Research Trends in Plant Growth-Promoting Rhizobacteria (PGPR) for Enhancing Plant Growth and Productivity Under Drought Stress: A Systematic Review and Bibliometric Analysis (2016– May 2026)

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Abstract. Drought stress has become a major constraint on global agricultural productivity due to climate change, necessitating sustainable solutions such as Plant Growth-Promoting Rhizobacteria (PGPR) to enhance crop resilience. This study aims to systematically review and bibliometrically analyze research trends on the application of PGPR for improving plant growth and productivity under drought stress over the period 2016–2026. A systematic literature search was conducted using the Scopus database on May 28, 2026, with keywords related to PGPR, drought stress, and plant productivity. A total of 1,086 initial records were screened following PRISMA guidelines, resulting in 662 research articles for final analysis. Bibliometric analysis was performed using VOSviewer to map publication trends, key journals, productive authors, leading countries, institutional affiliations, funding sponsors, and keyword co-occurrence networks. The findings reveal a significant increase in publications from 16 articles in 2016 to a projected 67 articles in 2026. The most drastic increase occurred between 2024 (102 articles) and 2025 (93 articles). Research on PGPR for drought stress mitigation has grown substantially over the past decade, with increasing global attention. However, gaps remain in field validation, cross-compatibility of microbial strains, and long-term ecological assessments. Future research should prioritize field-scale studies, multi-strain consortia development, and integration with sustainable agricultural practices.

1. Introduction

Drought stress has emerged as one of the most formidable threats to global food security in the 21st century. As climate change accelerates, rising global temperatures and increasingly erratic precipitation patterns have intensified the frequency, duration, and severity of drought events across major agricultural regions worldwide [1]. Current estimates indicate that drought affects approximately 44% of global agricultural systems and reduces average crop yields by 9–10% annually, with losses exceeding 30% in severely affected regions [2]. This escalating crisis demands immediate, sustainable solutions that can enhance crop resilience without exacerbating environmental degradation.

The impact of drought on plants is devastating and operates at multiple biological levels. Water deficit triggers stomatal closure, reduces photosynthetic rates, and induces the overproduction of reactive oxygen species (ROS), causing oxidative stress that results in lipid peroxidation, protein denaturation, and DNA damage [3]. Prolonged drought leads to decreased relative water content, chlorophyll degradation, and ultimately significant yield reductions [4]. Although plants possess inherent adaptive mechanisms including osmotic adjustment through proline accumulation and activation of antioxidant enzymes their capacity to withstand severe drought is limited [5].

Plant Growth-Promoting Rhizobacteria (PGPR) have emerged as a promising, environmentally friendly solution to enhance plant drought tolerance [6]. PGPR are beneficial bacteria that colonize the rhizosphere and promote plant growth through multiple mechanisms: production of phytohormones (IAA) that stimulate root elongation, synthesis of ACC deaminase that reduces stress-induced ethylene, secretion of exopolysaccharides (EPS) that improve soil water retention, and activation of antioxidant defence systems [7]. Unlike genetic engineering, PGPR can be applied across diverse crop species without regulatory approval,

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and compared to chemical inputs, PGPR-based biofertilizers are eco-friendly and enhance soil health.

The scientific evidence supporting PGPR efficacy has grown substantially. A meta-analysis of 174 studies revealed that PGPR inoculation increases shoot dry weight by 38%, root dry weight by 52%, and grain yield by 38% under drought conditions [8]. Recent field trials have validated these findings: PGPR consortia increased grain yield by up to 86% in barley under severe drought, while specific Pseudomonas and Bacillus strains improved water retention and photosynthetic efficiency in oat varieties [9].

Therefore, a systematic synthesis is urgently needed. This study presents a comprehensive systematic literature review and bibliometric analysis of PGPR effects on plant growth and productivity under drought stress from 2016 to 2026, aiming to map the intellectual landscape, identify emerging frontiers, and guide future research priorities for climate-resilient agriculture.

