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RESEARCH ARTICLE

Plant growth promoting rhizobacteria (PGPR) application for coping with salinity and drought: a bibliometric network multi-analysis

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ABSTRACT

- Rhizobacteria play a crucial role in plant growth and yield, stimulating primary production and improving stress resistance. Climate change has several consequences worldwide that affect arable land and agriculture. Studies on plant–soil–microorganism interactions to enhance plant productivity and/or resistance to abiotic stress may open new perspectives. This strategy aims to make agricultural-relevant plant species able to complete their biological cycle in extreme soils with the help of inoculated or primed plant growth-promoting rhizobacteria (PGPR).
- We provide an overview of the evolution of interest in PGPR research in the last 30 years through: (i) a quantitative search on the Scopus database; (ii) keyword frequencies and clustering analysis, and (iii) a keyword network and time-gradient analysis.
- The review of scientific literature on PGPR highlighted an increase in publications in the last 15 years, and a specific time gradient on subtopics, such as abiotic stresses. The rise in PGPR as a keyword co-occurring with salinity and drought stresses aligns with the growing number of papers from countries directly or partly affected by climate change.
- The study of PGPR, its features, and related applications will be a key challenge in the next decades, considering climate change effects on agriculture. The increased interest in PGPR leads to deeper knowledge focused specifically on researching agriculturally sustainable solutions for soils affected by salinity and drought.

INTRODUCTION

The urgency of climate change mitigation is the challenge of the present century. Climate change represents the main threat to sufficient food supply for the increasing global population (Lal 2005). One of the primary drivers of climate change is human emissions of carbon dioxide and other greenhouse gases (IPCC 2013). Specifically, increasing atmospheric CO_2 is the primary source governing global temperatures (Jungclaus *et al.* 2010; Lacis *et al.* 2010). Since the industrial revolution, average temperatures have risen to approximately 1.1 °C above the mid-19th century baseline (Delworth *et al.* 2016).

Global warming impacts include extreme weather events, sea level rises, altered crop growth and yield, and altered water resources, according to the Fifth Intergovernmental Panel on Climate Change (IPCC 2014). Notably, the IPCC provided relevant insights into land–climate interactions and the consequent processes of desertification, land degradation, and salinization from a climate change perspective (Jia *et al.* 2019). Mirzabaev *et al.* (2019) elaborated a map (from 1982 to 2015) showing increases in desertification worldwide, highlighting Central Asia, the Middle East, Inner China, Mongolia, Central-South USA, Eastern Brazil, and the Gran Chaco Plain. Desertification is land degradation occurring in drylands due to soil exploitation, poor land use management, and climate change, which, in recent decades, has reduced crop productivity (An *et al.* 2019; Mirzabaev *et al.* 2019). In the projection of 2 °C global warming, the number of people living in drylands exposed to desertification is expected to range between 974 and 1267 million, predominantly located in Central, East and South Asia, and East and West Africa (Mirzabaev *et al.* 2019).

According to FAO's Global Map of Salt Affected Soils (GSASmap) (FAO 2021), over 833 million ha of subsoil (30–100 cm depth) and over 424 million ha of topsoil (0–30 cm) worldwide are already salt-affected. Specifically, a total area of 397 and 434 million ha, respectively, have saline and sodic soils (FAO 2018; Negacz *et al.* 2022), with 37% in arid deserts, and 27% in dry hot/cold steppe (FAO 2021). According to the FAO GSASmap (FAO 2021) and Ecocrop model (FAO-Ecocrop 2008; Negacz *et al.* 2022), salt-affected subsoils are mainly in Central Asia, the Middle East and Turkey, Arabian Peninsula, Iran, Pakistan, western India, inner China and Mongolia, North Africa, and the Mediterranean area, together with some areas of the Horn of Africa and Namibia, central–south USA and parts of Mexico, the Gran Chaco plain and Patagonia.

The global environmental and climatic changes impact agriculture, land use, and food supply because of soil loss, desertification, and land salinization, specifically in those areas highlighted by Mirzabaev *et al.* (2019) and the FAO GSASmap (FAO 2021). The most detrimental consequences of drought on plants are limited absorption of photosynthetically active radiation (PAR), decreasing radiation-use efficiency, reducing plant establishment, and potentially inhibiting plant nutrient uptake (Harris *et al.* 2002; Earl & Davis 2003; Kaya *et al.* 2006; Elemike *et al.* 2019). Plant growth depends on cell division, expansion, and differentiation, encompassing genetic, ecophysiological, and morphological interactions. Water shortage inhibits cell elongation and mitosis by reducing turgor pressure and tissue water content (Nonami 1998; Seleiman *et al.* 2019), leading to reduced plant height, leaf area, and crop growth (Kaya *et al.* 2006; Hussain *et al.* 2008). Drought effects can manifest as changes in germination, flowering, reduced tillering and, consequently, less grain, lower grain filling, and putative sterility, depending on the timing and degree of stress experienced during the biological cycle (Wardlaw & Willenbrink 2000; Frederick *et al.* 2001; Yadav *et al.* 2004; Samarah 2005; Cattivelli *et al.* 2008; Estrada-Campuzano *et al.* 2008).

However, in agriculture, the main factor limiting plant productivity is toxicity from saline soils (Isayenkov 2012). High salt ion concentrations can result in hyperosmotic shock and ionic imbalance, leading to nutritional imbalance (Grattan & Grieve 1998), oxidative stress (Tsugane *et al.* 1999; Hernández *et al.* 2001), and eventual death (Bohnert *et al.* 1995; Alscher *et al.* 1997; Hasegawa *et al.* 2000; Isayenkov 2012). Additionally, Na^+ and Cl^- excess in the soil solution decreases osmotic potential that prevents water absorption by the root system. This may lead to plant dehydration and cytotoxic accumulation (Isayenkov 2012). Such growth declines are related to salt inclusion into the transpiration stream, injuring cells (Parihar *et al.* 2015). Also, germination decreases with increased salinity (Läuchli & Grattan 2007; Kaveh *et al.* 2011). Salinity affects crop yield reduction in terms of pod number per plant, seeds per pod, seed weight, plant height, biomass, and leaf area, resulting in a negative correlation with the salt concentrations (Hernandez *et al.* 1995; Chartzoulakis & Klapaki 2000; Wang & Nii 2000; Parihar *et al.* 2015).

