Emerging Frontiers in Nanotechnology for Salinity Stress Management: A Global Bibliometric Analysis

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Abstract

The use of nanotechnology to manage salinity stress has recently become a prominent focus in agricultural and environmental research, garnering substantial global attention. Soil Salinity encompasses three fundamental principles: minimizing salt accumulation, enhancing soil coverage, and rotating with salt-tolerant crops. This field has experienced a surge in research activity, with the number of peer-reviewed publications on nanotechnology and salinity stress increasing exponentially. This investigation aims to critically analyze all peer-reviewed documents on nanotechnology and salinity stress published between 2021 and 2024, as indexed in the Dimensions core database. The search yielded 500 papers processed using an R-based bibliometric package to examine annual scientific production trends, sources, authors, documents, citations, keyword analysis, and co-occurrence networking using VOS viewer. Our results indicate a significant expansion in conservation agriculture research from 2021 to 2024. Notably, the top 10 core source journals make the most substantial contributions to the field, while 2570 researchers have authored or co-authored at least one document on salinity stress and nanotechnology. The prominence of nanoparticle-based research for managing saline soil in countries such as China, India, Egypt, Pakistan, and Iran highlights the critical nature of this issue in these regions. Nevertheless, this field of study has attracted global attention. The overall conclusion of this study provides a bibliometric analysis and nanotechnological basis for salinity stress management.

Introduction

As the 21st century dawned, contemporary society has been confronted with numerous worldwide challenges. Agricultural abiotic stressors are defined as inanimate environmental factors that limit plant development and crop yield (Chakraborty *et al.,* 2022; Rajput *et al.,* 2015). Drought, salt, extreme heat or cold, flooding, nutrient deficiency, UV radiation, air pollution, wind, and heavy metal toxicity pose significant threats to agricultural practices (Ahmed *et al.,* 2020; Chakraborty *et al.,* 2022; Liu *et al.,* 2023). Soil salinity significantly compromises agricultural productivity, making it one of the most critical global challenges in modern farming. Salinization is classified into two forms: primary and secondary. Primary salinization arises from natural processes, such as the disintegration of rocks and the influence of saltwater in coastal areas through infiltration or the deposition of aerosols. Conversely, secondary salinization results from human activities, including the overuse of fertilizers, the use of poor-quality water for irrigation, soil becoming waterlogged, and improper disposal or accidental discharge of industrial effluents containing salt (Sahab *et al.*, 2021). Soil salinity is regarded as a form of soil degradation due to its presumed effects on various aspects of soil ecosystems. These include the growth of plants, the characteristics of soil microbes, the functioning of soil (such as nutrient cycling), and other ecosystem services provided by soil (Stavi *et al.*, 2021). Saline soil is typically defined as having a root zone where the electrical conductivity of the saturation extracts (ECe) surpasses 4 dS m^{-1} (around 40 mM NaCl) at 25 °C, along with an exchangeable sodium content of 15%. This level of ECe usually leads to reduced crop yields (Munns, 2002; Jamil *et al.,* 2012). Approximately 20% of all cultivated land and 33% of irrigated agricultural areas worldwide are affected by high soil salinity (Mukhopadhyay *et al.,* 2021). Furthermore, salinized regions are expanding at an annual rate of 10% due to a variety of factors, including insufficient rainfall, excessive surface evaporation, weathering of native rocks, the use of saline water for irrigation, and suboptimal agricultural practices. Globally, over 50% of irrigated croplands are experiencing soil salinization issues, which adversely affect plant growth, development, and survival (Guo *et al.*, 2022). Soil salinity poses a significant threat to global food security, a challenge that is exacerbated by the ongoing changes in our climate (Mukhopadhyay *et al.,* 2021). Global agricultural demands are continually changing in line with the stress on agricultural productivity for the burgeoning population. The global population is expected to reach over 9 billion by 2050. This requires a 57% increase in food production (Wild, 2003). According to Jamil *et al.* (2012) nearly half of the arable land is predicted to become salinized by 2050. This prediction also led to the idea that increasing saline soil conditions may reduce crop yield and quality, resulting from disturbances to physiological and biochemical processes, nutrient uptake, cellular harm, and photosynthesis of crop plants, which have raised concerns about food security (Sehgal *et al.*, 2018). Crop stress damage under soil salinity results primarily from ionic, osmotic, and oxidative stress. To achieve salt tolerance, plants must effectively manage stress through the regulation of ionic, osmotic, and reactive oxygen species (ROS) homeostasis (Figure 1) (Singh *et al.,* 2023a; Wang *et al.,* 2022).

