustained growth, driven by global concern for sustainability and food security. In addition, the increase in publications related to salinity tolerance and microbial interactions in agricultural environments confirms the preference for biological approaches to abiotic stress management. These findings reinforce the importance of continuing to investigate the interactions between PGPR and environmental stress conditions to develop more effective and sustainable strategies in modern agriculture [14,15]. A Google Scholar search with the terms rhizosphere, microorganisms, control, pests, and diseases showed that the number of records increased from 5000 (2000–2005) to 8500 (2006–2010) to more than 20,000 (2011–2019) [11]. Lahlali et al. [1] obtained a total of 1150 papers using the terms rhizobacteria, endophytes, and biocontrol agents in the SCOPUS database in the year 2021. Therefore, it is essential to highlight the relevance and novel contribution of this study, as well as its usefulness to the scientific community. Bibliometric analysis on the role of PGPR as biocontrol agents is a key tool to identify current and future trends in the development of sustainable alternatives to the use of agrochemicals. This type of analysis facilitates the identification of the most outstanding publications, the main scientific collaboration networks, and the most innovative strategies to control plant diseases by means of beneficial microorganisms. In addition, it allows guiding new research, detecting knowledge gaps, and promoting sustainable practices in integrated crop management. Therefore, this study provides a comprehensive overview of progress in this field and a solid basis for decision-making in agricultural research and policy. In the last two decades, researchers have been studying the use of antagonistic microorganisms specialized in the biocontrol of soil-borne diseases to reduce the use of pesticides. Given the above, the objective of this research was to perform a bibliometric analysis and systematic review of the scientific production regarding plant growth-promoting rhizobacteria as biocontrol agents in the period 2019–2023.

2. Materials and Methods

2.1. Bibliometric Analysis

The methodology for the present descriptive/retrospective study was to perform a bibliometric analysis and systematic review of the scientific literature from the Web of Science core collection [WoS; (A&HCI, ESCI, SCI-EXPANDED, SSCI)] on PGPR as biocontrol agents. The advanced search used was (TS = (PGPR OR "plant growth-promoting rhizobacteria" OR "plant growth promoting rhizobacteria" OR "rhizosphere bacteria" OR rhizobacteria)) AND TS = ("biocontrol agent*" OR biocontrol OR biocontrol OR bio-control OR "biological control"). Terms were searched for in titles, abstracts, and keywords. Data were collected on 27 December 2023. The documents resulting from the search were exported in tab-delimited text files (TXT) using Windows, with the content of complete dossiers.

The text files were first imported into Harzing's Publish or Perish 8.0 software. The following variables were identified: total scientific productivity, citations, average citations per year, average citations per publication, average citations per author, average citations per author per year, average number of articles per author, average number of authors per article, h-index, g-index, contemporary h-index (ch), individual h-index (hl), normalized hl index, AWCR index, AW index, e index, hm index, annual hl index, coverage H, and coverage G. The metric results obtained in Harzing's Publish or Perish 8.0 were saved in CSV format for Microsoft Excel®, making it possible to identify annual scientific productivity, number of citations, journals, type of documents, and most cited articles.

Second, the text files downloaded from WoS were imported into the VOSviewer 1.6.20 software, identifying the institutions involved in the publications through the analysis of co-authorship, with the metric "organizations". The countries involved in the research were verified through the analysis with VOSviewer by considering the co-authorship of the documents restricted to the countries. At least one publication was considered with the information obtained, and the data curation was carried out in Microsoft Excel. VOSviewer was used to create bibliometric maps with the main co-authorships between authors, co-occurrence of keywords per author, co-occurrence between keywords, and co-occurrence between countries. The figures for citations obtained by journals, countries, institutions, and authors were obtained by a VOSviewer co-occurrence analysis of citations with the unit of analysis of "documents". Finally, with the metrics of the descriptive analyses of the extracted documents, the annual growth rate, growth rate, duplication time, publication efficiency index of the countries, participation index of the institutions, collaboration index, degree of collaboration, and collaboration coefficient were calculated (Table 1).

Table 1. Indicators of scientific productivity calculated in this study.

Bibliometric Indicator	Description
Annual growth rate (AGR) [16]	$AGR = \left(\frac{NP_t - NP_{t-1}}{NP_{t-1}}\right) \times 100$ where NP_t = is the number of publications in the year t; and NP_{t-1} = is the number of publications in the year $t-1$.
Relative annual growth rate (RAGR) [17]	$RAGR = \left(\frac{In\ NP_2 - InNP_1}{t_2 - t_1}\right)$ where In = natural logarithm; NP_1 and NP_2 are the cumulative number of publications in the years t_2 and t_1; $t_2 - t_1$ = the difference between the final year and the initial year; here, the year can be taken as the unit of time.
Doubling time per year [17]	$DT = 0.693/TCR$ where $RAGR$ = relative annual growth rate.
Countries' publication efficiency index (PEI) [18]	$PEI = \frac{(TC_i/\sum TC)}{NP_i/\sum NP}$ where TC_i = the total number of citations for the country; $\sum TC$ = the total number of citations for all countries; NP_i = the total number of publications from the country i; and $\sum NP$ = the total number of publications from all countries.
Institutional participation index (IP)	$IP = \frac{the\ total\ number\ of\ publications\ by\ the\ institution}{total\ number\ of\ published\ documents} * 100$
Collaboration index, degree of collaboration, collaboration coefficient [19]	$Collaboration\ index = \frac{\sum_{j=1}^{A} jfj}{N}$ where j = the number of authors in a publication, i.e., 1, 2, 3. . .; fj = the number of j publications; N = the total number of publications in a year; and A = the total number of authors per publication.
	$degree\ of\ collaboration = 1 - \frac{f1}{N}$ $f1$= the number of publications by a single author; and N = total number of publications in a year.
	$collaboration\ coefficient = 1 - \frac{\sum_{j=1}^{A}\left(\frac{1}{j}\right)fj}{N}$ j = the number of authors in an article, i.e., 1, 2, 3. . .; fj = the number of j articles written; N = the total number of articles published in a year; and A = the total number of authors per article.

2.2. Systematic Review

After the bibliometric analysis, a systematic review was performed considering the 100 most cited original articles written in English in the period 2019–2023, using the aforementioned search terms. Articles indicating antibiotic and hydrocyanic acid (HCN) synthesis, siderophore and lytic enzyme production, and induced systemic resistance (ISR) as biocontrol mechanisms of PGPR against phytopathogens were included [20–22]. The data for each publication were tabulated using Microsoft Excel. Reproducibility criteria were ensured by the investigators independently applying the inclusion and exclusion criteria. Discrepancies were resolved by a third investigator (Table S1).

3. Results

3.1. Bibliometric Indicators

During the 17-year period concerning scientific publications on PGPR as biocontrol agents in WoS (2006–2023), a total of 2823 publications were identified, involving 11,277 authors, 484 journals, 7539 keywords, 106 countries, and 2583 organizations. The number of publications easily exceeded the threshold of 200 minimum publications required to perform a bibliometric analysis [23]. Regarding the language of the publications, English predominated (98.69%), followed by Portuguese (0.57%). The total number of publications accumulated 83,507 citations, equivalent to an average of 4912.18 citations per year and 29.58 citations per publication. In addition, an h-index of 115 was observed, indicating that 115 publications were cited at least 115 times, and a g-index of 206 was found (Table 2).

Table 2. Scientometric indicators of scientific production on PGPR as biocontrol agents.