From the perspective of climate change consequences of more extreme conditions, the role of of Plant Growth Promoting Rhizobacteria (PGPR) in plant–soil interactions and agriculture has been investigated. Rhizobacteria can colonize plant root systems and make an endosymbiotic association, as in the Fabaceae (Poole *et al.* 2018). The process of symbiosis involves a complex exchange of biochemical signals between the free-living microbe and the plant, leading to root invasion and, in the Rhizobiaceae, formation of root nodules containing N_2-fixing rhizobia (Gage 2004; Kereszt *et al.* 2011; Oldroyd 2013; Udvardi & Poole 2013). PGPR can colonize plant roots following inoculation of seeds and enhance plant growth (Aziz *et al.* 2012). PGPR can greatly improve plant growth – specifically of agricultural crops – allowing plants to thrive under biotic and abiotic stresses, such as oligotrophic, salty and arid soils (Santoyo *et al.* 2016; Waadt *et al.* 2022). These microbes ameliorate plant growth, triggering phytohormone, antioxidant and siderophore prduction (Kumar & Verma 2018). Rhizosphere PGPR employed as inoculants for biostimulation, biocontrol, and biofertilization include Achromobacter sp., Arthrobacter sp., Azotobacter sp., Azospirillum sp., Bacillus sp., Burkholderia sp., Enterobacter sp., Klebsiella sp., Microbacterium sp., Paenibacillus sp., Pantoea sp., Pseudomonas sp., Serratia sp. and Streptomyces sp. (Numan *et al.* 2018).

The new frontier of PGP microbe research is related to their use in extreme environments. Specifically, as plant growth-promoting microbes to improve crop health and growth in agriculture. However, use of native or allochthonous PGPB as priming or inoculation agents for crops is still controversial. Issues of cross-compatibility mainly related to microbe–plant recognition, and contextual adaptation, such as soil type and environmental conditions, can become obstacles to the strategy's effectiveness (Bouri *et al.* 2022). Indeed, plant stress tolerance-related microbiome association results from a coevolution process under specific habitat conditions (Riva *et al.* 2019).

Nevertheless, allochthonous psychrotroph bacteria from Antarctica have been reported to ameliorate plant physiological performance (Fardella *et al.* 2014). In general, extremophiles already associated with plants may enhance plant performance. Marasco *et al.* (2012) showed that PGP agents from desert farming increase plant stress tolerance. Hypersalinity-adapted rhizobacteria associated with *Salicornia* sp. confer resistance to high temperature, osmotic and saline stress (Mapelli *et al.* 2013). Consequently, mining extreme root microbes may enhance crop stress tolerance towards sustainable agriculture, by employing the plant root system microbiomes as reservoirs (Zhu *et al.* 2011; Kumar *et al.* 2019).

In this paper, we provide an overview of the shifting interest towards the topic of PGPR in the last 30 years, providing a quantitative literature search reporting information on publication distribution per country, keyword (and combinations), and year. Based on this first screening, we have implemented research exploring the sub-topics that co-occur with PGPR utilization and currently represent the scientific community's priorities on this topic.

MATERIAL AND METHODS

Data collection

A body of 6940 publications, based on authors' keywords in scientific articles recorded in the Scopus (Elsevier) database was gathered for "PGPR" and "PGPB" between 1992 and 2022 up to October 2023. We limited our approach to keywords to exclude biases in the information-flow network, possibly caused by less-strictly related words, repetitions, word similarity due to ending, conjugations and declensions. The here outlined approach is based on previous text mining analyses reported in Hay-Mele *et al.* (2019) and D'Alelio *et al.* (2021).

RStudio analysis on keyword frequencies and clustering

Our analyses were carried out with the open-source software RStudio v. 2023.06.1+524 according to the PRISMA guidelines (Moher *et al.* 2009). The search results were downloaded as two columns (keywords, DOI) csv files. The csv was scanned to remove inconsistencies such, as inaccessible DOI or keywords not related to the topic. The dataset was then imported in RStudio and filtered using the *tidyverse* package collection, eliminating inaccessible, unreadable, or uninformative publications, and used the remaining data (n = 1443) to investigate keyword frequencies and clustering (Hay-Mele *et al.* 2019).

The textmineR package was used to build the model. The tidied data frame was our input for the Document-term matrix

(DTM) building, with both single words and bigrams for a term frequency inverse-document frequency analysis (TF-IDF). The term frequency (TF) is the number of times the term appears in the DTM. Therefore, we retrieved single words and bigrams frequencies, the number of documents in which each term appeared and the inverse document frequency (IDF), a measure of how often a common or rare a term is across the set of documents (Tables 1 and 2). The IDF was calculated as

$$IDF = \log_{10}\frac{N}{N_t}$$

where N is the total number of documents, and N_t is the number of documents where the *t* term appears.

Then we examined the document clustering by term-based distance through TF-IDF and cosine similarity distance for both single words and bigrams. We proceeded to re-weight the term counts in the DTM by multiplying the TF by the IDF. The cosine similarity was calculated and changed to a distance. Eventually, documents were clustered on cosine distance. We used hierarchical clustering with Ward's method as merge rule, cutting the tree at ten clusters, then selected pertinent clusters, excluding those clearly related to the topic.

VOSviewer analysis on keyword networking and occurrences

We performed networking, occurrences, and clustering on the 6940 results from the previously mentioned Scopus data using the open-source software VOSviewer (version 1.6.19) (Van Eck & Waltman 2018). Network maps were elaborated displaying items according to their relatedness degree, and possibly generating clusters. The co-occurrence networks of keywords were based on the number of publications in which author keywords occur between two documents (Van Eck & Waltman 2014). We set a minimum threshold of 20 occurrences, (identifying 208 author keywords and removing those not clearly related to the topic) and a clustering resolution of 1. The outcome is represented by two network maps. One of which highlights the co-occurrences-based links between keywords using colours to separate clusters, and the other represents the network map based on the keyword occurrence in an average publication year through a colour gradient from blue (oldest publications) to yellow (newest publications). The time range is automatically elaborated by the software to highlight major changes in paper publication areas.

