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A Bibliometric Analysis of Seed Priming: Global Research Advances

Arinal Haq Izzawati Nurrahma[1,*], *Latifa Nuraini*[2], *Hana Haruna Putri*[3], *Ray March Syahadat*[4]

[1] Research Center for Food Crop, National Research and Innovation Agency (BRIN), Indonesia
[2] Research Center for Plant Conservation, Botanical Garden and Forestry, National Research and Innovation Agency (BRIN), Indonesia
[3] Graduate School of Agriculture, Forestry, and Fisheries, Kagoshima University, Japan
[4] Department of Landscape Architecture, National Institute of Science and Technology, Indonesia
Correspondence: E-mail: arin008@brin.go.id; arinal.brin@gmail.com

ABSTRACT

Seed priming techniques aim to enhance seed germination, improve plant growth, and increase resistance to environmental stress, resulting in better crop production. Recent studies show that the use of advanced technologies, such as nanotechnology and biotechnology, can increase the effectiveness of seed priming in improving crop quality and production. To identify trends and gaps in seed priming research, a bibliometric analysis is necessary. This study analyses the trends of seed priming research from 2002 to 2022 using science mapping, a bibliometric approach that involves quantitative and qualitative methods to analyze scientific publications, patents, grants, and other data sources to identify patterns, trends, and relationships. The study finds that seed priming research is becoming more widely recognized and cited, and the growth in publication and citation rates is accelerating. Pakistan, India, and China are the leading countries in seed priming research, as evidenced by the high number of publications and active author affiliations in these countries. The results can help researchers evaluate trends, gaps, and research direction in seed priming studies and propose future strategies for seed priming research and development..

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1. INTRODUCTION

Seed priming techniques were developed with the understanding that seeds stored for long periods or planted in non-optimal environmental conditions may experience dormancy or exhaustion, which can reduce germination and the quality of the plants grown (Shaban 2013; Long *et al*., 2015). The purpose of seed priming is to increase the rate and percentage of germination, improve germination, increase resistance to environmental stress, and accelerate overall crop production (Paparella *et al*., 2015). Seed priming can be done in various ways, including soaking the seeds in water, growth regulators, and nutrients before planting (Paparella *et al*., 2015; Saha *et al*., 2022). Some of the benefits provided by seed priming include: 1) seed priming can hasten the germination process and enhance the rate of seedling emergence, even under extreme climatic conditions, 2) it can improve drought tolerance in plants by acting as a growth regulator under limited soil moisture conditions, 3) priming treatments can be valuable for seed bank operators who need improved protocols for the conservation of germplasm collections and 4) the technique is widely used by seed technologists to enhance seed vigor and improve germination potential (Paparella *et al*., 2015; Marthandan *et al*., 2020; Devika *et al*., 2021).

Seed priming research continues to evolve in line with the increasing demand for higher-quality crop production as well as increased awareness of the importance of resource conservation and waste reduction in agricultural production (Garcia *et al*., 2022). Studies on seed priming have led to new findings. Pre-treating seeds with certain materials can increase the capacity of plants to cope with environmental stress such as drought, high humidity, high temperature, and pest and disease attacks and increase production even under adverse environmental conditions. Recent studies have also shown that the use of more advanced technologies, such as nanotechnology and biotechnology, can increase the effectiveness of seed priming in improving crop quality and production (Shang *et al*., 2019).

As technology and scientific understanding of plants continue to evolve, there will likely be further developments of seed priming research to improve crop quality and productivity in the future. To identify the trend and gap in seed priming research, it is necessary to conduct a bibliometric analysis. Science mapping is an important bibliometric approach to understanding the structure and dynamics of scientific research in a particular field or across multiple fields (Chen, 2017). This approach involves quantitative and qualitative methods to analyze scientific publications, patents, grants, and other data sources to identify patterns, trends, and relationships (Donthu *et al*., 2021). This information can be used to inform research policy, identify research gaps, and facilitate interdisciplinary collaborations (Karakose *et al*., 2022). Overall, science mapping provides a powerful tool for researchers to gain insights into the complex and dynamic nature of scientific research.

This study aims to analyze the trends of seed priming research from 2002 to 2022. The results will help researchers to evaluate trends, gaps, and research direction in seed priming studies. Specifically, this study aims to provide an accurate overview of the scientific publications on seed priming over time; understand the recent advances of seed priming research globally; and propose future strategies for seed priming research and development.

2. METHODS

We conducted a systematic review of academic research on seed priming worldwide. To provide visualizations, we used VOSviewer software version 1.6.18 from Leiden University in the Netherlands (Nurrahma *et al*., 2023), Bibliometrix 4.1.1 R Package (Aria and Cuccurullo,

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2017) and Microsoft Excel 2019. These tools are commonly used for bibliometric mapping and visualization.