Indicator	Result
Document	2823
Citations	83,507
Years	17
Citations/year	4912.18
Citations/articles	29.58
Citations/authors	24,423.29
Citations/authors/year	1436.66
Articles/author	695.76
Authors/article	5.26
h-index	115
g-index	206
ch index	96
hl index	25.53
Normalized hl index	54
AWRC	14,451.66
AW Index	120.22
e index	143.91
hm index	67.89
Annual hl index	3.18
Coverage H	40.6
Coverage G	51.1

3.2. Scientific Productivity and Citations

Figure 2 shows the annual distribution of publications and the number of citations related to PGPR as biocontrol agents. It highlights the upward trend of publications over the last 17 years (2006–2023). The productivity presented a polynomial increase ($y = 0.9032x^2 - 2.0883x + 70.738$) with an $R^2 = 0.89$, which indicates that the model presented an excellent fit. The input variable (years) explained 89% of the variation between publications. All years within the period 2006–2023 presented at least 40 publications related to the topic of this study. It should be noted that in 2019 (214 publications), there was an increase in the number of publications compared to the previous year (169 publications), whereas 2023 experienced a decrease in scientific production. The mean annual production was 156.72 publications, with a range of 292, a standard deviation of 88.49, and a coefficient of variation of 56.46%. Of the total number of publications, 1407 of them received more than 10 citations, representing 49.84% of the total number of publications. The year with the highest number of citations was 2009, with 8438 citations and an average of 80.36 citations per publication, and the year with the lowest number of citations was 2023, with 318 citations, that is, 1.23 citations per publication. It is worth mentioning that, as time goes by, publications have a lower number of citations (Figure 2). It is worth noting that, over time, publications tend to accumulate fewer citations, which could be a natural consequence of newer research being less cited initially or a shift in focus towards emerging topics with a different citation dynamic.

The results of scientific production in five-year blocks showed an increase between 2016–2020 (978) and 2021–2025 (907), representing 66.77% of the total number of publications. In the first five years, 2006–2010, 392 publications were recorded, yet this period had the highest number of citations, with a total of 26,612 citations. This suggests that older publications are likely to receive a higher number of citations. Therefore, publications published after 2010 will be able to accumulate citations over time. The highest citation rate of 88.46% was observed for publications from 2011 to 2015, while the lowest (68.80%)

was for the years 2021–2025. During the years 2016–2020, an average of 195.6 publications per year was maintained, surpassing the rest of the five-year blocks (Table 3).

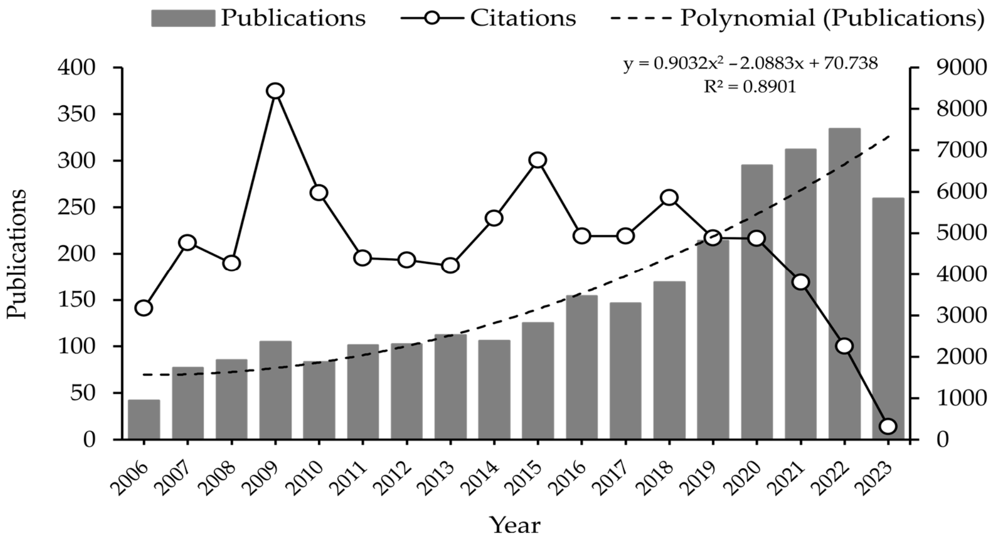

Figure 2. Evolutionary trend of the number of publications (n = 2823) and citations (83,507) on PGPR as biocontrol agents. ■ = publications, ○ = citations.

Table 3. Scientific productivity on PGPR as biocontrol agents in five-year blocks (n = 2823).

Year	TP	%NP	ACP	ACR	Cumulative TP	Accumulated TP	Total Citations
2006–2010	392	13.89	78.4	85.45	392	13.89	26,612
2011–2015	546	19.34	109.2	88.46	938	33.23	25,065
2016–2020	978	34.64	195.6	84.46	1916	67.87	25,468
2021–2025	907	32.13	181.4	68.80	2823	100.00	6362

TP = total publications, %NP = percentage of number of publications, ACP = average citation of publications, ACR = average citation rate (percentage of articles that have one or more citations).

3.3. *Typology of Publications*

Table 4 shows the five different typologies highlighted for articles on PGPR as biocontrol agents during the last 17 years. Of the total publications, 2482 (87.92%) are research articles and 381 (11.26%) are reviews. Together these publications have been cited 83,449 times. Other types of documents accounted for less than 1% of the total publications. In terms of average citations per publication, the highest value was recorded for review publications, with 318 publications and 28,399 citations, representing 89.31 average citations per publication, followed by articles with 2482 publications, 55,040 citations, and 22.18 average citations per publication.

Table 4. Typology of scientific productivity on PGPR as biocontrol agents.

Typology	Total Publications	Total % of Publications	Total Citations	Total % of Citations	Average Citations per Publication
Article	2482	87.92	55,040	65.91	22.18
Review	318	11.26	28,399	34.01	89.31
Correction	8	0.28	14	0.02	1.75
Editorial material	5	0.18	47	0.06	9.40
Meeting abstract	10	0.35	7	0.01	0.70

3.4. Annual Growth Rate of Publications

The annual growth rate (AGR) of total publications fluctuated from −22.46 to 83.33% throughout the study period. The reason for the fluctuation is that there is no constant growth each year. The AGR registered a growth trend of 83.33% in 2007; however, it decreased to 10.39% in 2008. The AGR was positive for the years 2007–2009, 2011–2013, 2015, 2016, and 2018–2022 with a fluctuation between 0.99 and 83.33%, while 2010, 2014, 2017, and 2023 registered negative AGR, ranging from −22.46 to −5.36%. It should be noted that no year presented a neutral AGR, indicating that at least one publication was recorded in the period 2006–2023. The years 2007 and 2020 presented the highest AGR, with 83.33% and 37.85%, respectively, while 2010 (−20.95%) presented the lowest negative AGR (Figure 3).

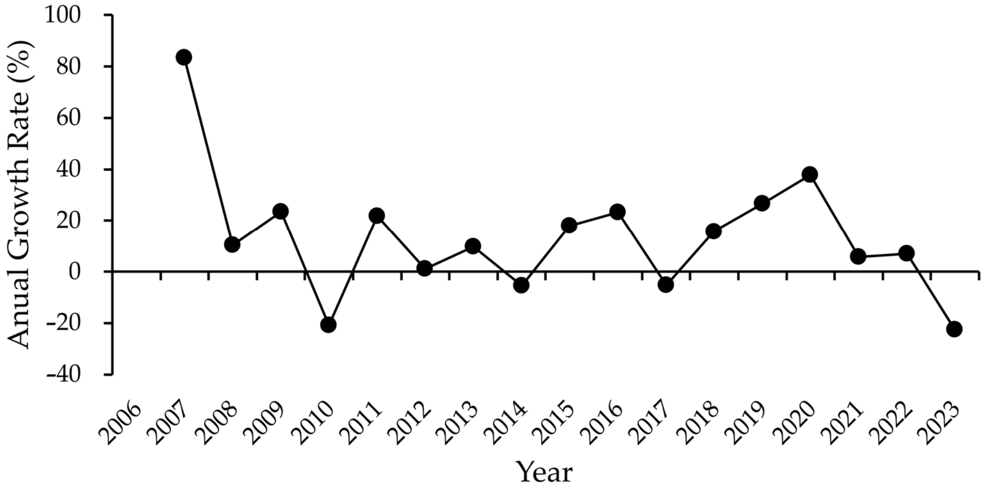

Figure 3. The annual growth rate of PGPR as biocontrol agents.