Table 1. RStudio elaboration of the 15 most frequent terms ordered by term frequency, excluding terms related to the topic from 1992 to 2023 (until October 2023).

keyword single word	TF	IDF
Soil	2062	0.732
Stress	1979	1.017
Inoculation	1214	1.078
Strains	1188	1.167
Root	1177	1.034
Rhizosphere	957	1.192
Bacillus	936	1.275
Yield	731	1.460
Inoculated	679	1.400
Salt	669	2.156
Isolates	617	1.918
Drought	616	2.362
Crop	564	1.422
Metal	555	2.033

Data source: Scopus. TF = term frequency; IDF = inverse-document frequency.

Table 2. RStudio elaborated the 15 most frequent bigrams ordered by term frequency, excluding terms related to the topic from 1992 to 2023 (until October 2023).

keyword bigram	TF	IDF
Salt_stress	278	2.630
Drought_stress	247	2.970
Acetic_acid	239	1.942
Indole_acetic	229	1.976
Heavy_metal	216	2.512
Abiotic_stress	149	2.583
Bacterial_strains	146	2.620
Systemic_resistance	138	2.905
Dry_weight	136	2.592
Growth_yield	135	2.763
*Bacillus*_sp	134	3.026
Inoculated_plants	134	2.753
Phosphate_solubilization	132	2.602
Nitrogen_fixation	126	2.905
Stress_tolerance	117	2.720

Data source: Scopus. TF = term frequency; IDF = inverse-document frequency.

RESULTS

Recently, interest in studying PGPB communities and their applications in plants – relevant for agricultural purposes – has remarkably increased with the aim to improve plant growth and yield under adverse conditions, such as drought and salinization. We examined a set of 6940 papers reported on Scopus by searching for PGPR or PGPB between 1992 and 2023, up to October 2023. Specifically, we operated on a three-level analysis, extrapolating our set of documents from Scopus – using the available tools on the database website to select our specific range of interests in the literature, then performed bibliometric analyses with RStudio and VOSviewer software.

Papers with the above-mentioned keywords have progressively increased in the last 30 years, as shown by the number of published papers and citations (Fig. 1a). We limited the research to four subject areas: "Agricultural and Biological Sciences", "Biochemistry, Genetics and Molecular Biology" (abbreviated in Fig. 1b, c as "Biochemistry"), "Immunology and Microbiology" (abbreviated in Fig. 1b, c as "Microbiology") and "Environmental Science" in order to exclude papers outside of our field of interest. The normalized trend of published papers over the years 1992–2023 (Fig. 1a) is a result of the vector ratio of number of ("PGPR" or "PRPB") published papers per year out of the total number of published papers per year (for the same above-mentioned subject areas). The decreased trend in number of published papers in 2023 (Fig. 1a, blue line) is ascribed to the fact that 2023 had not yet

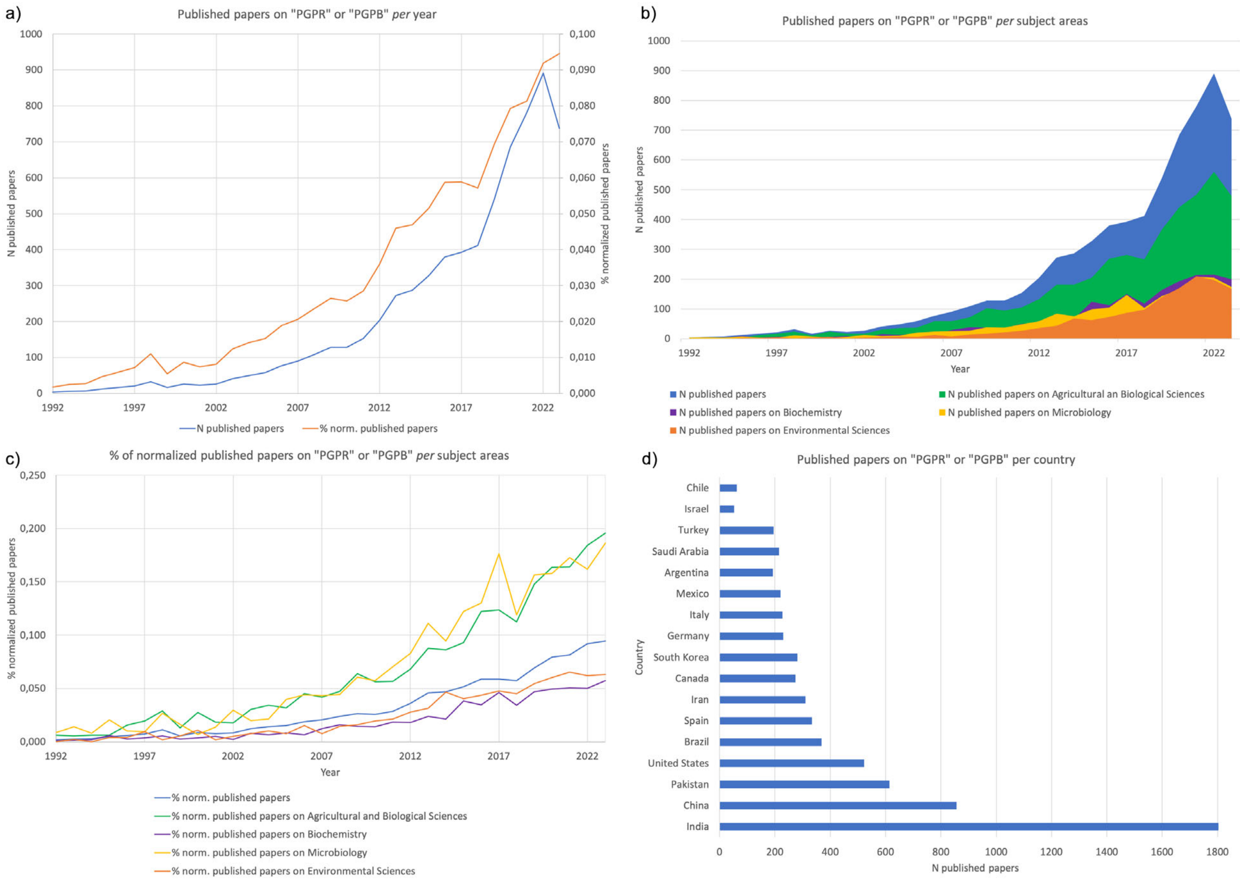

Fig. 1. (a) Normalized trend (orange line) and absolute number (blue line) of published papers in the timeframe 1992–2023 (until October 2023) containing the keywords "PGPR" or "PGPB". (b) Trend of published papers per subject area in this time frame containing the keywords "PGPR" or "PGPB" (not normalized). (c) Normalized trend of published papers per subject area in this time frame containing the keywords "PGPR or PGPB". (d) Number of published papers in this time frame containing the keywords "PGPR" or "PGPB" by country. Data source: Scopus.

