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Nanoparticles Enhance Plant Resistance to Abiotic Stresses: A Bibliometric Statistic

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Abstract: Using nanoparticles (NPs) to effectively mitigate the negative effects of abiotic stressors on plant growth and development will help to achieve sustainable agriculture. Although there have been some prior reviews in this area, bibliometrics is still lacking. In this study, the most productive nations or regions, journals, publishers, and scholars in this field were identified using an objective bibliometric examination of the pertinent material published in the Web of Science core database. To dig deeper for information, the keywords co-occurrence, collaboration network of countries/regions and authors, and network map of highly cited papers citation are used to characterize present advances and forecast potential future trends. The results show a growing interest in using nanoparticles to alleviate abiotic stressors. There has been an exponential increase in the number of relevant papers and citations. Moreover, Asian countries are the most active in this subject, even if the USA generates papers with the best overall quality. The most common publishers and journals in this area are Elsevier and Environmental Science-Nano, while Wu HH is currently the most active author. Even though many researchers have formed close partnerships, there is not yet a large collaborative group of researchers in this field. Gaps in the current scientific literature are highlighted, such as the lack of use of omics, especially multi-omics, to provide a more in-depth and comprehensive explanation of the molecular mechanisms by which NPs enhance plant resistance to abiotic stresses. This bibliometric study will provide a valuable reference for studying the evolution of the field and identifying research frontiers.

Keywords: abiotic stresses; bibliometric; NPs; plant; sustainable agriculture

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1. Introduction

By 2050, it is anticipated that there will be more than 9.7 billion people on the planet, which would significantly boost the demand for food [1]. Since plants cannot move, they are regularly subjected to a variety of abiotic stressors, which severely limit crop output and sharply lower agricultural yields [2,3]. It has been shown that about 50% of agricultural yields are directly or indirectly reduced by abiotic stress factors [4]. Furthermore, climate change and environmental degradation brought on by human activity exacerbate the negative impacts of abiotic stresses [5,6].

Therefore, new and effective technologies are urgently needed to mitigate the impacts of abiotic stress on crop growth, and nanoparticles (NPs) are a newly emerging and promising strategy to mitigate abiotic stress [7]. NPs refer to materials with a size of 1–100 nm [8]. NPs may be more reactive than bulk materials due to their distinct physical characteristics, such as their extremely small size and huge surface area, which could lead to more harmful or helpful effects on plants [9,10]. It has been shown that NPs can improve photosynthetic pigment production, regulate redox status, increase antioxidant defense mechanisms, regulate primary glucose metabolism, and modulate plant hormone signaling

to help plants adapt to and overcome abiotic stress [11–13]. For this reason, NPs have become a promising solution for fostering sustainable agriculture [14].

The potential of NPs to promote sustainable agriculture has gained increasing popularity among researchers [15]. However, the rapid expansion in the number of published papers in the field has made it increasingly difficult for researchers to follow the lead and capture the latest discoveries. Although several outstanding reviews on this subject can give researchers important knowledge and creative direction [14,16–18], there has not yet been a thorough examination of the literature in this field. By rigorously parsing vast amounts of unstructured data, the bibliometric approach can assist researchers in quickly locating the most crucial literature on the topic and mapping the research area without subjectivity [19]. Additionally, bibliometrics offers a variety of qualitative and quantitative indicators of the success of scientific research in the field, including the number of publications, citations, author collaboration networks, and national collaboration networks. This is crucial for understanding the state of the field and determining the future directions of research [20]. Thanks to the rapid advancement of bibliometric software and scientific databases, bibliometric analysis has been applied in more and more disciplines and is playing an increasingly vital role [21]. Additionally, there have been some excellent bibliometric studies on how plants respond to abiotic stresses [20,22–26].

This study aims to illustrate, using bibliometrics, the geographical distribution, variation in numbers, researchers, and keyword evolution of papers on the study of nanoparticle mitigation of abiotic stresses in plants. This will provide valuable references and information on the use of NPs to mitigate plant abiotic stress and achieve sustainable agriculture.