2.1. Data Source and Search Strategy

The search for relevant papers, articles, proceedings, and reviews was carried out in the Scopus database during the past 20 years (2002–2022). Scopus was chosen because of its easiness of navigation and wide coverage (Burnham, 2006). On the Scopus website (www.scopus.com), the search terms were as follows: keyword = (seed priming) AND publishing year = (2002–2022). On the subject area, documents from dentistry; arts and humanities; health and professions; business, management, and accounting; psychology; economics, econometrics, and finance; mathematics; nursing; neuroscience; social science; and veterinary were excluded. Finally, the search resulted in 2,944 articles for analysis.

In this study, for bibliometric analysis, Scopus was searched on 3 February 2023 to compile the bibliography of all publications related to seed priming research conducted in the world. The research protocol is displayed in **Figure 1**. The Scopus data was mined and exported into RIS, CSV, and BIB. Microsoft Excel 2019 was used to compile the results. Publication year, countries, co-authorship connections among countries, journals, and subject areas, author keywords, authorship trend analysis, and co-authorship interactions between authors were analyzed.

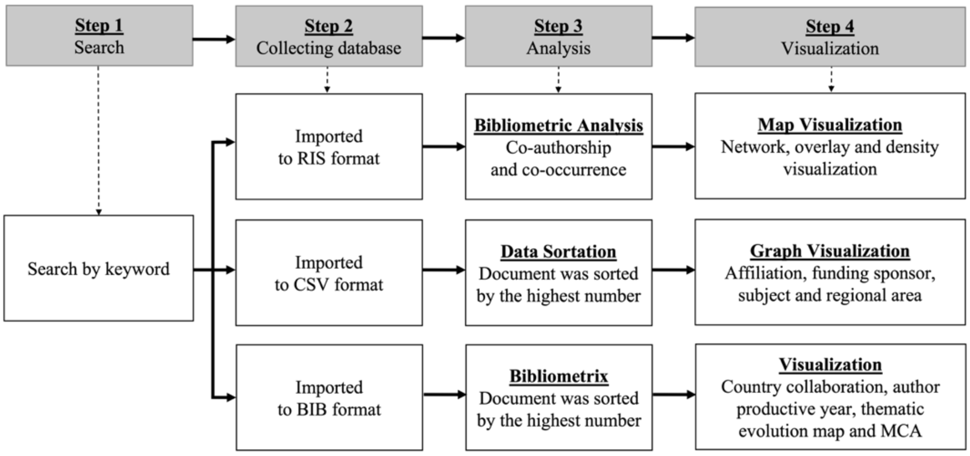

Figure 1. Step by step for searching, selecting, collecting, and visualizing data.

2.2. Data Visualization

VOSviewer was used to visualize co-occurrence and co-authorship using full counting methods. Eight minimum keywords from 10277 were used in the co-occurrence analysis, resulting in a 723 keyword that meets the threshold. While in the co-authorship analysis, we used five minimum authors from 8292 for the threshold. It only resulted in 351 authors for further analysis. For a specific study in Indonesia, one minimum keyword and author were used in the co-occurrence and co-authorship analysis, resulting in 160 and 102 thresholds, respectively. Then, the data were visualized by VOSviewer, consisting of a network, overlay, and density visualization map (Nurrahma *et al*., 2023).

Meanwhile, publication and citation number by year, and number of documents by country original, affiliation, funding sponsor, and document types were investigated and visualized using Microsoft Excel 2019 (Microsoft Corporation, USA). Country collaboration, author productive year, thematic map, thematic evolution map, and MCA analysis were conducted using Biblioshiny of Bibliometric 4.1.1 R Package.

3. RESULTS AND DISCUSSION

3.1. Growth of Publication and Citation Within 20 Years

Based on the Scopus database from 2002 to 2022, the number of publications and citation trends was limited until 2019, then continuously increased over time (**Figure 2A** and **B**). In the second decade (2012–2022), the average total publications and citations per year were higher, reaching a maximum in 2022. The overall curve for the number of publications and citations can be fitted into the exponential equation $y=24.412e^{0.1295x}$, $R^2= 0.9416$ and, $y=17.363e^{0.3344x}$, $R^2= 0.9921$ respectively. These equations show that the number of publications and citations has been increasing at an accelerating rate over time, with a higher growth rate in citations than in publications. This indicates that the growth in publication and citation rates is accelerating and that seed-priming research is becoming more widely recognized and cited.