ended at the time of our Scopus search. However, the normalization of data (Fig. 1a, orange line) indicated an increasing tendency in publications in 2023, compared to previous years. Specifically, Fig. 1a indicates that, in the last 30 years, published papers dealing with "PGPB" or "PGPR" increased 0.095% (normalized) over the baseline total amount of published papers in the referred subject areas. The relative increase of papers dealing with "PGPB" or "PGPR" is now 99.5%.

Fig. 1b, c show the distribution of the absolute number and normalized perceentage of published papers per the mentioned subject area for 1992–2023 (until October 2023) containing the keywords "PGPR" or "PGPB". As above, we normalized the trend, calculating the number of published papers per subject area containing "PGPR" or "PGPB" out of the total number of papers published in each subject area. According to Scopus, the subject areas "Agricultural and Biological Sciences" and "Microbiology" had a more relevant increase in publications on "PGPR" or "PGPB" from 1992 to 2023 (until October 2023) (Fig. 1c), representing 65% and the 23% of the entire set of papers, respectively.

Fig. 1d reports 17 countries per published papers, suggesting an enhanced focus on plant root communities and microbiomes to understand biochemical mechanisms of recruitment, phyto-signalling and effects on plant growth and yield, specifically in those countries affected by land loss due to several factors.

Fig. 2a shows five keywords combination with "PGPB" or "PGPR". Only the associations with "drought" and "salinity" increased remarkably in the last 15 years. As previously described, we normalized the number of papers published according to the keyword combination in the first mentioned sum of subject areas out of the total number of published papers in the mentioned sum of subject areas, from 1992 to 2023 (until October 2023). Considering the publications per country, analyses on keywords combination, it clearly emerges that the most prolific countries are those most affected by arable soil loss, as suggested by the previous general analysis per country (Fig. 1d). Scopus data report that the keyword combinations "desert" and "degraded soil" did not experience the same increase as "drought" and "salinity", except for the "climate change" combination that has increased in the last 5 years. This suggests more research and knowledge of local or more imminent issues – such as droughts and salinization events – rather than desertification and land/soil degradation, encompassing larger areas and macro-regions affected by climate change consequences, in the perspective of PGPR application in agriculture.

Fig. 3a shows five additional keywords combined with "PGPB" or "PGPR" related to phyto-hormones and

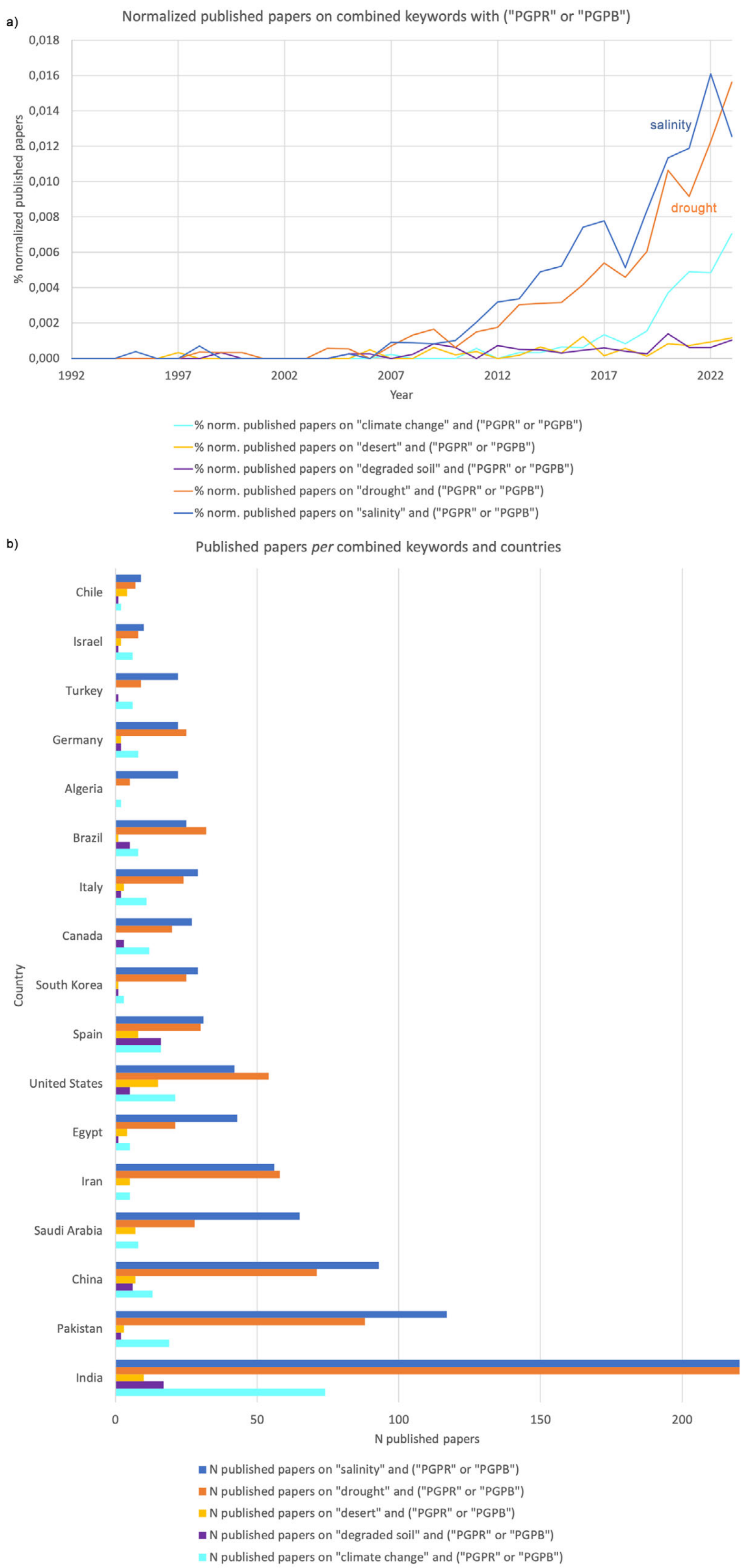

Fig. 2. (a) Normalized trend of published papers in the time frame 1992–2023 (until October 2023) containing the words "PGPR" or "PGPB" combined with the keywords "climate change", "degraded soil", "desert", "drought" and "salinity". (b) Number of published papers in this time frame containing the keywords "PGPR" or "PGPB" by country combined with the overmentioned keywords. Data source: Scopus.