2. Materials and Methods

2.1. Data Collection

In the search bar of the Web of Science core database, we entered the topics "nanoparticles or NPs," "abiotic stress," and "plant" on 4 January 2023. A total of 392 papers were retrieved. A total of 385 papers were obtained by selecting original research papers plus reviews. These 385 papers were then exported from the database. After that, we checked using Endnote 20 and Citespace 6.1 and discovered no duplicate papers. Thus, a total of 385 literature records—279 original research publications and 106 reviews—were eventually acquired.

2.2. Bibliometric Indicators

We used HistCite Pro 2.1 to analyze the year of publication, country of publication, author, and citation by other papers of all literature [27]. Then, depending on the number of articles, we created a globe map using ArcGIS 10.6 (Environmental Systems Research Institute, Inc., Redlands, CA, USA) to display the contribution of each nation or region. TLCS and TGCS represent the number of citations of a paper in local databases (databases composed of exported literature) and global databases, respectively, and are basic indicators of bibliometrics [28]. The TLCS and TGCS of all papers were obtained using HistCite Pro 2.1. The "analyze search results" function of the "Web of Science" was used to count the affiliated journals and publishers of all papers.

Impact factor (IF) and *h*-index are important evaluation indicators in bibliometric analysis. IF is an important indicator of the influence of journals, the quality of papers, and the level of scientific research [29]. The *h*-index has been increasingly used to assess the scholarly contributions of researchers and predict their future scientific achievements [30]. In short, if a researcher has co-authored h papers and each paper has been cited at least h times, he or she will have a corresponding *h*-index [31]. We queried the authors' *h*-index online using the Web of Science database. We also used the journal citation reports published by Clarivate Analytics to find the impact factors and JCR classifications of journals.

VOSviewer is excellent visualization software for bibliometric analysis and can be used to draw collaborative network diagrams of authors and countries and co-occurrence network diagrams of keywords [32]. We used VOSviewer 1.6.18 to display collaborative

network diagrams of authors and countries as well as co-occurrence network diagrams of keywords across all literature.

3. Results and Analysis

3.1. Number of Publications and Citations Per Year

First, an annual tally of all publications was taken (Figure 1). It was first published in 2008. From 2008 to 2013, the corresponding number of papers published and citations increased slowly. Since 2014, both the number of citations (NC) and the number of publications (NP) have shown rapid exponential growth. From 2014 to 2020, it was the first stage of rapid growth in achievements in the field. NC and NP skyrocketed 25.85 times and 10.75 times, respectively. The period from 2020 to 2022 represents the second stage of rapid expansion in outcomes in this field, with NC and NP continuing to soar from a substantial foundation, expanding by 2.88 and 1.81 times, respectively.

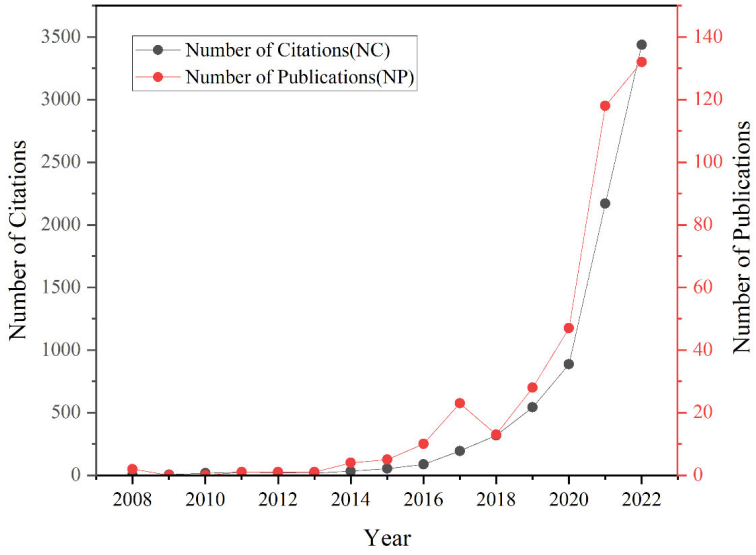


Figure 1. The trend of the number of publications (NP) and citations (NC) regarding NPs enhancing abiotic tolerance in plants from 2008 to 2022.