Soil salinity poses a significant challenge to agricultural output, hindering efforts to nourish the growing global population (Kopittke and Menzies, 2006). The properties, behavior, and physicochemical and biogeochemical aspects of soil salts are crucial (Haj-Amor *et al.*, 2022). Ionic and osmotic effects in soil can modify the makeup, enzymatic activities, and microbial populations in the rhizosphere (Liu *et al.*, 2022). Saline soil conditions influence nutrient accessibility, microbial function, and the relationship between soil organisms and fertility as well as plant nutrition (Chandra *et al.,* 2022; Zhang *et al.,* 2019). Thus, there is an urgent need to boost crop yields in salt-affected soils through various management approaches (Chandra *et al.*, 2022). These may encompass the use of mineral nutrients and beneficial elements like potassium (El-Mageed *et al.*, 2022), selenium (Abd-Elzaher *et al.*, 2022), titanium (Ghazi *et al.*, 2022), or silicon (El-Sherpiny and Kany, 2023). Salinity reduction can also be accomplished by utilizing of soil organisms, including nutrient-solubilizing microbes and mycorrhizal activities (Du *et al.,* 2023; El-Mageed *et al.,* 2022). Nano-management techniques, such as the application of NPs can also be advantageous (Butnariu and Butu, 2019; Chhipa and Joshi, 2016; Singh *et al.,* 2022, 2023b, 2023a). This bibliometric analysis aimed to examine the geographical distribution of research papers concerning nanoparticles that alleviate plant salinity stress, assess the number of researchers involved, and track the evolution of keywords over time. This research will integrate essential references and information regarding nanoparticles to promote sustainable farming practices and mitigate soil salinity stress, along with their effects on plants. To this end, the following research questions were formulated:

1. Which nations are spearheading the investigation into nanoparticle-based solutions for managing salt stress?
2. Which researchers and scholars have made the most significant contributions to the study of managing salt stress using nanoparticle-based approaches?
3. Which leading academic journals publish studies on utilizing nanoparticles to combat salinity stress?
4. What changes have occurred in the collaborative networks between institutions and countries, over time, within this area of research?
5. Research concerning salt stress and nanoparticle management strategies, which keywords are employed most?
6. Research exploring nanoparticles for managing salt stress, which Sustainable Development Goals (SDGs) are most addressed?
7. How many publications on nanoparticles in the context of salt stress management contribute to the SDGs?

Soil salinity

Soil salinity is closely connected to various global issues, primarily climate change, food security, and the UN SDGs. Hence, innovative strategies supporting the SDGs should be employed to mitigate soil salinity (Figure 1). Effective management of soil salinization is vital for attaining several SDGs, including SDG2 "Zero Hunger," SDG3 "Good Health and Well-Being," and SDG15 "Life on Land" (Chauhan *et al.,* 2023; Lal *et al.,* 2021; Singh, 2021). The correlation between worldwide population expansion and food requirements has prompted scientists to explore sustainable approaches, including nanotechnology, to address future needs. An examination of salinity stress and nanotechnology-based salinity stress management reveals