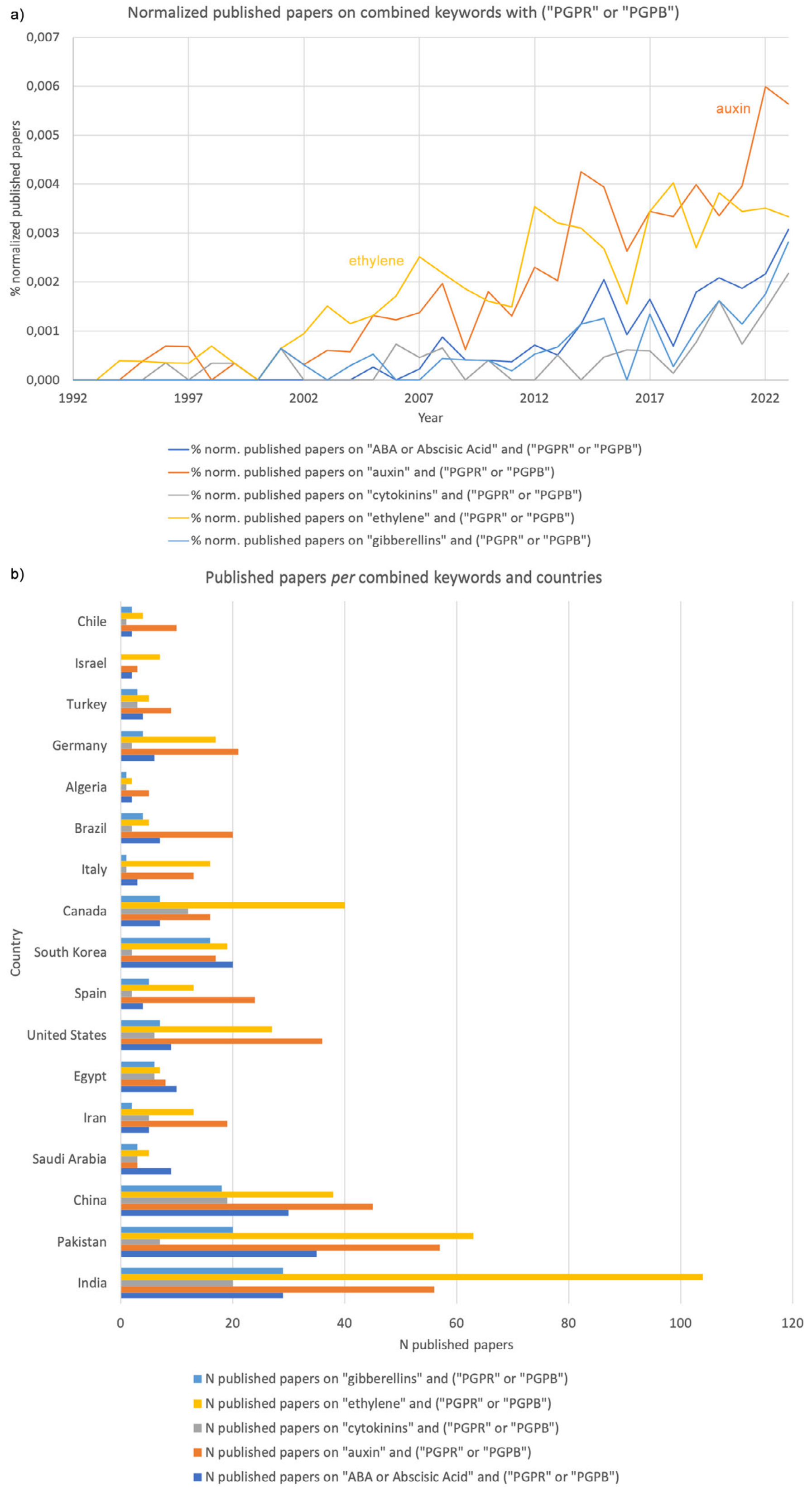

Fig. 3. (a) Normalized trend of published papers in the time frame 1992–2023 (until October 2023) containing the words "PGPR" or "PGPB" combined with the keywords "ABA or abscisic acid", "auxin", "cytokinins", "ethylene" and "gibberellins". (b) Number of published papers in this time frame containing the keywords "PGPR" or "PGPB" by country combined with the above-rmentioned keywords. Data source: Scopus.

Table 3. RStudio elaborated the single word for the first 5 clusters, based on size, excluding terms related to the topic from 1992–2023 (until October 2023).

cluster number	size	top words
1	686	PGPR, Microbial, Nutrient, Yield, Fe
2	252	Isolates, Rice, Strains, IAA, Phosphate
3	121	Metal, Heavy, Phytoremediation, Metals, Soil
4	96	Resistance, Control, Disease, Induced, Systemic
5	82	Salt, Stress, ACC, Salinity, Ethylene

Data source: Scopus.

phyto-signalling in response to abiotic stresses (Waadt *et al.* 2022). The associations with the terms "auxin" and "ethylene" increased remarkably in the last 20 years compared to the occurrence of combinations of "abscisic acid," "gibberellins," and "cytokinins". Considering publications per country analyses on keyword combination, the most paper-producing countries in this specific research field are India, Pakistan, and China.