3.2. Most Productive Publishers and Periodicals

HistCite Pro 2.1 was used to count the publishers and periodicals of all publications. The top publishers and journals are listed (Tables 1 and 2). It can be found that for publishers, the famous Elsevier ranked first, followed by MDPI and Springer Nature. The top three publishers together account for more than half of all publications. In terms of periodicals, "Environmental Science Nano" and "Frontiers in Plant Science" are the most popular, with 19 papers each. Plants-Basel has also published 18 related papers. It can also be seen that the popularity of papers in this field is relatively high, and the quality of the top several journals is all high, except for "Plants-Basel," where the IF of all the other journals is greater than five, and save for "Nanomaterials," all the other journals are classified as Q1 in the JCR partition.

3.3. Most Productive Countries/Regions

The countries involved in the publication of these papers were counted using HistCite Pro 2.1. A total of 65 countries or regions contributed (Figure 2). It is easy to see that Asia is the region with the greatest concentration and activity of relevant research. Likewise, the top five countries for NP and TGCS are listed (Tables 3 and 4). China and India have participated in more relevant papers published in the past, contributing 29.4% and 18.4% of all papers, respectively. However, the higher quality of the U.S. papers involved is reflected in the higher TGCS. This may be because the US has a developed economy and can invest more money in this area of research.

Table 1. The top seven publishers that published papers regarding NPs enhancing abiotic tolerance in plants from 2008 to 2022.

Publishers	Record Count	Percent (%)
Elsevier	89	23.117
MDPI	81	21.039
Springer Nature	66	17.143
Frontiers Media Sa	25	6.494
Royal Society of Chemistry	25	6.494
American Chemical Society	18	4.675
Wiley	13	3.377

Table 2. The top seven periodicals that published papers regarding NPs enhancing abiotic tolerance in plants from 2008 to 2022.

Periodicals	Record Count	Percent (%)	Affiliated Publisher	IF	JCR
Environmental Science-Nano	19	4.935	Royal Society of Chemistry	9.473	Q1
Frontiers in Plant Science	19	4.935	Frontiers Media Sa	6.627	Q1
Plants-Basel	18	4.675	MDPI	4.658	Q1
Ecotoxicology and Environmental Safety	14	3.636	Elsevier	7.129	Q1
Chemosphere	13	3.377	Elsevier	8.943	Q1
Plant Physiology and Biochemistry	11	2.857	Elsevier	5.437	Q1
Nanomaterials	10	2.597	MDPI	5.719	Q2

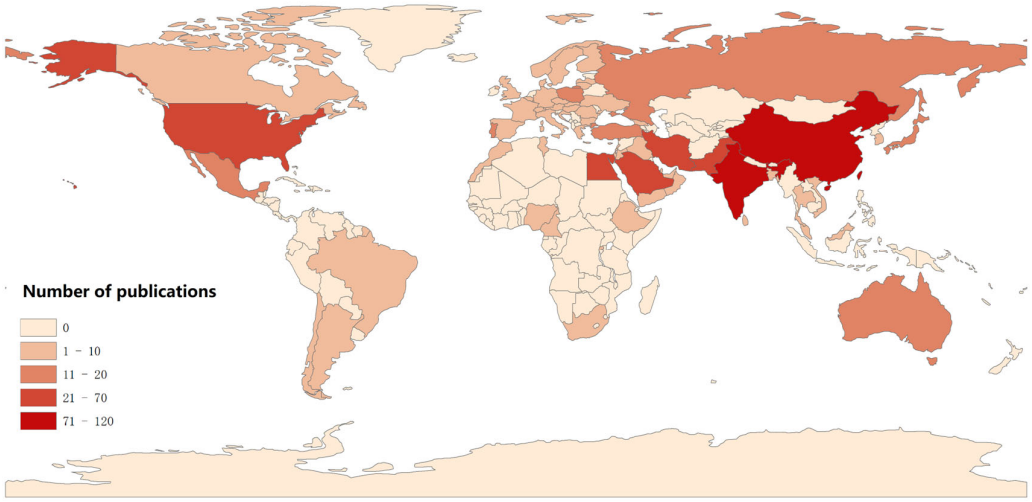


Figure 2. A globe map showing the contribution of each country/region based on the number of publications.

Table 3. The top five countries/regions that published papers regarding NPs enhancing abiotic tolerance in plants from 2008 to 2022.