3.5. Relative Growth Rate and Annual Doubling Time

The growth rate of all publications was measured on the basis of the relative annual growth rate (RAGR) and doubling time (DT) model. RAGR was calculated to analyze the increase in the number of publications per unit time, and TC (total citations) is related to RAGR. The RAGR started at 1.04 in 2007 and reached 0.10 in 2023. It denotes a decreasing trend in the number of publications on PGPR as biocontrol agents per unit time (Figure 4).

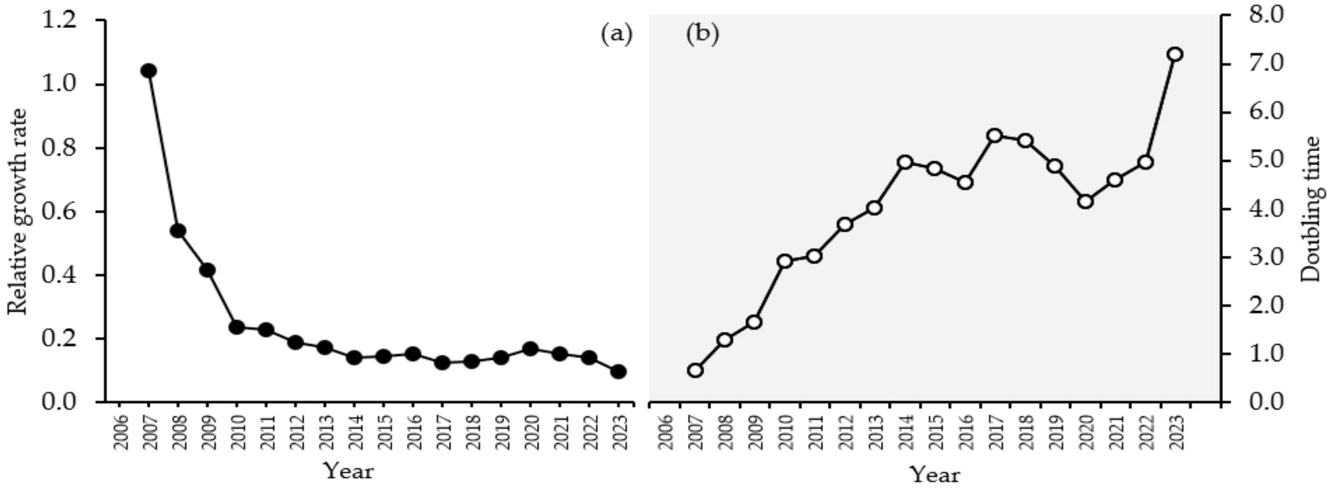

Figure 4. (**a**) Relative growth rate and (**b**) doubling time of publications on PGPR as biocontrol agents. ● = doubling time, ○ = relative growth rate.

The RAGR was not stable during the study period. The RAGR for the years 2007–2009 was the highest (mean value 0.67), and from 2020 to 2023 it decreased from 0.17 to 0.10. This means that the number of publications decreased. In contrast, the DT increased from 0.67 in 2007 to 1.26 in 2008. The DT for the publications at the aggregate level was 4.02 years. It could be argued that, in general, there is a progressive increase in the number of publications. However, the RAGR shows a downward trend, which means that the rate of increase is proportionally low, and this is highlighted by the DT, which is higher than the RAGR (Figure 4).

3.6. Influential Research Journals

In the present bibliometric analysis, the 2823 publications were published in 484 journals indexed in WoS. The analysis includes the 15 most productive journals that published 890 (31.53%) of the total publications. The publications in these 15 prolific journals have been cited 26,985 (32.14%) times, out of the total citations (83,507). The remaining 469 journals together produced 1933 (68.47%) publications and received 56,955 (67.77%) citations in the period 2006–2023 (Table 5).

Table 5. Top ten most productive scientific journals on PGPR as biocontrol agents.

Journal	TP	TC	ACP	ACR	SJR	IF 2022	Country
Biological Control	127	4326	34.06	89.76	0.9	4.2	United States
Frontiers in Microbiology	123	4241	34.48	71.54	1.19	5.2	Switzerland
Frontiers in Plant Science	80	2543	31.79	66.25	1.23	5.6	Switzerland
Microorganisms	62	969	15.63	69.35	0.9 1	4.5	Switzerland
Microbiological Research	58	3041	52.43	86.21	1.17	6.7	Germany
Biocontrol Science and Technology	53	739	13.94	86.79	0.45	1.4	United Kingdom
Plants-Basel	52	528	10.15	65.38	0.76	4.5	Sweden
European Journal of Plant Pathology	51	1474	28.90	76.47	0.53	1.8	Netherlands
Plant and Soil	47	3410	72.55	76.60	1.15	4.9	Netherlands
World Journal of Microbiology and Biotechnology	45	1123	24.96	75.56	0.73	4.1	Netherlands
Applied Soil Ecology	44	1385	31.48	90.91	1.15	4.8	Netherlands
Journal of Applied Microbiology	40	1564	39.10	82.50	0.77	4.0	United States
Crop Protection	38	967	25.45	78.95	0.71	2.8	United Kingdom
Egyptian Journal of Biological Pest Control	36	393	10.92	75.00	0.59	2.4	Egypt
Rhizosphere	34	282	8.29	73.53	0.68	3.7	Netherlands

TP = total publications, TC = total citations, ACP = average citation of publications, ACR = average citation rate (percentage of articles with one or more citations), SJR= SCImago Journal Rank, IF = impact factor 2022.

The journal *Biological Control* (ISSN: 1049-9644) from the United States was the most productive with 127 (4.50%) articles and 4326 (5.18%) citations. It is published by Elsevier® in the subject areas of agricultural and biological sciences: insect science, agronomy, and crop science. The second most productive journal was *Frontiers in Microbiology* (ISSN: 1664302X) from Switzerland. It resulted in 123 publications, 4241 citations, and 34.46 average citations per publication in the subject areas of immunology, microbiology, and medical microbiology. The journal *Microbiological Research* from Germany contributed 58 publications, 3041 citations, 52.43 average citations per publication, and a citation rate of 86.21% (50 publications with at least 1 citation). Thus, it had the highest impact factor (6.7), followed by *Frontiers in Plant Science* from Sweden, with 80 publications, 2543 citations, 31.79 average citations per publication, and a citation rate of 66.25% (Table 5).

3.7. Countries

The 2823 publications on PGPR as biocontrol agents were published in 106 countries. India is the leading country with the highest number of publications (540), with

16,082 citations and 29.78 average citations per publication during the period 2006–2023. China ranks second with 434 publications, 10,847 citations, and 29.78 average citations per publication, followed by the USA in third place with 219 publications, 10,455 citations, and 47.74 average citations per publication. The 15 most productive countries accounted for 67.98% of the publications and 63.87% of the total citations. The countries with the highest average citations were France with 75.56 in 68 publications, Germany with 61.26 in 104 publications, the United States with 47.74 in 219 publications, and Canada with 40.21 in 73 publications. Mexico is in 10th place, with 87 publications and 2577 citations, which represents an average of 29.62 citations. It is worth mentioning that the total number of publications according to contributing countries is 3489, surpassing 2823, which indicates that there were collaborative publications between different countries (Table 6).

Table 6. Publication efficiency index of the publications of the most productive countries on PGPR as biocontrol agents.