The RStudio analysis allowed us to retrieve keyword frequencies and clustering. Specifically, we operated following Hay-Mele *et al.* (2019) and D'Alelio *et al.* (2021) to obtain a clean dataframe to generate a tidy Document Term Matrix (DTM), eliminating non-accessible, unreadable or uninformative publications, based on PRISMA guidelines (Moher *et al.* 2009). Moreover, we limited our approach to keywords aiming to exclude biases in the information-flow network, possibly caused by not strictly related words, repetitions, word similarity due to ending, conjugation, and declension.

The most frequent words that emerge from the PGPR or PGPB Scopus search (excluding these and the corresponding acronyms, such as plant, growth, promoting, bacteria, rhizobacteria and related declensions) are shown in Tables 1 and 2. Concerning single words frequency, there was a prevalence of terms for "soil", "stress" and "inoculation". In view of this frequency and inverse-document frequency, the term "soil" seems to be the most counted in the DTM and one of the most common across the articles (Table 1). For bigram frequency, we operated merging symmetric-produced bigrams to avoid repetitions, specifically concerning indole-acetic acid. Beyond that, the top frequent bigrams are "salt stress", "drought stress", and "acetic acid", linked to "indole acetic" and "heavy metals" (Table 2).

The clustering analysis indicates that single word/bigram distributed according to topic. In Table 3, we observe a re-partition associated with the following clusters: PGPR techniques and effect on plants (cluster 1), bacterial application and phyto-signalling (cluster 2), heavy metals and phyto-remediation (cluster 3), induced systemic resistance (cluster 4), and salt stress (cluster 5). Bigram clustering indicates a re-partition associated with the following clusters (Table 4): salinity stress and plant growth promotion (cluster 1), induced systemic resistance (cluster 2), soil microbiome (cluster 3), drought stress (cluster 4), and heavy metals and phytoremediation (cluster 5). In addition, we observed that clustering repartition may overlap with keywords combination results (Fig. 2a), specifically with drought and salinity keywords in both single words and bigrams.

Table 4. RStudio elaborated the bigram for the first 5 clusters, excluding terms related to the topic from 1992 to 2023 (until October 2023).

cluster number	size	top words
1	1161	Plant_growth, Growth_promoting, Salt_stress, Promoting_bacteria, Growth_promotion
2	61	Systemic_resistance, PGPR_strains, Induced_systemic, Induced_resistance, Promoting_rhizobacteria
3	39	Bacterial_community, Microbial_community, Community_structure, Soil_microbial, Soil_bacterial
4	37	Drought_stress, Water_deficit, Deficit_stress, Drought_tolerance, Stress_conditions
5	21	Heavy_metals, Heavy_metal, Plant_growth, Phytoremediation_heavy, Growth_promoting

Data source: Scopus.

We performed networking, occurrences, and clustering on the 6940 results of the previously mentioned Scopus research using the open source software VOSviewer, elaborating network maps in which keywords are displayed according to their relatedness degree, possibly generating clusters. In Fig. 4a, the 208 keywords are grouped into seven different clusters and proportionally sized to their occurrences as reported in Table S1, indicating "PGPR" or "PGPB" connections to related topics. Specifically, we aimed to list Fig. 4a keyword relations and, thus, co-occurrences among the considered Scopus research, divided for the seven identified clusters, in Table S1. Cluster 1 (red, 57 items) focuses on the application of different PGPR strains – specifically *Bacillus* sp. – on agriculture-relevant plant species, considering biocontrol, growth promotion, and induced systemic resistance. Cluster 2 (green, 41 items) encompasses abiotic stresses, such as salinity and drought, through which PGPR application in agriculture should mainly improve results. We also highlight links to phytohormones resulting as stress response. Cluster 3 (blue, 33 items) consists of the application/inoculation of *Rhizobium* and *Azospirillum* spp. as PGPR on agriculture-relevant plant species. Cluster 4 (yellow, 25 items) is specifically focused on topics such as sustainable agriculture and use of biofertilizers, considering climate change. Cluster 5 (violet, 22 items) is mainly composed of PGPR research on phytoremediation techniques to manage soils affected by heavy metals. Cluster 6 (cyan, 21 items) encompasses interests in biofortification and bioinoculant techniques. Cluster 7 (orange, 9 items) focuses on PGPR features, *i.e.*, indole-acetic acid production, phosphate solubilization, siderophores in rhizosphere–soil interactions. However, clusters 4, 6 and 7 show a high degree of overlap, having some common keywords. Especially, cluster 6 seems to collect keywords from all the other clusters except for *biofortification* and *bioinoculants*. Overall, at least five areas of interests regarding PGPR research were identified, that may be summarized as growth promotion (red, cluster 1), abiotic stresses (green, cluster 2), inoculation of *Rhizobium* and *Azospirillum* spp. (blue, cluster 3), heavy metals (violet, cluster 5), and PGPR activities (orange, cluster 7). Figure 4b provide an overview on the shifting interest through time, from 2014 to 2020, showing that the latest publications, where the keywords occur, involve abiotic stress (green, cluster 2) and biofertilizers/phytoremediation