Country/Region	NP	Percent (%)
China	113	29.4
India	71	18.4
Pakistan	64	16.6
USA	61	15.8
Egypt	52	13.5

Table 4. The top five most influential countries/regions that published papers regarding NPs enhancing abiotic tolerance in plants from 2008 to 2022.

Country/Region	TGCS	Percent (%)
USA	2236	14.87
China	1777	11.82
Saudi Arabia	1365	9.08
Pakistan	1329	8.84
Egypt	1024	6.81

3.4. Most Influential Researchers

A total of 1848 researchers are involved in this field. Among them, the most productive one is Wu HH from Huazhong Agricultural University. He is involved in a total of 13 outstanding publications from 2017 to 2022. He was followed by Ali S from Government College University and Rizwan M from Qatar University, both of whom were involved in the completion of 12 publications. The analytical hierarchy process (AHP), a crucial multiple-criteria decision-making method, has been extensively investigated and used in the past due to its broad applicability and simplicity [33,34]. Han et al. (2004) used AHP stratified analysis to synthesize the influence of researchers, and indicated that the weights of NP, *h*-index, and ACI (the average number of citations per paper by the researcher) were 24.39%, 16.64%, and 58.97%, respectively [35]. Consequently, we calculated the final scores of researchers with larger outputs (NP $\geq$ 7) according to this weighting factor (Figure 3). The results showed that Giraldo JP from the University of California scored 39.80 and ranked first, followed by Ali S (36.08), Wu HH (35.24), and Rizwan M (34.73).

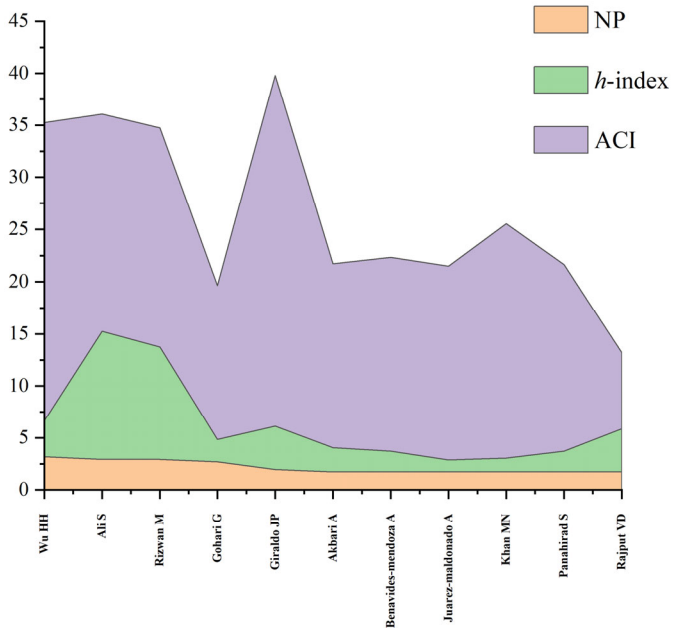


Figure 3. The number of publications (NP) of the most productive authors and their corresponding *h*–index, ACI.

3.5. Network of Collaboration

In this area, numerous countries/regions have worked together to create a sophisticated network of cooperation (Figure 4A). The countries that collaborate and exchange the most internationally are China, India, the USA, Saudi Arabia, Pakistan, and Egypt. For collaboration between researchers, the outstanding contributors are Wu HH, Rizwan M, Ali S, and Gohair G from the University of Maragheh (Figure 4B). However, no sizable team of collaborators has emerged in this area.