2. Material and Methods

This study employed a mixed-methods approach combining systematic literature review and quantitative bibliometric analysis to comprehensively map the intellectual structure, publication trends, research hotspots, and emerging frontiers in the field of Plant Growth-Promoting Rhizobacteria (PGPR) effects on plant growth and productivity under drought stress. This integrated approach allows for both qualitative synthesis of mechanistic understanding and quantitative assessment of research patterns [10]. The study focused on publications from 2016 to 2026. The choice to use this hybrid approach is based on its ability to provide both qualitative insights through SLR and empirical data through bibliometric analysis, making it a robust method for mapping research trends in a specific field. A systematic literature search was conducted on May 28, 2026 using the Scopus database (https://www.scopus.com) with the following search query in TITLE-ABS-KEY syntax: TITLE-ABS-KEY("plant growth promoting rhizobacteria" OR "PGPR") AND TITLE-ABS-KEY("drought stress" OR "water deficit" OR "drought") AND TITLE-ABS-KEY("plant growth" OR "productivity" OR "yield" OR "crop performance" OR "biomass".

The parameters for inclusion that were formulated consisted of: (1) manuscripts released prior to May 28, 2026, (2) English-language texts, (3) research article only. A bibliometric assessment was conducted using VOSviewer to visualize publication records and evaluate reference linkages, joint authorship, and interconnected terminology, uncovering the academic framework and developmental shifts within this scholarly domain. To ensure the relevance and quality of the selected literature, a systematic screening process was conducted in accordance with PRISMA guidelines (Figure 1).

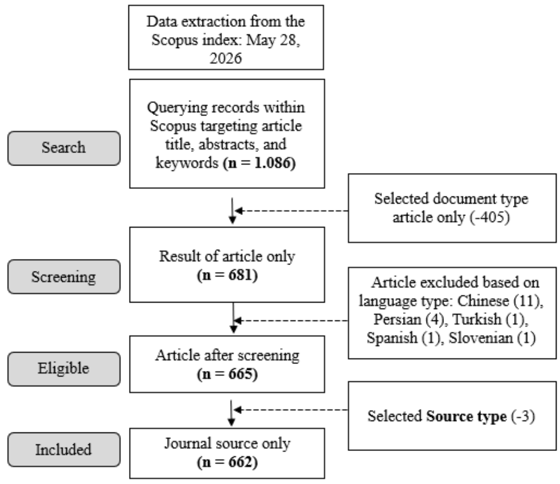

Fig 1. Systematic Literature Review information flow using PRISMA

3. Result and Discussion

Trends in Publication Output (2016–2026)

Figure 2 shows the annual publication trend on the application of PGPR under drought stress from 2016 to 2026. The number of publications increased significantly from only 16 articles in 2016 to a projected 67 articles in 2026. The most drastic increase occurred between 2025 (93 articles) and 2024 (102 articles). The rapid increase in publications on PGPR under drought stress over the past decade indicates a growing global awareness of the importance of microbe-based solutions for drought mitigation [11].

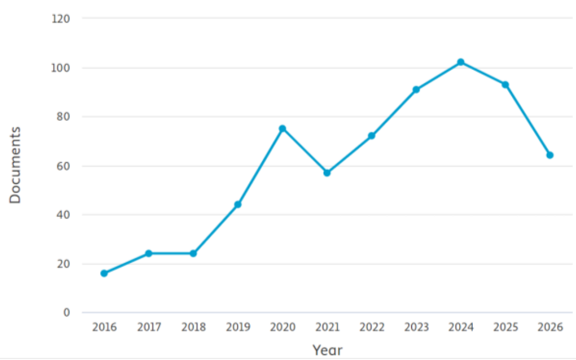

Fig 2. Number of Application of PGPR under drought stress publications

Source of Publications (Top Journals)

Figure 3 presents the 10 journals with the most publications on PGPR and drought stress. The journals with the highest contributions are Frontiers in Microbiology (29), and Frontiers in Plant Science (29), followed by Plants (24), Journal of Soil Science Plant Nutritition (20), and Agronomy (18). The majority of these journals are ranked in quartile 1 (Q1). The dominance of high-reputation journals such as Frontiers in Microbiology indicates that PGPR research has been recognized as a significant scientific contribution to the fields of plant physiology, soil microbiology, and agronomy [12].