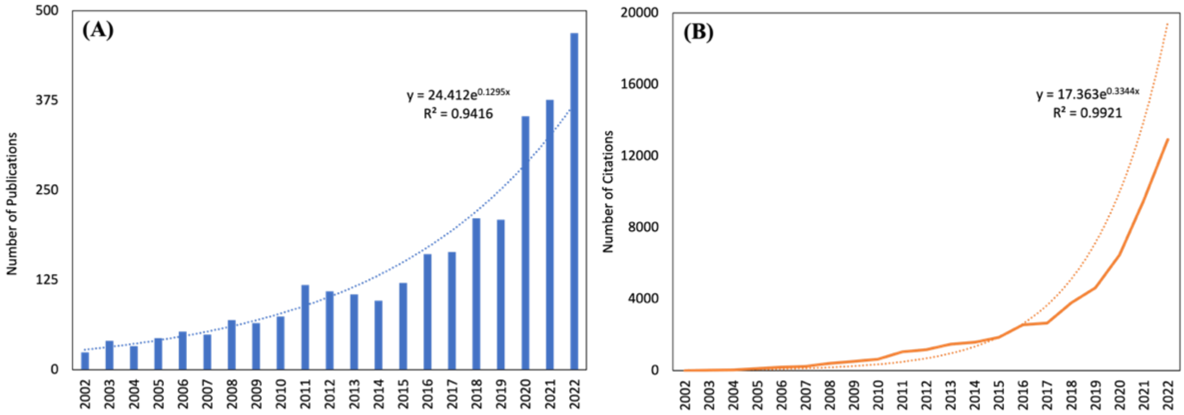

Figure 2. Number of publications (A) and citations (B) on seed priming research.

3.2. Productive Countries and Institutions

The number of papers published on seed priming research in a country reflects its level of development in this area. **Figure 3A** shows the top 10 countries with the highest publications on seed priming research, including four Southeast Asian countries. This information helps identify productive regions, cited institutions, and research hotspots. Our study found that 109 countries engaged in seed priming-related studies during the study period, with India, Pakistan, China, Iran, the United States, Brazil, Egypt, Saudi Arabia, Turkey, and Australia being the most productive countries. These countries contributed to 88.62% of all published documents (2609 documents). Although cooperation between Pakistan, India, China, Australia, and the United States was relatively close, these countries had limited collaboration with European, African, and Southeast Asian countries, which needs to be strengthened in future research (**Figure 3B**).

Author affiliations and funding sponsors are important indicators of academic attention in seed-priming research, as well as identifying active and influential institutions. In this study, the top 10 most marked author affiliations contributed 783 published documents, accounting for over 26% of the total number of publications (**Figure 4A**). Over the past 20 years, the University of Agriculture in Faisalabad, Pakistan ranked first with the largest number of papers, followed by Bahauddin Zakariya University and King Saud University. Notably, most of the top 10 productive author affiliations were based in Pakistan, India, and China. Similarly, the top 10 funding sponsor institutions contributed 418 documents, accounting for 15% of the total number of publications (**Figure 4B**), with most of them also coming from China, India, and Pakistan.

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Countries that produce more research papers on seed priming are likely to be more advanced in this research area for several reasons, i.e. availability of funding and expertise, application of research findings, and access to resources. The interest of Asian countries in researching seed priming is very large. It can be seen that 11 of the top 15 countries (73.3%) that researched this topic were Asian countries. Some of the reasons that are thought to be the cause are: 1) farmers and agricultural practitioners may have limited awareness and knowledge about seed priming techniques and their benefits, 2) limited access to quality seeds, priming agents, and equipment required for seed priming may hinder its widespread implementation 3) the diverse agro-climatic conditions in Asia may require different seed priming techniques for different crops and regions, making it challenging to standardize the process 4) the cost of seed priming materials and the additional labor required for the priming process may be prohibitive for smallholder farmers and 5) implementing seed priming techniques on a large scale may be challenging, especially in regions with small landholdings and fragmented agriculture (Kola *et al*., 2020; Elouadi *et al*., 2021; Bellia *et al*., 2022).

Pakistan, India, and China are the leading countries in seed priming research, as evidenced by the high number of publications and active author affiliations in these countries. The high concentration of productive author affiliations in certain regions may reflect the existence of research networks and collaborations within those areas. Moreover, the fact that most of the top funding sponsors are based in these countries suggests that there is significant financial support for seed priming research in these regions. These three countries also have a population of more than 30% of the world's total population. Therefore, they need a lot of effort to produce more food sources, so the seed aspect becomes very crucial for them.