two key aspects: first, the challenges posed by soil salinity and second, the use of NPs for managing these issues. This is particularly relevant for nations that have conducted substantial research in this field. The outcomes of these funded research projects are typically scientific publications that highlight the current state of the problem and the application of various technologies to manage the issue at hand.
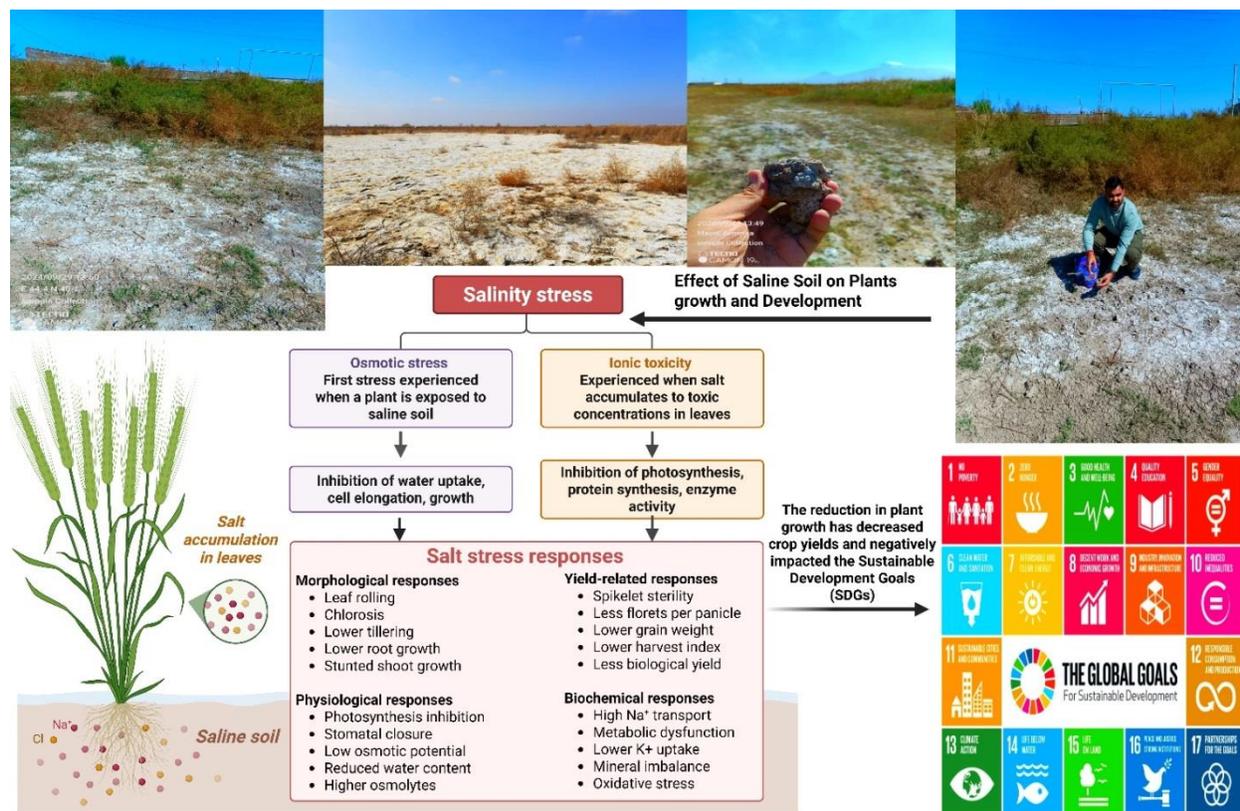

Figure 1. Soil salinity has a negatively affects the plant growth effect on SDG achievement. Consequently, soil salinity threatens food security and complicates efforts to achieve the UN SDGs by 2030

Materials and Methods

1. Database and Source

In the current study used the *Dimensions* database was used to get author information, abstracts, and keywords for this study (Hook *et al.*, 2018). This database was selected because Dimension is a collection of databases that document various research inputs-outputs (collectively called "research objects"), and the many forms of attention those objects received. The database is an essential step in painting a comprehensive picture of the research landscape; it provides background information on research projects, researchers, fields, institutions, funders, countries, and a host of other research-related entities that stakeholders in the field may find interesting (Hook, 2020; Hook *et al.,* 2018; Hook and Porter, 2021; Porter and Hook, 2022). This makes it particularly beneficial for monitoring trends in emerging fields, including

nanotechnology and stress management in agriculture. According to (Hook *et al.*, 2018). The database's construction is detailed.

2. Data Selection Parameters

The dataset for the bibliometric review is obtained from the Dimensions database, which is a well-acknowledged database. The formation of the appropriate query is the major challenge of bibliometric analysis. To maximize the number of publications in our search, a straightforward query approach was employed. In this study applied various filters in Dimensions database across different sections to obtain more informative data. In the article search, used the keywords *"crop AND salinity AND stress AND management AND by AND nanoparticles"* were used. For publication types, we specified *"Article OR Chapter OR Edited Book"*. To identify articles related to Sustainable Development Goals (SDGs), we utilized the keywords *"2 Zero Hunger OR 12 Responsible Consumption and Production OR 13 Climate Action OR 6 Clean Water and Sanitation OR 15 Life on Land OR 3 Good Health and Well Being OR 8 Decent Work and Economic Growth"*. Limited our data extraction to the years 2021-2024 by using the *keywords "2024 OR 2023 OR 2022 OR 2021"*. Additionally, all document types are exclusively limited to as English language. The initial search query conducted was focused on the topic of "crop AND salinity AND stress AND management AND by AND nanoparticles" yielding a total of 500 documents as search results and these all documents have articles, book chapters and edited books.