Ranking	Country	TP	TC	ACP	PEI
1st	India	540	16,082	29.78	0.84
2nd	China	434	10,847	24.99	0.71
3rd	USA	219	10,455	47.74	1.35
4th	Pakistan	150	5015	33.43	0.95
5th	South Korea	147	4414	30.03	0.85
6th	Brazil	122	2748	22.52	0.64
7th	Germany	104	6371	61.26	1.73
8th	Egypt	102	2118	20.76	0.59
9th	Italy	98	3469	35.4	1.00
10th	Mexico	87	2577	29.62	0.84
11th	Spain	83	3153	37.99	1.08
12th	Iran	77	1912	24.83	0.70
13th	Canada	73	2935	40.21	1.14
14th	France	68	5138	75.56	2.14
15th	Saudi Arabia	68	1467	21.57	0.61
	Others	1117	44,510	39.85	1.13
	Total	3489	123,211	35.31	

TP = total publications, TC = total citations, ACP = average citation of publications, PEI = publication efficiency index.

The publication efficiency index (PEI) is a measure of the quality of research, indicating whether the impact of publications in a given country and given field of research is consistent with the amount of research devoted to that field. A PEI value greater than 1 for a country suggests that the impact of its publications is greater than the amount of research devoted to them in that country, and vice versa. This index is calculated by dividing the percentage of citations by the percentage of publications.

Countries such as the United States, Germany, Italy, Spain, Canada, and France had PEIs of greater than 1, which indicates that the impact of their publications exceeds their own percentage of publications. Meanwhile, in the rest of the countries, the impact of their publications is less than the percentage of publications (Table 6).

3.8. Institutions

Although 3 of the 15 most productive institutions were in India, the outstanding productivity of five institutions from China points to a significant leadership in publications on PGPR as biocontrol agents. Nanjing Agricultural University with 71 publications and the Chinese Academy of Agricultural Sciences with 44 publications occupy the top two positions in terms of total publications. Nanjing Agricultural University also has the highest total number of publications, average citation index (47.79), and productivity index (2.52) (Table 7). Therefore, it produces a large amount of research that tends to be frequently cited, indicating a great scientific impact. Institutions such as Auburn University of the United States, with 38 publications, 1913 citations, and 50.34 average citations per publication, followed by the University of Agriculture, Faisalabad of Pakistan, with 35 publications, 1372 citations, and 39.20 average citations per publication, are also well positioned in terms of total publications and citations (Table 7). This reflects the diversity of PGPR research and the significant contributions of institutions from different regions of the world. Accordingly, it is important to evaluate not only the quantity of publications but also the quality and impact of research in a specific area, as some institutions may have more publications while others may have a more concentrated and significant impact in terms of the average citation index.

Table 7. Most productive institutions on PGPR as biocontrol agents.

Ranking	Institution	TP	TC	ACP	PI	Country
1st	Nanjing Agricultural University	71	3393	47.79	2.52	China
2nd	Chinese Academy of Agricultural Sciences	44	975	22.16	1.56	China
3rd	North-West University	41	1347	32.85	1.45	South Africa
4th	Auburn University	38	1913	50.34	1.35	United States
5th	University of Agriculture, Faisalabad (UAF)	35	1372	39.20	1.24	Pakistan
6th	Tamil Nadu Agricultural University	34	1260	37.06	1.20	India
7th	Chinese Academy of Sciences	31	772	24.90	1.10	China
8th	King Saud University	30	801	26.70	1.06	Saudi Arabia
9th	Banaras Hindu University	29	1136	39.17	1.03	India
10th	Aligarh Muslim University	27	604	22.37	0.96	India
11th	China Agricultural University	26	419	16.12	0.92	China
12th	Agriculture and Agri-Food Canada	22	817	37.14	0.78	Canada
13th	Russian Academy of Sciences	21	626	29.81	0.74	Russia
14th	Kyungpook National University	20	555	27.75	0.71	South Korea
15th	Shandong Agricultural University	20	403	20.15	0.71	China

TP = total publications, TC = total citations, ACP = average citation of publications, PI = productivity index.

3.9. Pattern of Authorship

According to the analysis of authorship in relation to PGPR as biocontrol agents, a total of 11,200 authors were registered. The 15 authors with more than 12 publications are shown in Table 8. These 15 authors represent 10.34% of the total number of publications, with a total of 292 publications, and have received 16.76% of the citations, with a total of 14,001. The main authors with more than 30 publications were Kloepper, J. W. (Auburn University, United States) with 31 publications, 1581 citations, and 51 average citations per publication, and Babalola, O. O. (North-West University, South Africa), with 38 publications, 1287 citations, and 33.87 ACP. The author Shen, Qirong (Nanjing Agriculture University, China) with 25 publications had the highest h-index with a value of 105, followed by Berg, Gabriele (Universitat Potsdam, Germany) with 19 publications and an h-index of 83. This indicates that the number of research projects related to PGPR mainly comprises a small number of authors. This can be observed with a productivity index of Lotka > 1, resulting in a high level of productivity (>10 publications) by 32 authors, representing 0.28% of the total number of authors. Of the authors, 9191 (81.50%) belong to the group of small producers (Table 9). This suggests the need for further international research and collaboration to address current challenges in the use of PGPR as biocontrol agents and to promote agricultural sustainability.

Table 8. Authors with more publications on PGPR as biocontrol agents.

Author	TP	TC	ACP	h-index	Lotka Productivity Index Log(n)	Country
Babalola, O. O.	38	1287	33.87	47	1.6	South Africa
Kloepper, J. W.	31	1581	51.00	76	1.5	United States
Shen, Qirong	25	1224	48.96	105	1.4	China
Ryu, Choong-Min	22	957	43.50	57	1.3	South Korea
Guo, Jian-Hua	20	790	39.50	39	1.3	China
Berg, Gabriele	19	2701	142.16	83	1.3	Germany
Borriss, Rainer	18	1247	69.28	59	1.3	Germany
Sang, Mee Kyung	17	355	20.88	23	1.2	South Korea
Ongena, Marc	16	561	35.06	42	1.2	Belgium
Naveed, Muhammad	15	214	14.27	45	1.2	Pakistan
Samiyappan, R.	15	961	64.07	45	1.2	India
Santoyo, Gustavo	15	465	31.00	32	1.2	Mexico
Hassan, Muhammad Nadeem	14	435	31.07	23	1.1	Pakistan
Kim, Ki Deok	14	325	23.21	28	1.1	South Korea
Gao, Xuewen	13	898	69.08	31	1.1	China

TP = total publications, TC = total citations, ACP = average citation of publications.

Table 9. Lotka index of authors of publications on PGPR as biocontrol agents.

Productivity Level	Number of Publications	Authors	% of Authors
Major producers	10 or more	32	0.28
Medium producers	2 to 9	2054	18.21
Small producers	1	9191	81.50

In addition to the above, publications written by only one author were the least frequent, making up 54 (1.91%) of the total. Articles written by four and five authors were more significant, reaching 463 (16.40%) and 450 (15.94%), respectively. Publications with four authors stood out in relation to the number of citations, accumulating a total of 14,713, which represents 17.62% of the total number of citations. This indicates that publications with four or five authors may be of higher quality and, therefore, attract a higher number of citations compared to those with six or more authors (Figure 5).