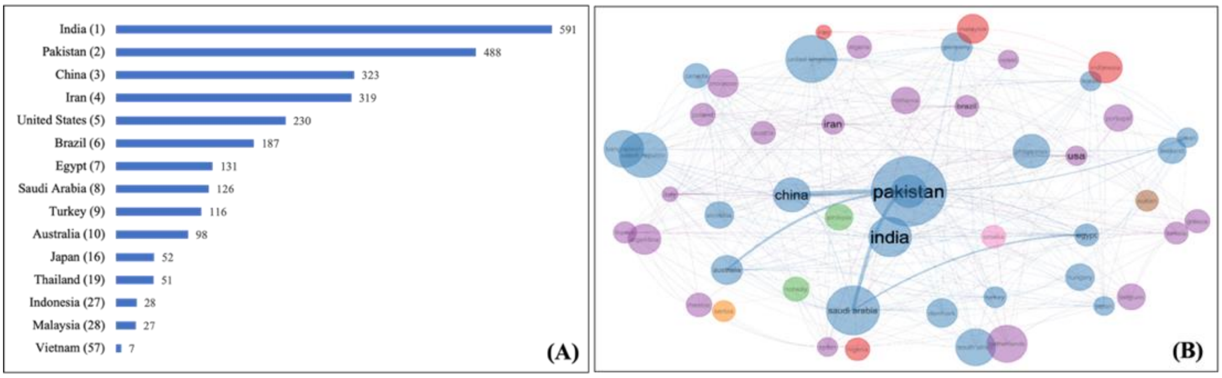

Figure 3. The most productive country (A) and country collaboration network (B). The number inside brackets behind the country name represents the global ranks.

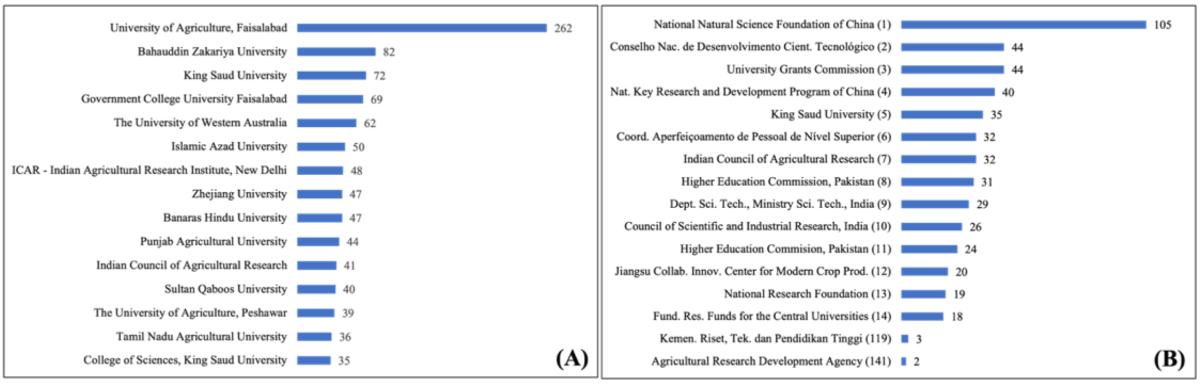

Figure 4. Number of published documents by affiliation (A) and funding sponsor (B). The number inside brackets behind the country name represents the global ranks.

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3.3. Authors Active Years, Their Networks and Research Focus

The active years and networks of the authors are shown in **Figure 5**. Farooq, M., Basra, S.M.A., Afzal, I., Wahid, A., and Nawaz, A. collaborate with other authors in different active years. The network overlay visualization can explain why certain authors may have more publications during the same productive period as other authors. Farooq, M. has the most collaborations among all authors, followed by Basra, S.M.A. and Afzal, I., each with 44, 39, and 31 links respectively, within the active range of 2014s-2020s. Wahid, A. and Nawaz, A. have 27 and 25 links, respectively, with fewer active authors in the year 2020s.