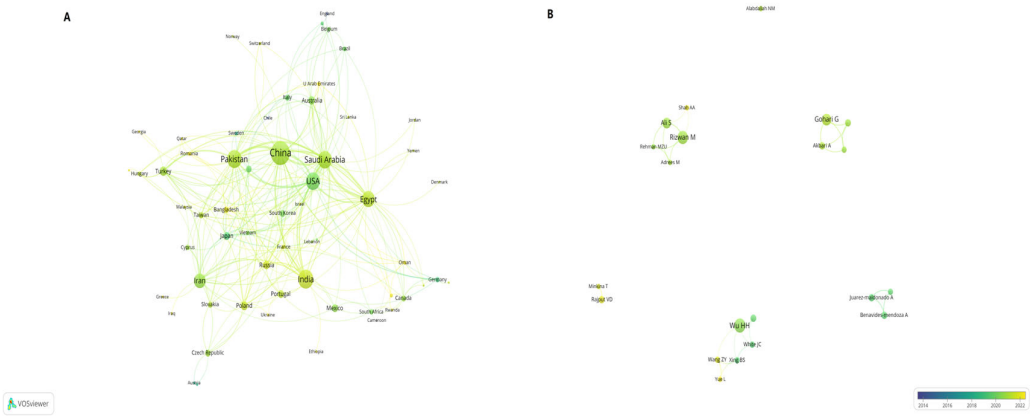


Figure 4. The collaboration network of countries/regions and authors. Note: The node's size reveals how frequently it is used. The simultaneous relationship between the nodes is indicated by the link between the two nodes. The co-occurrence frequency of the two sets of nodes is shown by the thickness of the connection between the two nodes. Different node colors signify various clustering outcomes. The same as below.

3.6. Highly-Cited Publications

The TLCS of a publication is the number of times it has been cited in the local database (the selected database for bibliometric analysis) (Table 5), and the higher the TLCS of a publication, the higher its importance and peer recognition [20]. Based on TLCS, 385 literature records were sorted, and the first 30 records were selected for citation network mapping (Figure 5). Each circle represents a publication. The number in the circle is the serial number of the publication in the current database, and the size of the circle is proportional to the TLCS of the corresponding publication. The arrows between the circles show citation links between publications, with the arrows pointing to the cited literature. The number of node links is 25. The TLCS ranges from 6 to 40. These 30 papers with the highest peer recognition can roughly represent the major evolution of research on the effects of nanomaterials on plant stress resistance.

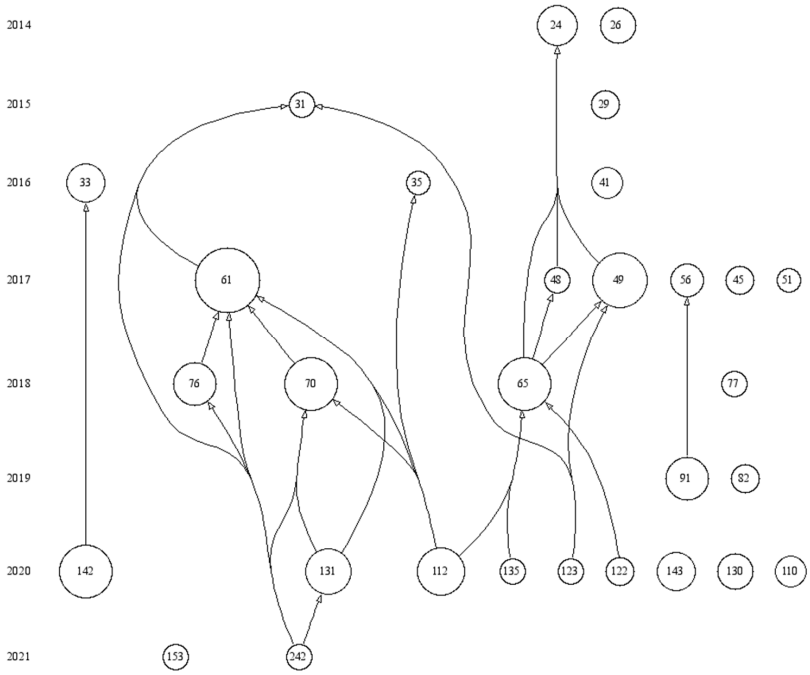


Figure 5. The top 30 publications highly cited by peers in the local database. Note: The number in the circle refers to the serial number of the document in the local database.

Table 5. Details of the top peer-cited papers in the local database.