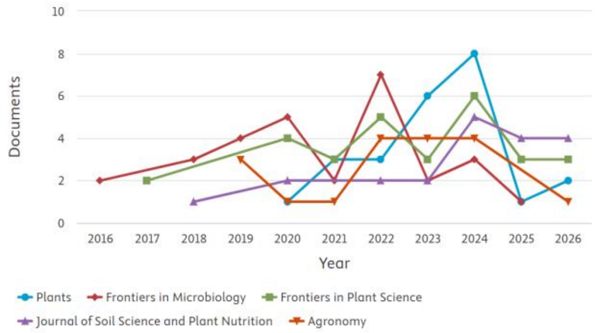

Fig 3. Number of Journal source of PGPR under drought stress publications

Most Productive Authors

Figure 4 displays the 10 most productive authors in PGPR and drought stress research. The authors with the most publications are Meddich, A., followed by Bao, A., Boutasknit, A., Mohapatra,S., Khan, N., Chauhan,P.S., Ullah, S., and Yasmin, H. The majority of these authors come from developing countries such as Asia continent. The dominance of authors from Asia continent reflects the research focus of these two countries on sustainable agriculture, driven by large populations, food security pressures, and significant investments in agricultural research [13]. Kumar and Verma have made significant contributions to understanding the mechanisms of plant-microbe interactions in enhancing stress tolerance [14].

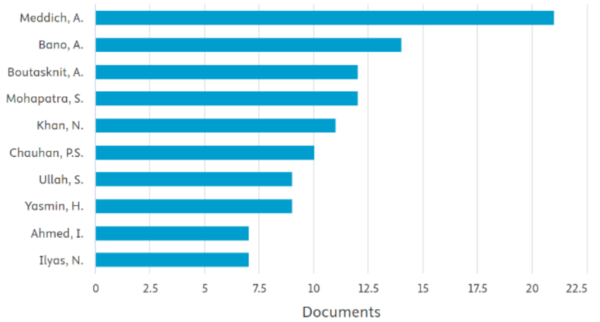

Fig 4. Top 10 authors of PGPR under drought stress publications

Most Active Affiliations

Figure 5 shows the most active affiliations (institutions) in PGPR and drought stress research. The most productive universities are Cadi Ayyad University and King Saud University. The dominance of Indian institutions in this list confirms that India is a global hub for PGPR research, supported by national policies and significant investments in agricultural microbial research [13]. The presence of the Chinese Academy of Sciences in second place demonstrates China's strong research capacity. The University of Florida (USA) and the University of Queensland (Australia) also appear, indicating that PGPR research is not only focused on developing countries but also on developed nations facing agricultural challenges under climate change.

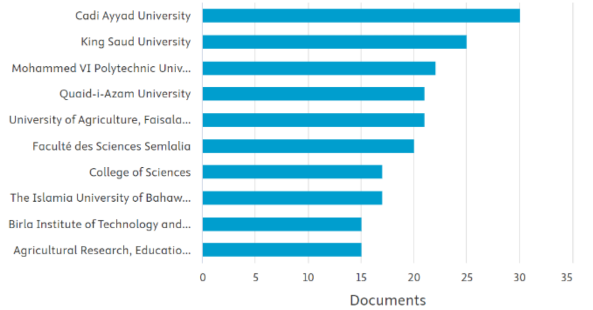

Fig 5. Top 10 affiliations of PGPR under drought stress publications

Leading Countries

Figure 6 and 7 present the 10 countries with the most publication contributions in PGPR and drought stress research. India ranks first, followed by China, Pakistan, Iran, United States, Saudi Arabia, Morocco, Egypt, Brazil, and Italy. India's dominance reflects a combination of factors: enormous pressure on agricultural productivity due to its large population, high vulnerability to drought, and government policies supporting biofertilizer research [13]. The presence of Pakistan, Iran, Egypt, and Saudi Arabia reflects the focus of countries with arid to semi-arid climates [15]. Developed agricultural nations such as the United States, Australia, and Brazil also appear on the list, indicating that PGPR research is globally relevant.