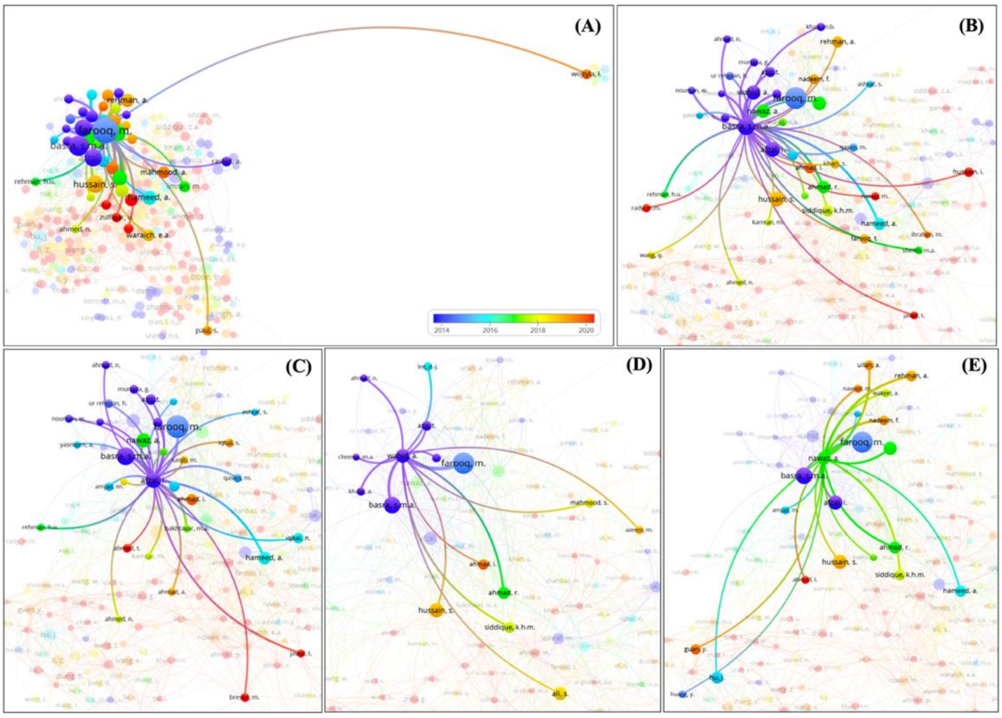

Figure 5. Top five author network overlay visualizations (A) Farooq, M., (B) Basra, S.M.A., (C) Afzal, I., (D) Wahid, A., and (E) Nawaz, A. Different color represents different active years.

The top five author-specific information in Table 2 were summarized from their published paper. All authors are focused on improving crop performance under different types of stress conditions, like drought, salinity, and allelopathic stress. They are experts in plant physiology, biochemistry, and agronomy, and they use seed priming to enhance crop performance. Farooq, M. has published many studies on the effects of different treatments, like polyamines, calcium, and sorghum extracts, on crop germination, growth, yield, quality, and biofortification under different tillage and cropping systems *(Hussain et al., 2008; Farooq et al.,* 2009). Basra, S.M.A. examines the physiological and biochemical changes induced by seed priming and explores the use of different priming agents, like zinc, moringa leaf extract, and glycine betaine. Afzal, I. investigates various seed conditioning and enhancement techniques, like exposure to magnetic fields and halopriming, and their effects on physiological and biochemical parameters, which lead to improvements in crop performance. Wahid, A. studies the physiological mechanisms that lead to improvements in crop performance, like changes in nutrient homeostasis, photosynthesis, and membrane properties. Additionally, he explores the use of plant extracts, like *Moringa oleifera*, to improve crop performance under stress conditions. Nawaz, A. investigates the effects of seed pre-treatment and application of specific nutrients, like zinc, boron, and manganese, on plant growth, yield, and quality, with a focus on biofortification.

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Table 2. Top five authors' specific research information.

Author	Expertise	Research Focus	Crops Studied	Techniques Used	Substances Studied
Farooq, M.	Plant physiology and agriculture, seed priming, drought tolerance, and nutrient application	Application of various treatments to improve plant performance, productivity, and profitability	Rice, wheat, chickpea, maize, soybean, faba bean, cowpea, barley, canola	Polyamines, micronutrients, calcium, selenium, zinc, boron, manganese, sorghum extracts, biopriming	Germination, growth, yield, quality, and biofortification
Basra, S.M.A.	Physiological and biochemical changes induced by seed priming	Seed priming to improve crop performance under abiotic stress	Rice, wheat, barley, sunflower, maize, rangeland grasses	Polyamines, zinc, moringa leaf extract, salicylic acid, glycine betaine, chitosan, ethanol	Integration with synthetic growth-promoting substances
Afzal, I.	Plant physiology and agricultural practices, seed conditioning, and enhancement techniques	Seed priming and physiological enhancements in various crops	*Moringa oleifera*, maize, bread wheat, *Zinnia elegans*, *Silybum marianum*, rice, sunflower, tomato, French marigold, pea	Moringa leaf extract, boron, calcium chloride, cytokinin, polyamines, mannitol, magnetic fields, halopriming	Antioxidant enzyme activity, reserve metabolism, protein profiles, ionic contents
Wahid, A.	Plant physiology, biochemistry, and agronomy	Improving crop growth and yield under stress	Various crops	Seed priming, exogenous application of substances such as polyamines, salicylic acid, and boron	Calcium, zinc, and plant extracts
Nawaz, A.	Agronomy, crop science, and plant nutrition	Improving productivity and biofortification of crops	Bread wheat, chickpea, rice, maize	Seed priming, seed pre-treatment, application of nutrients such as zinc, boron, and manganese	Plant growth, yield, quality