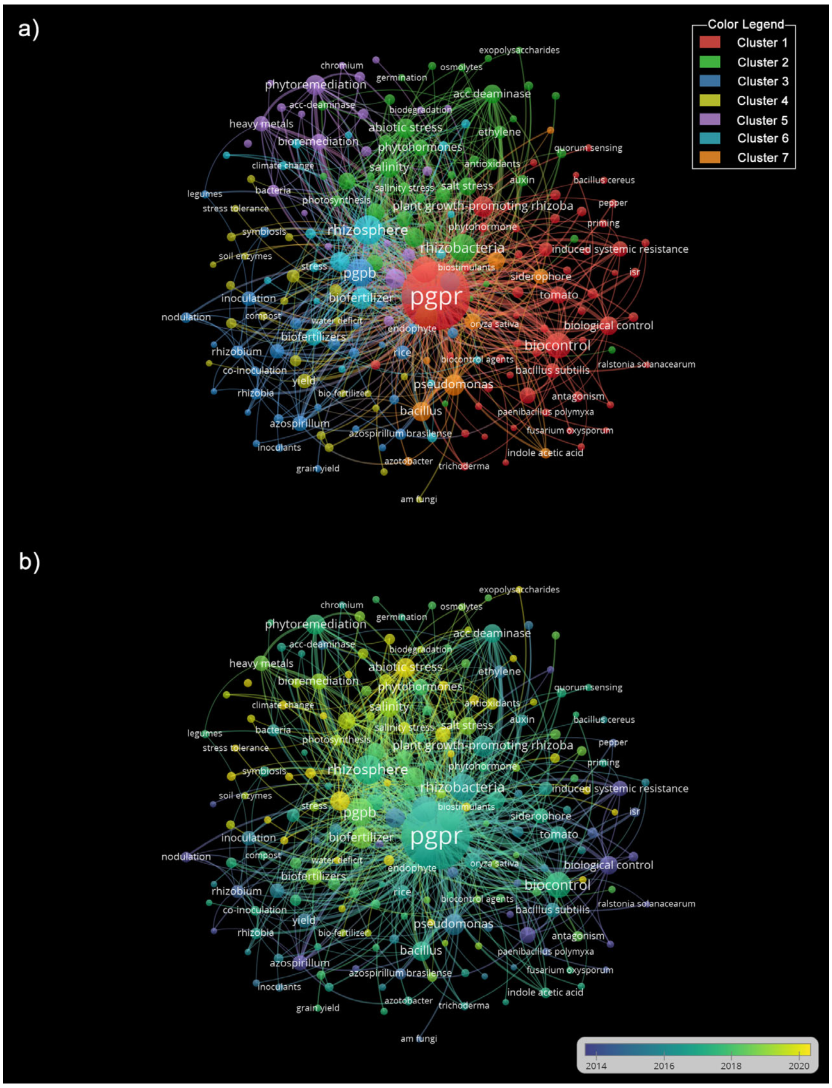

Fig. 4. (a) Co-occurrence network map of keywords in the published papers in the time frame 1992–2023 (until October 2023) containing the words "PGPR" or "PGPB" (Scopus source). The size of the nodes (keywords) is proportional to the occurrences number in the document set. Colours indicate clusters to which keywords are assigned for their reciprocal relatedness. (b) Overlay of the co-occurrence network map representing keywords on average occurrence in documents per publication year. Colour gradient indicates older publication in blue to recent publication in yellow. Colour gradient time range is automatically chosen by VOSviewer to highlight major differences through time. Data source: Scopus.

clusters (yellow, cluster 4 and violet, cluster 5). However, elaboration of the clusters and network mapping is consistent with the results obtained with RStudio, clearly emphasizing the shift of interest in the PGPR towards abiotic stresses such as salinity and drought, and on phytoremediation.

DISCUSSION

The bibliometric analyses showed increasing interest in the topic during the last 30 years, and in which countries published most of this topic. Additionally, we shed light on the shift of interest over time in sub-topics, highlighting that abiotic stress – salinity and drought – became more frequently linked to PGPR papers.

In the last 15 years, PGPR interest generally increased, with more publications in Agricultural and Biological Sciences and Microbiology. This indicates that the scientific community is working on this topic from two different sides and backgrounds: plant sciences/ecophysiology and microbiology, eventually meeting, such as in Castaldi *et al.* (2021) and Petrillo *et al.* (2022). Additionally, as reported in the network map analysis, there is a growing trend in the temporal gradient to encompass abiotic stresses, specifically salinity and drought, in the PGPR research, mainly from 2015 to 2020s. This confirms that studies integrating PGPR to enhance or ameliorate plant tolerance to salinity or drought stress are increasing, opening new research subtopics in a PGPR scenario. Moreover, the most prolific countries for paper publication on the topic PGPR and main sub-topics match the IPCC (2014) and FAO (2021) papers, highlighted areas of Earth affected by soil salinization and drought. This should agree with most frequently identified word '*soil*' in PGPR papers (RStudio analysis), considering the relevance of soil status and conditions in light of land degradation events encompassing salinization and drought. PGPR studies mainly contain '*bacteria*' and/or '*consortia*' suitability for growth on degraded substrates, and/or their capacity to enhance and ameliorate plant performances on overexploited soils. Not by chance, s*alt stress* and *drought stress* are in the first and second positions of the most frequent bigrams, agreeing with the network map, indicating the *abiotic stress* cluster (2, green), being one of the more recent issues of scientific community interest (2018–2020s). There has been a decreasing trend in 2023 in normalized data for the keyword combination with *salinity*, probably due to a shift of attention towards *drought*, since this has been most prominent in recent years (Bonaldo *et al.* 2023; Cao *et al.* 2023; Faranda *et al.* 2023; Nendel *et al.* 2023; Qiu *et al.* 2023), and because 2023 data were complete at the moment of the Scopus search (October 2023). On the other hand, RStudio elaboration indicates, both for single words and bigrams, two distinct cluster for salinity and drought stress. In both, it seems that salinity clusters are always bigger in size than drought clusters, probably indicating higher interest in salinization events, since these may often be a consequence and a direct effect of droughts. In addition, the increase in frequency of keyword combinations on auxin and ethylene as phyto-hormone responses against abiotic stress likely indicates rising interest in the scientific community on salt and drought stress phyto-signalling issues in the last 20 years. Indeed, auxin production is mainly enhanced by salt stress, which causes root-bending heliotropism (Galvan-Ampudia *et al.* 2013; Korver *et al.* 2020), drought stress induces lateral roots growth as hydro-patterning strategy (Bao *et al.* 2014; Orosa-Puente *et al.* 2018), while heat stress determines hypocotyl elongation (Wang *et al.* 2016). Ethylene production is also related to salt stress (Achard *et al.* 2006). Besides auxin and ethylene, abscisic acid (ABA) co-occurrence also increased, even if not remarkably compared to these. ABA production is related explicitly to plant physiological response to salt, drought, and heat stresses. ABA may cause inhibition of lateral root development and endodermal suberization (Barberon *et al.* 2016; Dietrich *et al.* 2017), root hydrotropism (Duan *et al.* 2013) and promote seedling survival (Larkindale *et al.* 2005). Our network analysis demonstrates that the frequency of other phytohormones, such as gibberellins and cytokinins, has slightly increased in the last 10 years. Our overall results suggest an increased shift in the scientific community's interest towards PGPR research and in the potential role of PGPRs in enhancing plant survival and growth under drought, salinity, and other abiotic stressors rather than stress-induced phyto-signalling pathways.