Order	Article Title	PY	TLCS	Author
61	Anionic cerium oxide nanoparticles protect plant photosynthesis from abiotic stress by scavenging reactive oxygen species	2017	40	Wu HH, Tito N, Giraldo JP [36]
49	Role of nanomaterials in plants under challenging environments	2017	30	Khan MN, Mobin M, Abbas ZK, et al. [16]
70	Hydroxyl radical scavenging by cerium oxide nanoparticles improves Arabidopsis salinity tolerance by enhancing leaf mesophyll potassium retention	2018	28	Wu HH, Shabala L, Shabala S, et al. [37]
65	Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions	2018	26	Latef AAHA, Srivastava AK, Abd El-Sadek MS, et al. [38]
142	Amelioration of salt induced toxicity in pearl millet by seed priming with silver nanoparticles (AgNPs): The oxidative damage, antioxidant enzymes and ions uptake are major determinants of salt tolerant capacity	2020	26	Khan I, Raza MA, Awan SA, et al. [39]
112	Nano-Biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance	2020	22	Zhao LJ, Lu L, Wang AD, et al. [14]
131	Emerging investigator series: molecular mechanisms of plant salinity stress tolerance improvement by seed priming with cerium oxide nanoparticles	2020	21	An J, Hu PG, Li FJ, et al. [40]

Note: Order refers to the serial number of the publication in the local database. PY: the publication year of the paper.

The literature with high TLCS first appeared in 2014, which is consistent with the above-mentioned that this field has gradually attracted wide attention since 2014. Literature with high TLCS was published from 2014 to 2020, while literature published from 2020 to 2022 had a decline in peer recognition. The literature with a high TLCS value was No. 61, 49, 70, 65, 142, 112, and 131 (The serial number here refers to the serial number of the document in the local database). In general, references 61, 70, 65, and 112 (The serial number here refers to the serial number of the document in the local database)serve as key bridges connecting the interconnections and citations in this field.

3.7. Keyword Co-Occurrence

Keyword co-occurrence uses keywords from the literature to construct a semantic map of the domain, enabling scientific discovery of connections between sub-domains and facilitating researchers to track trends [41]. Figure 6 shows the keyword co-occurrence mapping generated using VOSviewer. Older keywords are shown in purple, while newer keywords are shown in yellow. As can be seen, the most notable keywords are nanoparticles, abiotic stress, growth, tolerance, and salt stress. This suggests that the selected literature is primarily concerned with NPs improving plant tolerance to abiotic stresses and, as a result, plant growth in abiotic stress environments. The value of NPs in mitigating salt stress has been studied the most in the past. Early important keywords were mainly: "phytotoxicity", "toxicity", "*Arabidopsis thaliana*", etc. The bulk of research on the effects of NPs on plant abiotic stress resistance began, like many studies, with the study of *A. thaliana*, the model plant [42–45]. Later, the keywords became antioxidant enzymes, responses, and proline. This suggests that studies targeting the mitigation of abiotic stresses in plants by NPs at that time were focused on physiological aspects such as antioxidant enzymes and osmoregulation. Currently, the most important keywords, apart from the largest ones mentioned earlier, are ZnO nanoparticles, drought stress, cerium oxide nanoparticles, foliar application, *Triticum aestivum* L., and soil. ZnO NPs are currently one of the most popular NPs, with global production expanding from 550 to 33,400 metric tons in a short period and

still rising [46]. Many studies have now shown that ZnO NPs can effectively enhance plant resistance to abiotic stresses. According to our previous research, ZnO NPs can enhance antioxidant systems and photosynthesis in tomato (*Lycopersicon esculentum*) and rice (*Oryza sativa*) seedlings, enhance the activity of antioxidant enzymes, plant hormone crosstalk, and late embryogenesis-abundant protein in developing seeds of *Styrax tonkinensis* to alleviate abiotic stress [11,47–50]. The change in keywords indicates that research on NP mitigation of abiotic stresses is gradually developing in-depth, and not only is the variety of NPs increasing, but so are the application methods, with a broad scope of application in both agriculture and forestry.