3.4. Cluster Analysis and Multiple Correspondence Analysis (MCA) of Trending Keyword

After conducting keyword analysis using VOSviewer network visualization, five major clusters were identified in seed priming research. These clusters are Cluster #1 germination (●), Cluster #2 metabolism (●), Cluster #3 gene expression (●), Cluster #4 antioxidant (●), and Cluster #5 seedling (●). Germination was found to be the largest cluster, appearing in 717 documents and having 563 links. It was followed by seedling with 263 documents and 523 links, metabolism with 272 documents and 511 links, an antioxidant with 191 documents and 474 links, and gene expression with 103 documents and 374 links (see **Figure 6A**). The keywords overlay visualization shows trending keywords in certain years represented by different colors. In recent years, the most commonly used keywords in seed priming research

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were Oryza, nanoparticles, abiotic stress, zinc oxide, malondialdehyde, and selenium (see **Figure 6B**).

The keyword analysis using VOSviewer network visualization provides insights into the major clusters and trending keywords in seed priming research. The five major clusters identified suggest that germination is the most researched topic in seed priming, followed by seedling, metabolism, antioxidant, and gene expression. Seed priming research investigates the effects of treating seeds with specific compounds or techniques before planting, to improve germination rates, support healthy seedling establishment, enhance metabolic activity, increase antioxidant activity, and modulate gene expression to optimize plant growth and resilience. As a result, seedlings that have undergone seed priming exhibit improved growth, stress tolerance, and increased yield potential (Garcia *et al*., 2022).

The visualization also indicates that certain keywords have gained popularity in recent years, such as *Oryza sativa*, nanoparticles, abiotic stress, zinc oxide, malondialdehyde, and selenium, indicating that these topics are currently of interest to researchers in the field. Nanoparticle priming, simply referred to as nanopriming, is the use of nanoparticles (particle size range of 1–100 nanometers) to enhance the performance of plant seeds. Some common nanoparticles used for nanopriming are Silicon (Si), Zinc (Zn), Copper (Cu), Silver (Ag), Iron (Fe), Selenium (Se), etc. Nanoparticle priming is a novel approach that involves coating seeds with nanoparticle solutions, which can penetrate the seed coat and improve water uptake and nutrient absorption.

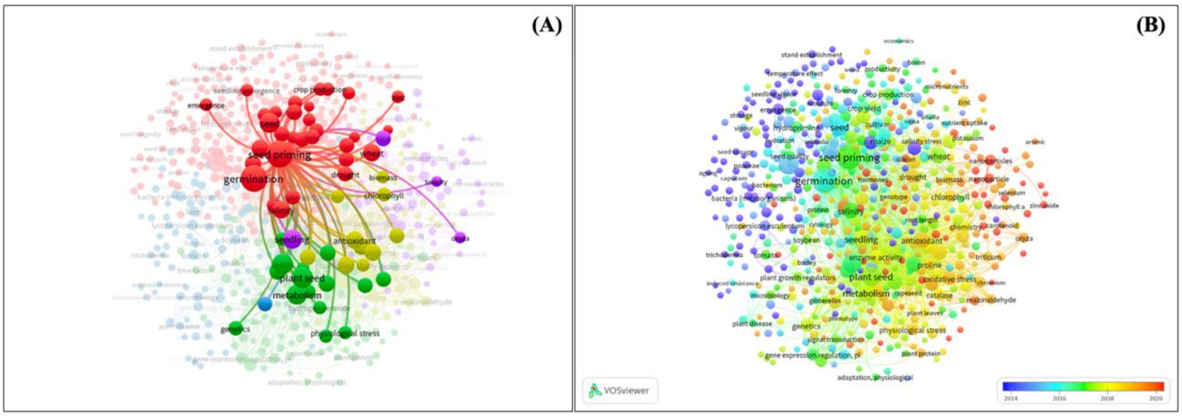

Figure 6. Visualization of seed priming research (A) and overlay map in 20 past years (B).

Multiple Correspondence Analysis (MCA) is a statistical technique that compresses large amounts of data with multiple variables into a lower dimensional space, creating a two-dimensional graph that represents the similarity between keywords through plane distance. The analysis provides a useful tool for identifying the key topics and trends in the literature on seed priming, and for visualizing the relationships between different keywords and topics (Aria and Cuccurullo, 2017). The Multiple Correspondence Analysis (MCA) of the keywords on seed priming was performed using the R Package of Bibliometrix 4.1.1.