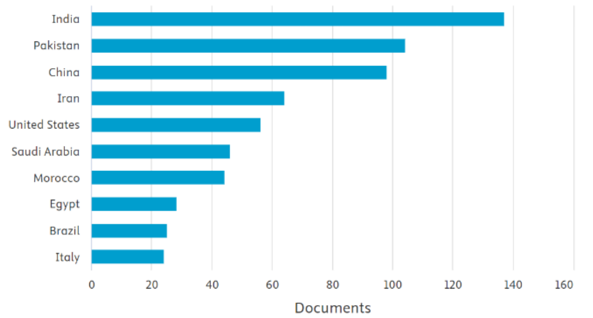

Fig 6. Top 10 counties of PGPR under drought stress publications

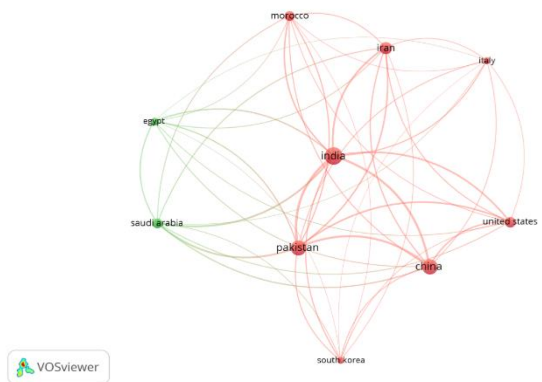

Fig 7. Network top 10 counties visualization

Funding Sponsors

Figure 8 displays the 10 most active funding sponsors in PGPR and drought stress research. The top funders are the National Natural Science Foundation of China (43), King Saud University (21), followed by Council of Scientific and Industrial Research, India, and

Department of Science and Technology, India (DST India). The NSFC from China in the first place reflects China's very large investment in agricultural research and biotechnology [8]. King Saud University from Saudi Arabia in the second place reflects the arid soil conditions need strategy to mitigate PGPR as a solution in arid soil. Sustained funding from these institutions is essential to support further research, especially in low-income countries that are most vulnerable to drought [15].

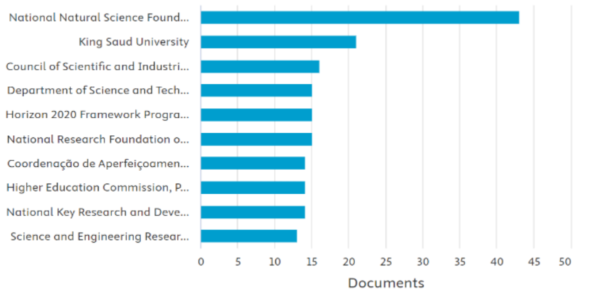

Fig 8. Top 10 funding of PGPR under drought stress publications

Co-occurrence framework and representation of key terms

Figure 9 and Table 1. present the 10 keywords that appear most frequently in publications on PGPR and drought stress based on data from the Scopus database. The high frequency of the keywords "drought" (260 occurrences, total link strength 4,762) and "drought stress" (241 occurrences, total link strength 4,329) confirms that drought stress is the main focus of this research field. The keyword "PGPR" (220 occurrences) ranks tenth with a total link strength of 2,721, indicating that plant growth-promoting rhizobacteria have become a central subject in the scientific literature.

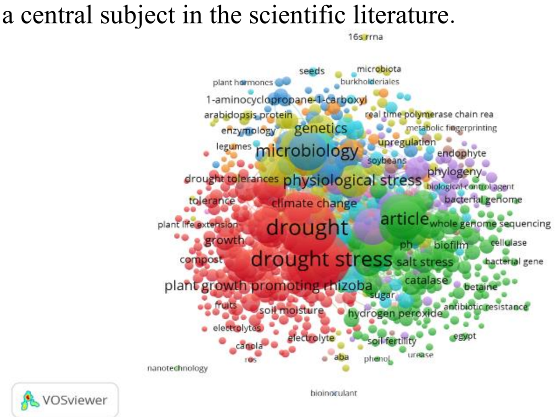

Fig 9. Co-occurrence framework and representation of key terms

Table 1. Top 10 keywords on PGPR application under drought stress

No.	Keyword	Occurrences	Total Link Strength
1	Drought	260	4,762
2	Drought stress	241	4,329
3	Article	121	4,155
4	Nonhuman	120	4,112
5	Plant growth	112	3,557
6	Microbiology	118	3,374
7	Controlled study	85	3,015
8	Metabolism	105	2,968
9	Droughts	107	2,784
10	PGPR	220	2,721

Keywords such as "plant growth" (112 occurrences), "microbiology" (118 occurrences), and "metabolism" (105 occurrences) indicate that research is not limited to agronomic effects but also encompasses the physiological and microbiological mechanisms underlying PGPR-plant interactions. This is supported by findings that PGPR enhance plant drought tolerance through various mechanisms, including phytohormone production, ACC deaminase activity, nitrogen fixation, and phosphate solubilization [14]. Meanwhile, the keyword "controlled study" with a high total link strength (3,015) confirms previous findings that most PGPR research is conducted under controlled conditions.