3. Tools of Analysis

This study utilizes the usage of two bibliometric analytic tools: VOSviewer and R-Studio. A lot of people use R-Studio to produce bibliographic data for their analyses (Bhat *et al.,* 2023). All content and network analyses were done in VOSviewer. Users can build and view bibliometric networks in VOSviewer (Bukar *et al.,* 2023; Kirby, 2023; Zhang *et al.,* 2024). The Bibliometric suite of software allows users to compile information about documents, authors, sources, and topics.

Results and Discussions

Figure 2 in our research, utilizing the Dimensions database, showcases the cumulative scholarly output on nanoparticle-based strategies for addressing salinity stress. The examination, covering encompasses 109 sources and 500 documents, incorporating 357 keywords. This corpus of research represents the combined endeavors of 2570 scholars in this domain.
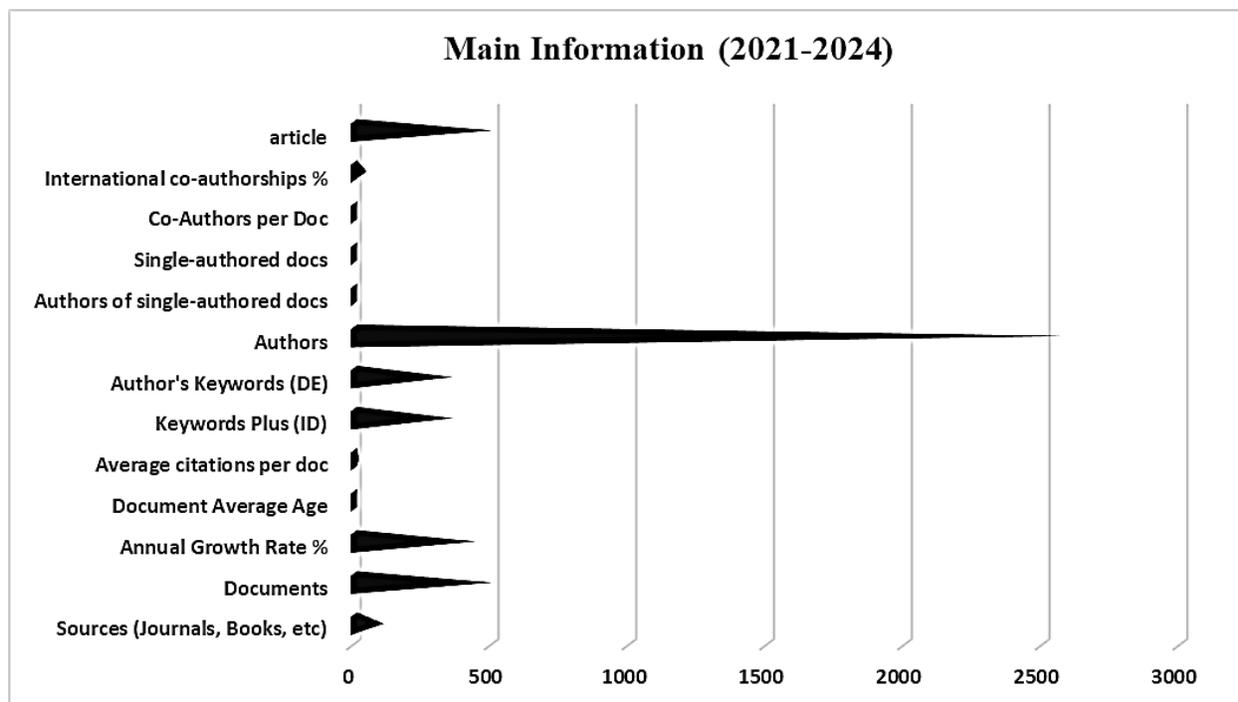
Figure 2. Bibliometric analysis of nanotechnology and salinity stress research (2021-2024) using Dimensions database

1. Studies on Salt Stress and NPs-Based Management Approaches

Between 2021 and 2024, there was an increase in research trends focusing on NPs-based salinity stress, indicating a rise in NPs-related studies. The current analysis reveals that 201 scientific articles were published in the agricultural science field, while 190 scientific papers appeared in the biological sector (Figure 1, supplementary). Additionally, the environmental section has the publication of 43 scientific articles. Among all the agricultural sciences shares a larger 43.8% of the total publication percentage compared to biological and environmental sciences.