Figure 7 presents a conceptual structure map of the keywords associated with the seed-priming articles analyzed in this study. This map compresses extensive data with multiple variables into a low-dimensional space, creating an intuitive two-dimensional graph that represents the similarity between keywords through plane distance. The positions of the points and their distribution along the dimensions reflect the relative similarity between the words, with closer proximity indicating greater similarity (Caparrós *et al*., 2021). The analysis employed automatic clustering with a maximum of 50 terms, following the parameters suggested (Aria and Cuccurullo, 2017; Caparrós *et al*., 2021).

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The result of the analysis shows a conceptual structure map of the keywords associated with the seed-priming articles. Cluster 1 is the more scientifically influential cluster, as it comprises a larger number of keywords and topics related to seed priming. The keywords in Cluster 1 are related to various aspects of plant growth and development, including crop yield, seed treatment, and cultivation. Cluster 2, on the other hand, includes keywords related to genetics, plant physiology, and stress. This could be because seed priming research has been predominantly focused on practical applications, such as improving crop yield and seed treatment methods, rather than on basic research in genetics and plant physiology. Seed priming is a technique used to enhance seed germination and early seedling growth, which ultimately leads to better crop yield. Therefore, it is not surprising that research topics related to crop production, seed treatment, and cultivation would be of greater interest to seed priming researchers. However, this does not mean that research in genetics, plant physiology, and stress is not important in seed priming. These areas of research could have significant implications for improving the efficacy of seed priming techniques, and researchers will likely continue to explore these topics in the future.

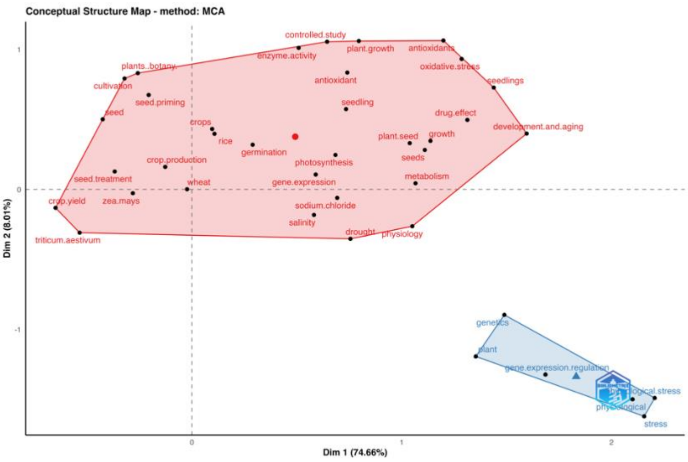

Figure 7. Conceptual structure map of keywords on seed priming research.

In the theme's evolution, the 20 years was divided into five stages: 2002–2004, 2005–2009, 2010–2014, 2015–2019, and 2020–2022 (**Figure 8**). The time evolution of all the keywords in seed priming research showed that the most used keywords have changed significantly in the research process. Seed priming research has evolved over the years, with different research topics and keywords being popular in different periods. From 2002 to 2004, the main research keywords were germination, fungi, hydration, and seed, and specific research topics included *Helianthus annuus*, *Brassica napus*, *Oryza sativa*, *Beta vulgaris subsp. vulgaris*, *Phaseolus* (angiosperm), *Triticum aestivum*, *Zea mays*, *Momordica charantia*, and *Allium cepa*. This research focus could be attributed to the fact that these were the key areas of concern at that time. Research on specific crops such as *Helianthus annuus* and *Brassica napus* may have been driven by the need to improve seed quality and crop productivity in these crops, which were of economic importance in many regions.

Between 2005 and 2009, the use of bacteria (microorganisms) for seed priming gained popularity, and specific research topics were limited to *Pennisetum glaucum*, *Oryza sativa*, *Cucumis*, and *Daucus carota*. The possible reason for the shift towards the use of bacteria for seed priming in the 2005–2009 period could be the growing interest in sustainable and environmentally friendly agricultural practices. Bacteria have been known to have beneficial effects on plant growth and can act as biofertilizers and biocontrol agents against plant pathogens. Therefore, the use of bacteria for seed priming could have been seen as a

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promising alternative to chemical fertilizers and pesticides. Additionally, the specific research topics limited to *Pennisetum glaucum*, *Oryza sativa*, *Cucumis*, and *Daucus carota* could have been influenced by the significance of these crops in local agriculture and the demand for improved crop yield and quality. *Abelmoschus* was added as a specific research topic in 2010–2014. The shift in seed priming research focus towards *Abelmoschus* in 2010–2014 could be due to its economic importance as a crop or the interest of researchers in exploring its potential for seed priming. From 2015–2022, plant seed replaced the popularity of physiological studies on metabolism as the main research keyword, and germination remained a research hotspot throughout, given that improving the germination rate is the ultimate goal of seed priming.