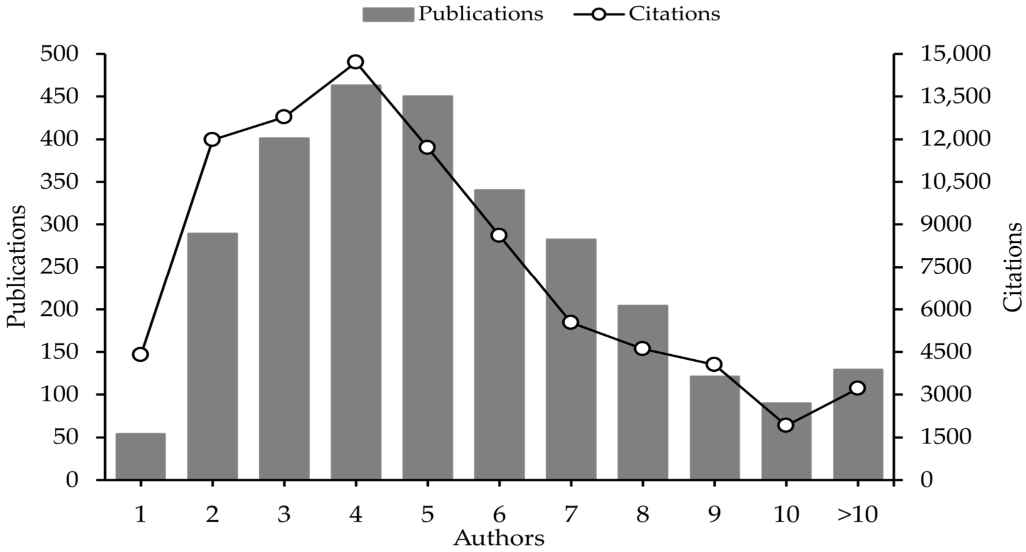

Figure 5. Pattern of authorships and citations received on PGPR as biocontrol agents. ■ = publications, ○ = citations.

3.10. Collaboration Index, Degree of Collaboration, and Collaboration Coefficient

The collaboration index (CI) is the average number of authors per publication. Table 10 shows that the average CI was 5.17, and the highest index was recorded in the period 2021–2025 with 6.12, followed by the years 2016–2020 with 5.48, while the lowest was for 2006–2010 with 4.19, so the research teams are generally between four and six authorships in the field of PGPR as biocontrol agents. The CI increased over time, suggesting that the trend of publications is proportional to the increase in authorships in collaborative publications. The degree of collaboration (DC) was shown to be between 0.96 and 0.99 during the study period as a whole. It was determined that the DC increased, indicating that co-authored publications increased. The collaboration coefficient (CC) was 0.69 (2006–2010) and 0.79 (2021–2025), both higher than 0.5, indicating multiple collaborations among authors. In general, co-authorships were 0.75; therefore, there was greater collaboration between authors in the last five-year block (2021–2025).

Table 10. Several publications on PGPR as biocontrol agents are distributed according to the number of authors and the period.

Years	NP	Single Author Publication	Multiple Author Publication	Total No. of Authors of Total Joint-Authored Publications	Total No. of Single-Authored Authors	Total No. of Authors	CI	DC	CC
2006–2010	392	16	376	1627	16	1643	4.19	0.96	0.69
2011–2015	546	12	534	2666	12	2678	4.90	0.98	0.74
2016–2020	978	16	962	5345	16	5361	5.48	0.98	0.76
2021–2025	907	10	897	5537	10	5547	6.12	0.99	0.79

NP = number of publications, CI = collaboration index, DC = degree of collaboration, CC = collaboration coefficient.

3.11. Most Cited Publications

Table 11 shows the most cited publications on PGPR as biocontrol agents, with a total of 13,220 citations. It is worth mentioning that 87.66% of the documents are reviews. The average number of citations of the most cited publications was 881, with a range of 501 to 2137. The review article “Plant-growth-promoting rhizobacteria” by Lugtenberg and Kamilova [24] published in the *Annual Review of Microbiology* registered 2137 citations. This publication presents the beneficial effects of PGPR on plant growth through direct and indirect mechanisms. The direct mechanisms were (i) biofertilizers, (ii) stimulation of root growth, (iii) rhizoremediation, and (iv) control of plant stress. The indirect mechanisms were (i) disease reduction, (ii) antibiosis, (iii) induction of systemic resistance, and (iv) competition for nutrients and niches. The review article “Modulation of host immunity by beneficial microbes” by Zamioudis and Pieterse [25] at the bottom of the list received 501 citations. These authors indicate how beneficial soil microorganisms, symbiotic and non-symbiotic, modulate the plants’ immune systems. The countries of France (3), the United States (3), and Pakistan (2) participated with the highest number of most cited publications. Citation analysis makes it possible to identify the most cited and relevant publications in a given area of study. When an article receives a higher number of citations, it is considered to have a more significant influence on a specific topic than other less-cited articles.

Table 11. Most cited publications on PGPR as biocontrol agents.

Title	Source	Year	Citations	Country/ies	Type	Reference
Plant-growth-promoting rhizobacteria	*Annual Review of Microbiology*	2009	2137	Netherlands	Review	Lugtenberg and Kamilova [24]

Table 11. *Cont.*

Title	Source	Year	Citations	Country/ies	Type	Reference
Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation	*Saudi Journal of Biological Sciences*	2015	1260	India	Review	Shrivastava and Kumar [26]
Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization	*Soil Biology and Biochemistry*	2010	1183	Austria and France	Review	Compant et al. [27]
Plant biostimulants: definition, concept, main categories and regulation	*Scientia Horticulturae*	2015	1141	Belgium	Article	du Jardin [28]
Soil beneficial bacteria and their role in plant growth promotion: a review	*Annals of Microbiology*	2010	1041	Pakistan	Review	Hayat et al. [29]
Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture	*Applied Microbiology and Biotechnology*	2009	908	Austria	Review	Berg [30]
Plant growth-promoting rhizobacteria and root system functioning	*Frontiers in Plant Science*	2013	744	France	Review	Vacheron et al. [31]
Plant-driven selection of microbes	*Plant and Soil*	2009	676	Germany, Austria, and France	Review	Hartmann et al. [32]
Plant growth-promoting rhizobacteria PGPR: their potential as antagonists and biocontrol agents	*Genetics and Molecular Biology*	2012	669	Brazil	Review	Beneduzi et al. [33]
Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils	*Biotechnology Advances*	2011	654	Portugal, India, and Japan	Review	Ma et al. [34]
Root-secreted malic acid recruits beneficial soil bacteria	*Plant Physiology*	2008	642	United States	Article	Rudrappa et al. [35]
Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013)	*Plant and Soil*	2014	579	Mexico, USA, and Canada	Review	Bashan et al. [36]
Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media	*Plant and Soil*	2010	563	Israel	Article	Graber et al. [37]
The role of mycorrhizae and plant growth promoting rhizobacteria (pgpr) in improving crop productivity under stressful environments	*Biotechnology Advances*	2014	522	Pakistan	Review	Nadeem et al. [38]
Modulation of host immunity by beneficial microbes	*Molecular Plant–Microbe Interactions*	2012	501	United States	Review	Zamioudis and Pieterse [25]

3.12. Co-Authorship Network

Figure 6 shows the network of authors who participated in at least 10 publications on PGPR as biocontrol agents. The network records the relationships between the authors and the number of publications that they co-authored. The number of publications is indicated by the node size. Co-authorships between specific authors and other authors are indicated by connecting links with different colors symbolizing the collaboration groups, and the strength of a link shows the level of the relationship. A total of 11,277 authors were recorded to have participated in the publications of PGPR papers as biocontrol agents, of which 32 authors have published at least 10 publications. Four main co-authorship networks were recorded. Borriss, R., Gao, X., and Wu, H. (cluster 1, red), participated in five publications, reaching 269 citations [39–43]. As a result, the Nanjing Agricultural University of China affiliation of Gao, X. and Wu, H. is among the most important in terms of the number of publications. The most recent article co-authored by Borriss, R., Gao, X., and Wu, H. was in 2023. It was entitled “Profiling of antimicrobial metabolites synthesized by the endophytic and genetically amenable bio-control strain *Bacillus velezensis* DMW1” and published in the journal *Microbiology Spectrum* ISSN: 2165-0497. It aimed to identify and characterize the endophytic bio-control bacterium DMW1 and explore the mechanisms underlying its effect on plant growth promotion and disease control [37]. Likewise, the collaboration of the authors Babalola, O. O., Glick, B. R., and Santoyo, G. (cluster 2, green) positioned them as the authors with the highest number of publications. Babalola, O. O., affiliated with North-West University, South Africa, had a link strength of 5, with 38 publications and 1287 citations, and Santoyo, G., affiliated with Universidad Michoacana de San Nicolás de Hidalgo, Mexico, had a link strength of 5, with 15 publications and 465 citations. The final two most important clusters consisted of the authors Kim, K. D., Park, K., and Sang, M. K. (cluster 3, blue), with a link strength of 32, and Moenne-Loccoz, Y., Ongena, M., and Prigent-Combaret, C., with a link strength of 18 (cluster 4, yellow).