Indeed, PGPR determine changes in important metabolites involved in plant growth regulation and primary production, having a significant effect on growth and survivability of the plant under stress conditions. Generally, PGPR functions involve N_2 fixation, phosphate solubilization, acclimation of micronutrients, release of phytohormones, maintenance of soil composition, bioremediation of polluted soil, and induced resistance to pests and pathogens.

The keywords: *growth promotion*, *induced systemic resistance* and *PGPR* are predominant, specifically in the VOSviewer cluster 1 (red), representing – in terms of time gradient – the starting point of the shifting interest in abiotic stresses. RStudio cluster 1 defines PGPR techniques and effects on plants and merges *salinity* and *drought* into the same cluster (2). On the other hand, it is possible to identify two macro-cluster regions in both analyses, encompassing (I) the general benefits of PGPR application, and (II) PGPR utilization in the context of abiotic stresses. From the VOSviewer network map, the two macro-cluster regions are time-related in a keywords co-occurrence shifting perspective.

Several PGPR genera – such as *Rhizobium*, *Acetobacter*, *Bacillus*, *Serratia* and *Azospirillum* – have been already used and tested (Choudhary *et al.* 2016), providing mechanisms/processes to improve salinity stress and mediate the induced systemic tolerance, e.g., 1-amino cyclopropane-1-carboxylic acid (ACC) deaminase, extracellular polymeric substances, volatiles production, P_i solubilization, IAA production (Vaishnav *et al.* 2016). It is possible that all these terms related to mediated strategies to cope with abiotic stresses tend to cluster together, according to VOSviewer elaboration, into the same abiotic stress cluster (cluster 2, green). We may interpret this association as a macro-grouped cluster, encompassing abiotic stresses and the corresponding niche of studies, specifically focused on physiological and biochemical mechanisms involving PGPR applications to cope with salinity and drought stress. Notably, this niche developed in publications from 2015 to 2020. An overlapping group is found in cluster 7 (orange), mainly focused on specific bacterial strains and species and the benefits from their applications. This observation agrees with RStudio most frequent bigrams ranking, finding IAA at the third/fourth position and phosphate solubilization at the thirteenth position.

As anticipated, PGPR provide several mechanisms of drought and salinity resistance, ameliorating plant performance in dry or arid conditions (Novo *et al.* 2018; Numan *et al.* 2018; Pathania *et al.* 2020). In the literature, there are several examples of enhanced plant functional traits after PGPR inoculation to seedlings under drought stress, such as increased root and shoot length in mung bean by *Pseudomonas aeruginosa* (Kang *et al.* 2014), enhanced seed germination rates and root-adhering soil/root tissue dry mass ratio (RAS/RT) in foxtail millet by *P. fluorescens* (Niu *et al.* 2018), and improved foliar nutrient concentrations, root and shoot length in wheat by *Variovorax paradoxus* and a *Pseudomonas* spp. consortia (Chandra *et al.* 2019). Many papers report that PGPR application stimulates production of IAA by enhancing the number of root tips and surface area, with higher water absorption and nutrient uptake, root branching, germination, and leaf growth (Mantelin & Touraine 2004; Albacete *et al.* 2008; Dardanelli *et al.* 2008; Cassán *et al.* 2009, 2014; Egamberdieva & Kucharova 2009; Marulanda *et al.* 2009; Arzanesh *et al.* 2011). It has been demonstrated that increased IAA production mediated by *P. azotoformans* FAP5 under drought stress improved growth, germination rate, and root length in wheat (Ansari *et al.* 2021).

On this regard, the VOSviewer elaborated network map highlighted an entire cluster (7, orange) focused on *Azotobacter*, *Bacillus*, and *Pseudomonas* and their induced benefits. Even though it may be considered as an overlapped cluster, this indicates specific interest towards these genera in PGPR application. In the time gradient network map, cluster 7 (orange) may be located in the above-mentioned macro-cluster region (I). Indeed, it represents the starting point for genera, along with *Rhizobium* and *Azospirillum* from cluster 3 (blue), in PGPR utilization until 2014–2015. This time range was identified by

VOSviewer as the period of higher co-occurrence of *Pseudomonas*, *Rhizobium*, and *Azospirillum* in the chosen dataset of papers, before the move in interest towards *biocontrol*, *biofertilizer*, and *phytoremediation* keywords, and then to *abiotic stress*. For this, as well as the focus on *abiotic stress*, interest in more holistic and encompassing subtopics arose in recent years. Specifically, there has been clear growth in *sustainability* co-occurrence among PGPR publications, and related keywords, such as *biofertilizer*, *biostimulant*, *phytostabilization*, and *phytoremediation*. This indicates an increase in interest in PGPR utilization instead of employing pesticides and fertilizers (Chennappa *et al.* 2018; Riaz *et al.* 2021).

CONCLUSION

In summary, the study of PGPR, their features, and their application is a pivotal challenge for forthcoming decades, considering climate change effects on agriculture and food supply. The interest in this topic has increased significantly in the last 15 years, proving that global warming consequences on arable land is matter of urgency. This research field is now focusing on PGPR application to enhance crop growth and health in different soil contexts – specifically, salinity and drought affected areas – so that plantsroot systems can harbour inoculated microbes. The bibliometric network multi-analyses revealed many clusters. In both analyses, there was a clear grouping between the general benefits of PGPR application and PGPR utilization in the context of abiotic stresses. In particular, the time-gradient network map shed light on the shifting interest in PGPR, with moves towards abiotic stresses in light of climate change consequences affecting arable lands, and expanding to encompass sustainability, and thus sustainable agriculture, using PGPR as an alternative to pesticides and fertilizers.

AUTHOR CONTRIBUTIONS

C.L.: conceptualization, bibliographic research, bibliometric analyses, writing (original draft, review and editing). E.V.: writing (review and editing). B.H.M.: bibliometric analyses advice and conceptualization for RStudio analyses, writing (review and editing). C.A.: conceptualization, writing (review and editing). All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Cluster and keywords list from the “PGPR” or “PGPB” research results depicted in the Fig. 4 network map in the time frame 1992–2023 (until October 2023). Data source: Scopus.

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