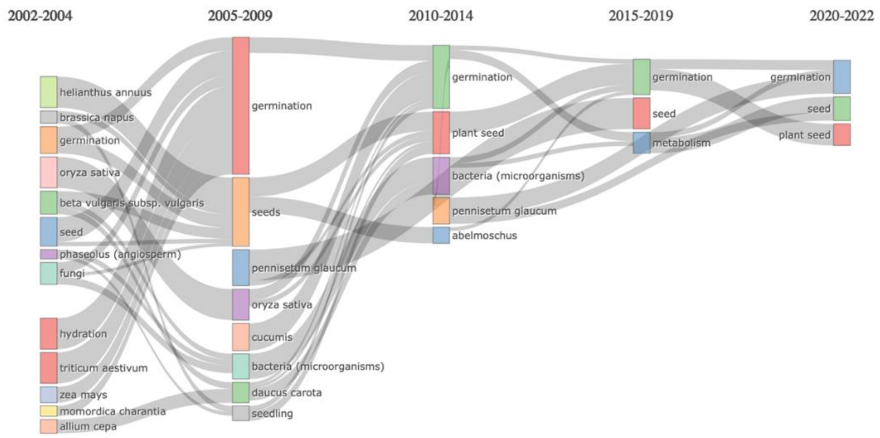

Figure 8. The temporal evolution of popular keywords on seed priming study. The horizontal axis displays the years, while each node corresponds to a frequently cited keyword, with its size indicating its relative frequency of use. The lines connecting the nodes depict the evolution of these keywords over time and represent the transfer and relationship of their heritability. Different colours are used to distinguish between the various keywords.

There are several possible reasons why the focus of seed priming research has changed over time. One reason could be the advancement of technology and the availability of new research methods and equipment, allowing researchers to explore new aspects of seed priming. Another reason could be the changing needs and priorities of the agricultural industry, which may drive research toward certain crops or specific aspects of seed priming. Scientific discoveries and breakthroughs in related fields may also influence the direction of seed-priming research. Finally, the availability of funding and resources for research could also play a role in determining the focus of seed priming research.

3.4. Future Direction

Seed priming research is a dynamic and evolving field that holds great promise for sustainable agriculture and food security in the face of climate change and environmental stress. Recent developments in seed priming have focused on new priming methods, understanding the physiological and molecular mechanisms underlying priming effects, and identifying optimal priming conditions for different crops and stress environments. Nanoparticle priming is a novel approach that uses silver, zinc, or silicon nanoparticles to improve water uptake and nutrient absorption in seeds, enhancing germination and growth under stress conditions. Hormonal priming using gibberellins, abscisic acid, or salicylic acid has been found to enhance antioxidant defenses, osmotic regulation, and seedling vigor under stress. Additionally, seed inoculation with beneficial microorganisms, such as rhizobia

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or plant growth-promoting bacteria, has been used to improve nutrient uptake and plant growth, and recent studies have shown that microbial priming can also enhance plant tolerance to abiotic stress. Advances in genomics, transcriptomics, proteomics, and metabolomics have provided new insights into the molecular mechanisms underlying seed priming effects, identifying key genes, proteins, and metabolites involved in priming-induced stress tolerance and revealing the complex signaling pathways that regulate seed germination and early growth. There are still some crops that have not been studied much in terms of the effects of seed priming on germination rate and seed vigor, indicating a need for further research in this area. Additionally, there is a lack of research comparing the effectiveness of different seed priming methods and considering the interaction between seed priming and environmental factors such as temperature, humidity, and soil quality.

4.CONCLUSION

Seed priming research is a technique used in agriculture to improve the germination and establishment of crops. This is primarily conducted in the fields of agricultural and biological sciences, biochemistry, genetics, molecular biology, and environmental science. The controlled hydration of seeds activates various physiological and biochemical processes in the seed, facilitating faster and more uniform germination and enhancing seedling growth and stress tolerance. Pakistan, India, and China are the leading countries in seed priming research, as evidenced by the high number of publications and active author affiliations in these countries. The most popular topics covered in articles on seed priming research include induced systemic resistance, pre-sowing seed treatments, seed priming, and direct seeding of rice. Farooq, M. is the most published author in this field, followed by Basra, S.M.A. and Afzal, I.

5. AUTHORS' NOTE

The authors guarantee that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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