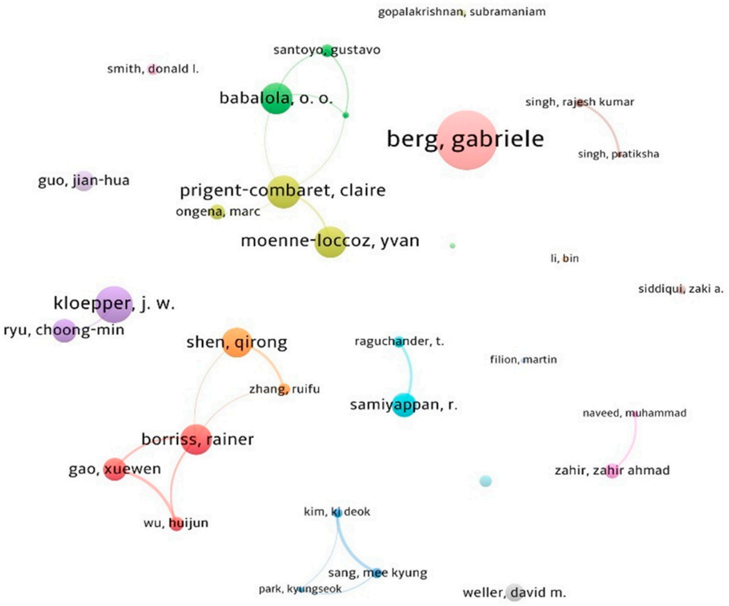

Figure 6. Co-authorship network of the most cited authors with at least 10 publications on PGPR as biocontrol agents, made in VOSviewer. The size of the circles indicates the relevance of each author, while the colors represent research groups with high interaction. The lines reflect co-authorship, where their thickness indicates the frequency of collaboration and their length indicates the closeness in the scientific network.

3.13. Analysis of Authors’ Keywords

Keywords are essential in order to summarize publications’ central themes, and their co-occurrence is used to detect novel areas of research. In the present study on PGPR as biocontrol agents, 4730 keywords were identified, of which 169 showed at least 10 co-occurrences. The keywords with the highest frequency were biocontrol (519 co-occurrences, link strength of 1075), PGPR (384 co-occurrences, link strength of 774), biological control (339 co-occurrences, link strength of 596), rhizobacteria (219 co-occurrences, link strength of 441), plant growth-promoting rhizobacteria (137 co-occurrences, link strength of 243), rhizosphere (123 co-occurrences, link strength of 270), *Bacillus* (117 co-occurrences, link strength of 301), *Pseudomonas* (109 co-occurrences, link strength of 284), and plant growth promoting (107 co-occurrences, link strength of 217) (Figure 7a). Previously used keywords in the publications are shown in purple, while more recent keywords are shown in yellow. Previous keywords include *Bacillus cereus*, *Bacillus megaterium*, *Bacillus pumilus*, *Pseudomonas fluorescens*, *Paenibacillus polymyxa*, *Rhizobium*, and *Trichoderma harzianum* as biocontrol agents for nematodes as well as *Meloidogyne incognita*, *Meloidogyne javanica*, *Phytophthora capsici*, *Rhizoctonia solani*, *Sclerotium rolfsii*, *Ralstonia solanacearum*, and *Botritis cinérea* in tomato (*Lycopersicum esculentum*), chili (*Capsicum annuum*), and potato (*Solanum tuberosum*) crops. This indicates that publications of various PGPR in horticultural crops were for the control of root phytopathogens (Figure 7b). However, recent keywords were sustainable agriculture, abiotic stress, biotic stress, bioinoculants, biofertilizers, microbial inoculants, plant growth-promoting bacteria, secondary metabolites, phytopathogens, microbial diversity, and bioremediation. This indicates that these topics are of growing interest and are critical points in researching PGPR as biocontrol agents. In addition to the above, the size of the nodes and their central or peripheral position allow us to appreciate the relationships of a keyword with others. The edges of the network of co-occurrences of recent keywords indicate knowledge gaps or topics where more research is needed. In the network of keywords in this study, it is shown that topics related to environmentally friendly PGPR-based bioproducts should be addressed. These topics include biopesticides, biofertilizers, bioinoculants, bioremediators, and biostimulants, which can be used to reduce or mitigate the negative effects of the application of synthetic fertilizers or pesticides (Figure 7b).

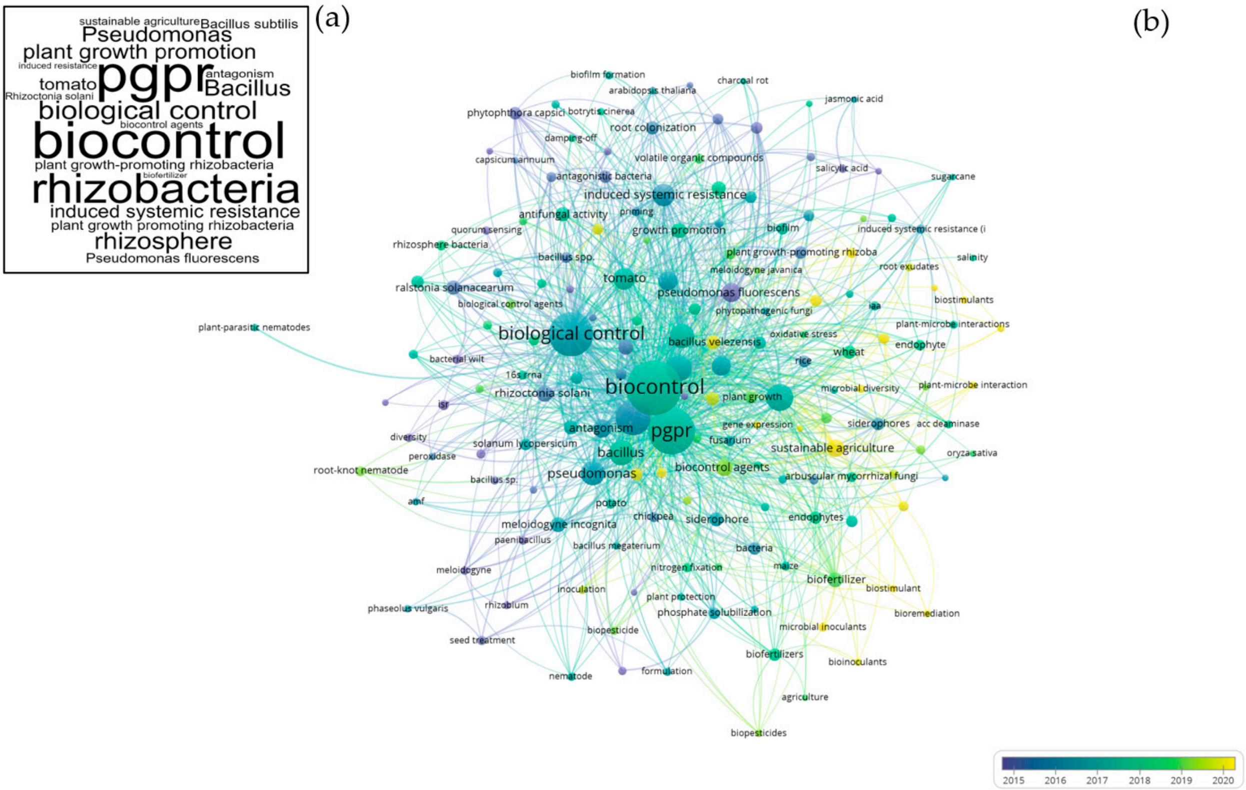

Figure 7. (**a**) Cloud of the 20 keywords with the highest co-occurrences, and (**b**) network of keywords per author with at least 10 co-occurrences on PGPR as biocontrol agents, made in VOSviewer.