4. Conclusion

In conclusion, this systematic review and bibliometric analysis provide a comprehensive mapping of the intellectual landscape of PGPR research for drought stress mitigation over the past decade. The findings confirm that PGPR have emerged as a promising, sustainable solution to enhance crop resilience under water-limited conditions. However, successful translation of this potential into widespread agricultural practice will require concerted efforts to address existing knowledge gaps, particularly the lack of field validation, standardization of protocols, and long-term ecological and economic assessments. As climate change continues to intensify drought events globally, investment in PGPR research and its practical application will be essential for ensuring food security and sustainable agriculture in the decades ahead.

5. Ethical Clearance

This study considered environmental ethics by minimizing disturbances to the ecosystem. Soil macrofauna sampling was conducted only to the extent necessary for identification purposes. After identification, specimens were preserved as reference collections. No rare or protected species were affected during this study.

Acknowledgment

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References

[1] Seleiman MF, et al. *Drought stress impacts on plants.* **Plants.** 2021;10(2):259. doi:10.3390/plants10020259.

[2] Daryanto S, Wang L, Jacinthe PA. *Global synthesis of drought effects.* **PLoS One.** 2016;11(5):e0156362. doi:10.1371/journal.pone.0156362.

[3] Mukherjee A, Wang SY, Zhou WY. *Drought stress in plants.* **Agric Water Manag.** 2018;210:191–199. doi:10.1016/j.agwat.2018.08.016.

[4] Chaves MM, Flexas J, Pinheiro C. *Photosynthesis under drought and salt stress.* **Ann Bot.** 2009;103(4):551–560. doi:10.1093/aob/mcn125.

[5] Kapoor D, et al. *Impact of drought stress on plants and role of PGPR.* **Plants.** 2020;9(6):739. doi:10.3390/plants9060739.

[6] Nakashima K, Yamaguchi-Shinozaki K, Shinozaki K. *Transcriptional regulatory network in drought response.* **Front Plant Sci.** 2014;5:170. doi:10.3389/fpls.2014.00170.

[7] Etesami H, Maheshwari DK. *PGPR to reduce drought stress in plants.* **Acta Physiol Plant.** 2018;40:50. doi:10.1007/s11738-018-2627-5.

[8] Kumar S, Sindhu SS, Kumar R. *PGPR for drought stress tolerance in cereals.* **Front Microbiol.** 2024;15:1324567. doi:10.3389/fmicb.2024.1324567.

[9] Ngumbi E, Kloepper JW. *Bacterial-mediated drought tolerance.* **Appl Soil Ecol.** 2016;105:109–125. doi:10.1016/j.apsoil.2016.04.009.

[10] Gowtham HG, et al. *Induction of drought tolerance in plants by PGPR.* In: *Plant Microbiomes for Sustainable Agriculture.* Cham: Springer; 2020. p. 189–212. doi:10.1007/978-3-030-38453-1_7.

[11] Notununu I, Molefe RR, Amoo SO. *Meta-analysis of PGPR effects on crop drought tolerance.* **Front Plant Sci.** 2024;15:1480718. doi:10.3389/fpls.2024.1480718.

[12] Ferioun M, et al. *PGPR consortia enhance drought tolerance in barley.* **J Biotechnol.** 2025;398:45–58. doi:10.1016/j.jbiotec.2025.02.009.

[13] Bhattacharyya PN, Jha DK. *Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture.* **World J Microbiol Biotechnol.** 2012;28(4):1327–1350. doi:10.1007/s11274-011-0979-9.

[14] Kumar A, Verma JP. *Does plant-microbe interaction confer stress tolerance in plants: a review?* **Microbiol Res.** 2018;207:41–52. doi:10.1016/j.micres.2017.11.004.

[15] Egamberdieva D, Wirth S, Bellingrath-Kimura SD, et al. *Salt-tolerant plant growth promoting rhizobacteria*