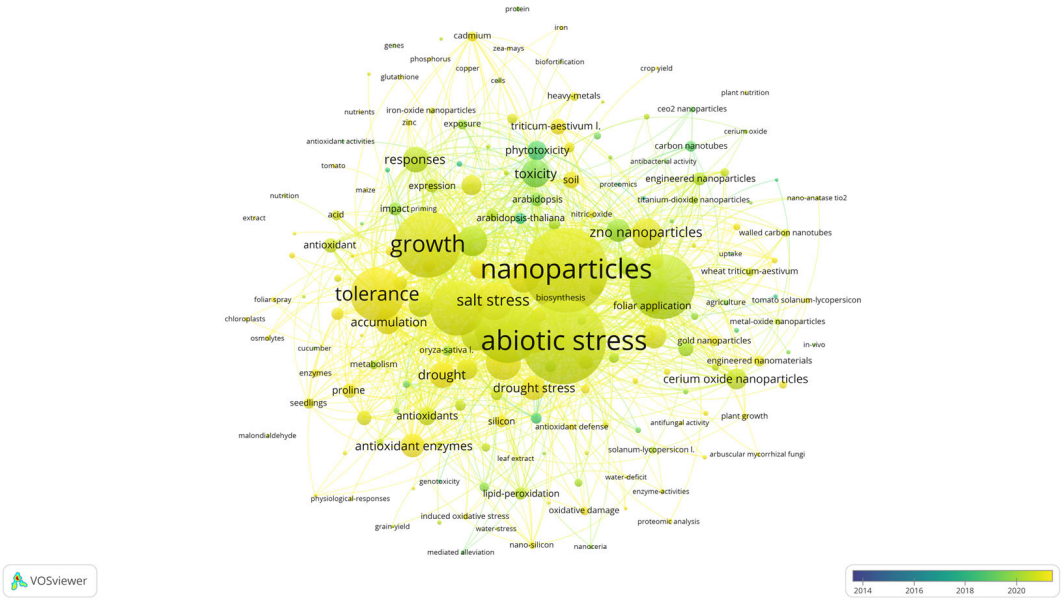


Figure 6. The main keywords of network co-occurrence.

4. Discussion

4.1. Attention Is Being Drawn to the Efficiency of Using NPs to Increase Plants' Tolerance to Abiotic Stress

A serious challenge for humanity in the coming decades will be to meet future food needs without further disrupting the integrity of the planet's environmental systems [51]. Abiotic stressors are a major factor in crop yield losses globally because they generate a variety of morphological, physiological, biochemical, and molecular changes in plants that negatively impact plant growth and productivity [52]. To make matters worse, various abiotic stressors frequently harm plants simultaneously in the field environment [53]. NPs provide a viable method to handle multiple abiotic stresses. Currently, related research is booming, with a rapidly growing number of publications and citations. The topic of NPs for enhancing plant resilience to abiotic stresses is gaining more attention, and more resources are being invested.

4.2. Cooperation Has Produced Rich Results

The secret to success is effective collaboration. Currently, there is cooperation between several countries in this field (Figure 4A). Asia is the region with the highest concentration and activity of related research. Although the quality of papers from Asian countries is not the highest, the fact that Asian countries account for three of the five highest TGCS countries speaks volumes about the results achieved by Asian countries in this area. Although food insecurity is a global threat, its severity may vary from country to country. One study suggests that more than 88% of the world's undernourished population lives in Asia or Africa [54]. This may explain the fact that among the countries that have made significant contributions to international cooperation in this area, all of them, except for the United

States, are in Asia or Africa. Understandably, because Asia's economic prosperity is greater than that of Africa, Asian countries have achieved better results in this field than in Africa. It is believed that, with the future economic development of Africa, African countries will also put more resources into this field.

The outstanding contributors to the researcher exchange collaboration are Wu HH, Rizwan M, Ali S, and Gohair G (Figure 4B). Among them, Wu HH is the most influential. Giraldo JP, the top scorer in AHP, has co-authored most of his works in this field with Wu HH. Hence, here we mainly discuss the relevant research on the cooperative group composed by Wu HH et al. The studies involving Wu HH et al. mainly focused on how cerium oxide NPs enhance plant resistance to abiotic stresses. They first gave the synthesis method for cerium oxide NPs and characterized their physical traits [55]. They further demonstrated that cerium oxide NPs can alleviate abiotic stresses by promoting K retention and Na exclusion in leaf sarcomeres, enhancing their ability to scavenge reactive oxygen species, and maintaining the photosynthetic capacity of leaves [36,37,56,57]. The results of a recent study showed that foliar spraying was a more effective application method compared to root application when using cerium oxide NPs to enhance salt stress tolerance in *Cucumis sativus* L. [58]. Moreover, not only for direct application to seedlings, seed priming with cerium oxide NPs has also been shown to be an effective strategy for adapting to abiotic stresses, substantially enhancing the resistance of subsequent seedlings to abiotic stresses [40,59].