3.14. Co-Authorship Network Across Countries

It is important to note that the thicker the lines in a network of co-authorships between two countries, the more collaborations they have had with each other. The distance between the circles indicates the strength of the link and the similarity between the countries' publications. Furthermore, the presence of several countries of the same color indicates that they have had higher levels of collaboration, forming the clusters. In the present study, a total of 106 countries were found to have participated in publications on PGPR as biocontrol agents; however, only 66 of them were recorded in at least five papers, grouping them into six clusters (Figure 8). The size of the circle indicates the number of publications per country. India (yellow cluster) ranks first with 540 publications and 16,082 citations, as mentioned above, followed by China with 434 publications and 10,847 citations (turquoise cluster), Brazil with 122 publications and 2748 citations (red cluster), Italy with 98 publications and 3469 citations (green cluster), Iran with 77 publications and 1912 citations (blue cluster), and Canada with 73 publications and 2935 citations (violet cluster) (Figure 8).

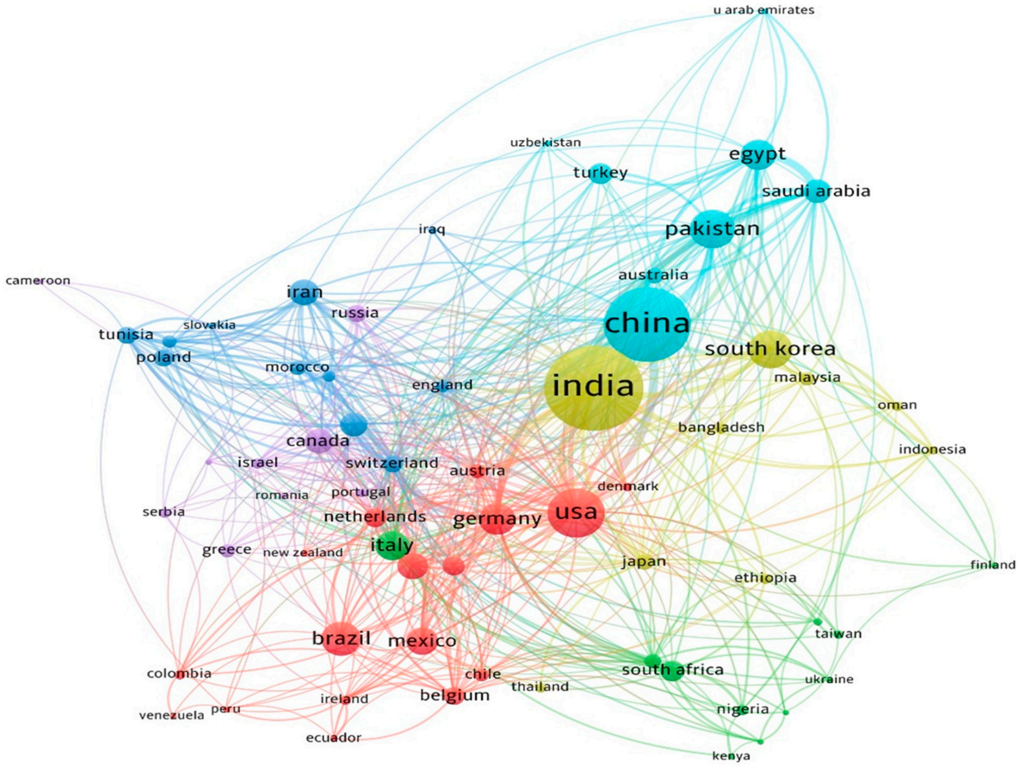

Figure 8. Co-authorship network across countries with at least 5 publications on PGPR as biocontrol agents, made in VOSviewer.

The first yellow cluster with publications in common is made up of 10 countries, including India, South Korea, Japan, Malaysia, Indonesia, Thailand, and Ethiopia. The second cluster, in turquoise, consisted of eight countries, including China, Pakistan, Turkey, Australia, and Egypt. The third cluster, in red, was made up of 18 countries, including Brazil, the United States, Germany, Mexico, Belgium, and Austria. The fourth cluster in purple was made up of nine countries, such as Canada, Portugal, Israel, Greece, Serbia, and Russia. The fifth cluster, in green, was made up of 11 countries, including Italy, South Africa, Nigeria, Taiwan, Ukraine, and Kenya. The sixth cluster, in blue, grouped 11 countries, such as Iran, England, Poland, Switzerland, and Morocco (Figure 8).

4. Discussion

Despite the promising potential of PGPR as biocontrol agents, their widespread implementation in agriculture faces multiple challenges. One of the main drawbacks is the variability in their efficacy, influenced by factors such as geographical location, soil characteristics, host crop species, and environmental conditions. Several studies have indicated that the effectiveness of PGPR is usually evaluated in controlled environments, such as greenhouses, which do not always accurately represent field conditions, where adverse environmental factors can affect their performance. Another important challenge is the stability of PGPR formulations during transport and storage, which requires the development of advanced formulation technologies to improve their shelf life and maintain the viability of these beneficial microorganisms. The use of PGPR represents a key opportunity to deepen our knowledge of beneficial microorganisms and their ability to optimize crop development, strengthen resistance to disease and abiotic stress, and improve the nutritional quality of food. Ongoing research on PGPR-based biostimulants contributes to our understanding of soil fertility within a sustainable agricultural production approach. The results of the 100 most cited articles on the use of PGPR as biocontrol agents strengthen the hypothesis that biocontrol under in vitro or in situ conditions is a sustainable method for combatting plant pathogens in field conditions or productive agriculture. The use of PGPR or their metabolites demonstrates their potential to prevent and/or suppress diseases caused by phytopathogens, either in the root and/or foliar system, mitigating their adverse effects and promoting plant health.

The analysis of the scientific production on PGPR and bacterial consortia in the ScienceDirect database between 2017 and 2022 reveals a sustained increase in the number of publications. In 2017, 27 articles were registered, increasing to 34 in 2018, 65 in 2019, 95 in 2020, 126 in 2021, and 178 in 2022. This coincides with the present study's finding for the period 2021–2025 of 907 publications, representing 66.77% of the total number of publications. This trend indicates the scientific community's growing interest in PGPR research. During this period (2017 to 2022), research articles represented the highest proportion of publications (194), followed by book chapters (170) and review articles (108), while the rest corresponded to encyclopedias and other reports [44]. This is similar to that found in the present analysis of the total number of publications, in that 2482 (87.92%) are research articles and 381 (11.26%) are reviews. From the analysis of 6056 publications on rhizosphere microorganisms, reflecting the expansion of the scientific literature between 2012 and 2021 in the Web of Science Core Collection (WoSCC), key topics such as PGPR, biocontrol, and phytoremediation were identified. This evidence shows the fundamental role of these microorganisms in mitigating environmental stress and improving soil health. In addition, the emergence of terms related to "microbial interactions" and "sustainability" suggests a progressive integration of microbial ecology in agricultural applications. These results underline the importance of continuing to explore the action mechanisms of rhizosphere microorganisms in order to optimize their use in sustainable agriculture [18]. There was sustained growth in terms of publications about *Bacillus*-based biofertilizers as PGPR between 1985 and 2023 in WoSCC, reflecting a growing interest in their agricultural application. Of the 3242 articles retrieved, 91.8% corresponded to original research, with a three-phase growth pattern: a slow increase (1985–2002), a moderate acceleration (2003–2014), and a rapid growth (2015–2023). This increase can be attributed to people's growing preoccupation with "sustainability" and "food security". The keyword analysis reinforces this trend, with 6453 terms identified and 42 mentioned more than 30 times. Terms such as "PGPR", "biofertilizer", and "plant growth" highlight the relevance of *Bacillus* in promoting plant development. Likewise, the frequency of "microbial community" and "biological control" underlines its role in soil ecological stability. These findings emphasize the importance of continuing to investigate the impact of *Bacillus* in sustainable agriculture [14].

Ma et al. [15] reported a significant increase in scientific production related to PGPR, especially in the context of salt stress mitigation in agricultural soils. From the analysis of 875 papers extracted from WoSCC, an increasing preference for biological approaches to soil salinity management is evident, suggesting a paradigm shift in sustainable agriculture. This phenomenon is reflected in the keyword co-occurrence mapping, where concepts such as "halotolerant PGPR" emerge as key areas of interest along with widely studied bacterial genera such as *Pseudomonas*, *Rhizobium*, and *Bacillus*. This coincides with those found with the present analysis, where *Bacillus* had 117 co-occurrences and a link strength of 301, and *Pseudomonas* had 109 co-occurrences and a link strength of 284. These results reinforce the importance of continuing to explore the interactions between PGPR and abiotic stress conditions in order to develop more effective strategies to improve agricultural productivity in salinity-affected environments.

An analysis of 6940 publications in Scopus from 1992 to October 2023 on the role of PGPR in plant resilience to salinity and drought reveals a significant growth in academic output in recent years, with a prominent increase in 2023. Five main groupings were identified: techniques and effects of PGPR on plants, bacterial applications and phytosignaling, heavy metals and phytoremediation, induced systemic resistance, and salt stress. These groupings indicate the implications of PGPR in enhancing ISR and highlight the potential of these microorganisms to serve as biological agents in integrated pest management strategies, reducing our reliance on chemical inputs. In terms of practical implications, the findings may guide future research toward field trials that evaluate the efficacy of various PGPR strains in diverse soil types and climatic conditions. By understanding the specific mechanisms through which PGPR confers stress resistance, researchers can develop customized microbial inoculants that optimize plant growth and performance under adverse conditions [45].

Moreno-Espindola et al. [46] identified four key thematic focuses within the literature in Scopus and WoSCC on microbial genetic resources, including PGPR. The first, "soil microbiology and biofertilizers", focuses on methodologies and findings related to improving soil quality through microbial inoculation, highlighting sustainable agricultural practices in land management. The second group, dedicated to "endophytic bacteria, activities, and properties", addresses studies on bacteria inhabiting plant tissues and how they contribute to plant health and resistance, suggesting a promising avenue of research with great potential for agriculture. The third group, "the role of microbial agents in improving crop yield and resilience to abiotic stress", focuses on the use of microorganisms to strengthen plant defenses and improve plant productivity under adverse environmental conditions. The last group, "crop tolerance to abiotic stress mediated by microorganisms", examines the mechanisms by which certain soil microorganisms can increase plant resistance to extreme environmental conditions, thus favoring more sustainable agricultural practices. In addition to the aforementioned, the exploration of microbial biostimulants, particularly PGPR, presents promising avenues to improve the mobilization of macro- and micronutrients, which are crucial for plant health. The collaboration observed between several countries in advancing research on biostimulants indicates a global recognition of the benefits that these substances can offer. Countries such as Italy, Spain, and Brazil are at the forefront, amplifying collaborative efforts that could lead to innovative applications of biostimulants in various agricultural systems [47]. In the present study, India ranks first with 540 publications and 16,082 citations, followed by China with 434 publications and 10,847 citations, Brazil with 122 publications and 2748 citations, Italy with 98 publications and 3469 citations, Iran with 77 publications and 1912 citations, and Canada with

73 publications and 2935 citations. As the field of PGPR research continues to evolve, there are opportunities for further exploration. The use of bibliometric analysis can provide information on publication trends and the impact of PGPR studies. This approach allows researchers to identify influential journals, key authors, and emerging topics within the PGPR field, ultimately guiding future research efforts and fostering transdisciplinary collaborations. The large-scale implementation of PGPR in agriculture faces challenges related to inoculant formulation, commercial production, and adaptation to different agroecological conditions. Bashan et al. (2014) [36] emphasize the importance of developing efficient formulations that ensure the viability and effectiveness of microorganisms in the field. Additionally, the scalability of microbial inoculants requires advancements in storage and application methods tailored to the specific needs of each region. Overcoming these challenges is key to maximizing the potential of PGPR in promoting more sustainable and resilient agricultural systems. The PGPR have demonstrated multiple benefits in agriculture, such as increased crop yield, improved nutrient content, and pathogen suppression. Furthermore, their use is considered a sustainable alternative that can reduce dependence on chemical fertilizers and improve soil health. However, although their application has grown over the past two decades, there are still gaps in research on their long-term effects on the soil microbial community. A critical aspect that requires further attention is antibiotic resistance in PGPR, as many of these bacteria possess resistance genes or intrinsic mechanisms such as efflux pumps. This characteristic could represent an environmental risk if resistance genes are transferred to other soil bacteria. However, it is also possible that resistance is part of biological processes essential for plant growth promotion. Since survivorship bias can lead researchers to focus on the positive effects of PGPR and overlook the negative ones, it is essential to take a balanced perspective. To achieve this, a greater number of studies are required to evaluate both the benefits and risks associated with its use, considering its impact on the soil microbiome and its potential relationship with antibiotic resistance [48].

5. Conclusions

This study highlights the exponential increase in scientific publications on PGPR as biocontrol agents, reflecting a growing interest in their potential for sustainable agriculture. Original research and review articles play a key role in enhancing visibility and citation impact. Among the most influential contributors, *Biological Control* emerged as the leading journal, while Indian and Chinese institutions, particularly Nanjing Agricultural University and the Chinese Academy of Agricultural Sciences, were the most productive in terms of publications and citations. Key researchers driving this field include Babalola, Kloepper, and Shen, with 38, 31, and 25 publications, respectively. Recent research trends indicate a shift towards the development of PGPR-based bioproducts, including biopesticides, biofertilizers, bioinoculants, bioremediators, and biostimulants. PGPR contribute to sustainable agriculture through mechanisms such as biological nitrogen fixation, phosphorus solubilization, phytohormone production, and phytopathogen biocontrol. However, the practical application of PGPR in real-world agriculture remains challenging, requiring further advancements in formulation stability, large-scale production, and adaptation to diverse agroecological conditions. To accelerate the adoption of PGPR-based biocontrol strategies, researchers and policymakers should focus on integrating PGPR with emerging agricultural technologies, such as precision agriculture and smart microbial formulations, to enhance their effectiveness and scalability. Future research should explore synergies between PGPR and other biocontrol approaches, including beneficial microorganisms, plant-derived biostimulants, induced systemic resistance, crop rotation, polycultures, and organic amendments. Additionally, the potential of PGPR in integrated pest management

(IPM) and its impact on long-term soil health warrants further investigation. A critical area for future studies is assessing the adoption of PGPR in different global agricultural contexts, particularly in regions facing urgent sustainability challenges. Understanding farmer perceptions, regulatory frameworks, and economic feasibility will be key to bridging the gap between scientific advancements and field application. Strengthening interdisciplinary collaborations among microbiologists, agronomists, policymakers, and industry stakeholders will be essential to fully harness the potential of PGPR-based biocontrol for resilient and sustainable agricultural systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae11030271/s1, Table S1: The 100 most cited articles in 2019–2023 on PGPR as biocontrol agents [1–10,13,20–22,49–134]

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