4.3. Future Research Hotspot

At the outset, it is perfectly normal and necessary for people to be concerned about the toxicity of nanoparticles, a new material. What is more, due to the unique size and properties of NPs, their mass production and release into the environment could have profound effects on humans, plants, animals, and terrestrial microorganisms [43]. Handy et al. (2008) first reviewed the possible risks associated with the large-scale use of manufactured NPs, noting that NPs could be toxic to bacteria, algae, invertebrates, fish, and mammals [60]. However, at the time, the ecotoxicological data on NPs were relatively homogeneous in terms of species, with a particular lack of data on higher plants. Mustafa et al. (2016) noted that for metalloid NPs and metal oxide NPs, it is crucial to determine whether the toxicity is due to the properties of the metal ion or the nano properties of the material [61]. Exploring the possible adverse effects of NPs on plants and ecosystems has been a hot topic of research since the beginning [62–66]. This is because ensuring that NPs do not cause unacceptable negative impacts on plant growth, particularly on the ecological environment, is a prerequisite for large-scale applications in sustainable agriculture. Currently, terrestrial risk assessment of NPs released into the environment is still in its infancy, and therefore continued attention will be paid to assessing the risks of nanoparticle applications in the foreseeable future, taking into account both the physical properties of NPs and the type of NPs [67,68].

In addition to the traditional applications of ZnO NPs and CeO_2 NPs, in recent years, various other NPs such as carbon NPs, potassium NPs, gold NPs, copper NPs, manganese NPs, magnetite NPs, selenium NPs, silicon NPs, and graphene have shown great potential in attenuating the adverse effects of abiotic stresses on plants and improving their resistance to abiotic stresses [69–79]. In addition, there is also a result that showed that the mixture of Se NPs and other substances can alleviate salt stress in bitter melon (*Momordica charantia* L.) [80]. Excitingly, in the field of sustainable agriculture there is an increasing number of family members made up of different types of NPs. At the same time, it has been shown that the positive effects of NPs on plant resistance to abiotic stresses vary by species and dose used [81]. In consideration of that, in the future, exploring the species and dose of NPs best suited to mitigate abiotic stresses in a particular plant will be a hot topic of research.

4.4. Future Research Proposal

Most of the current studies on the effects of nanoparticles on plant stress resistance are limited to the physiological level. Omics allows researchers to identify changes in genes, mRNA, proteins, metabolites, etc. at the plant temporal and spatial system level as a whole, providing a key strategy for understanding plant responses to abiotic stresses [82,83]. Additionally, as a result of rapid technological advancement, omics has grown in popularity and declined in cost, allowing it to be applied to the study of an increasing number of plants [84]. With the advancement of technology, many new omics approaches have emerged, such as ionomics, RNomics, epigenomics, fluxomics, glycoproteomics, glycomics, regulomics, secretomics, lipidomics, and phosphoproteomics and the integration of multidimensional biological information from different omics is forming a relatively new branch of life sciences: systems biology [85,86]. As a consequence, when studying plant growth and development in abiotic stress environments, the omics approach opens up many new possibilities and has grown in importance and feasibility. However, there is currently a paucity of excellent and landmark literature on the use of histological tools to study nanoparticles for abiotic stresses in plants. In the future, it will be essential and highly recommended to apply omics, especially multi-omics, to explore more deeply and comprehensively how nanoparticles might assist plants to mitigate abiotic stresses, which is a crucial step toward attaining sustainable agriculture.

5. Conclusions

The application of NPs to help plants adapt to and overcome abiotic stresses is a relatively new and promising approach to sustainable agriculture that is still in its infancy. Much research has been conducted in this area in many countries, particularly in Asia, although the United States still holds the number one position in terms of global citations for papers published. There is an urgent need for a large collaborative group of researchers to work together in this field. Finally, we believe that future research trends will revolve around the toxicity of nanoparticles, the types of nanoparticles and the doses used, and the use of omics, particularly multi-omics, approaches for extensive and in-depth studies.

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Conflicts of Interest: The authors declare no conflict of interest.

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