2. Key Nations, Contributors, and Journals in Research on Salt Stress and Nanoparticle-Based Management Strategies

2.1 Most Impactful Top 10 Nations by Corresponding Authors Bibliometric Analysis

An examination of the top 10 nations based on corresponding author affiliation provides crucial insights into global research output (Figure 3). At the top of the list is China, with 131 articles, which represents 26.2% of publications. Next is India with 92 articles (18.4%) and Egypt with 40 articles (8%). 26 articles (5.2%) for Pakistan and 20 for Iran (4%) (Figure 3). With a 3.6% of contribution rate Australia published 18 articles. Bangladesh contributed 13 articles (2.6%); Brazil (2.4%) Germany (1.8%) and Italy (1.6%) had 12, 9 and 8 articles (Figure 3). This analysis examines the range of research outputs from prominent countries in the global scientific community, focusing on the challenges of salinity stress and the use of nanoparticles as a solution to these issues. Several factors may contribute to this trend: urgent agricultural salinity issues in these regions, substantial investment in nanotechnology research, large agricultural

sectors that could benefit from such research, and robust research funding and infrastructure. The strong performance of countries in all these top 10 suggests that this research is especially relevant to areas facing significant agricultural soil salinity challenges (Tuteja *et al.*, 2012). These data notably suggest that the research is predominantly centered in the top 10 countries most directly affected by agricultural salinity issues. This geographical concentration of research might influence the advancement and deployment of nanoparticle-based solutions to combat salinity stress in agriculture, potentially fostering innovations and strategies that are tailored to specific regions.
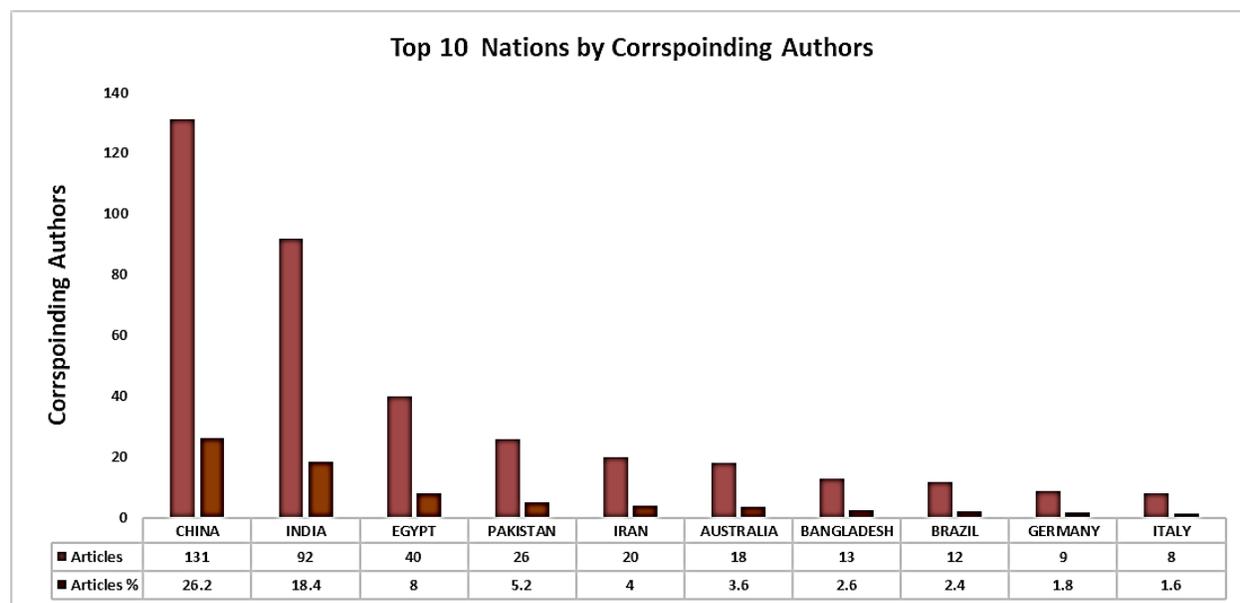

Figure 3. Examining the top 10 nations with the greatest impact in publishing scientific articles concerning nanotechnology and salinity stress

2.2 Top 10 Nations by Citations Biblometric Analysis

Figure 4 offered an in-depth analysis of citation metrics across various countries concerning salinity stress and NPs research. The examination of citations unveils distinct trends in research influence and output among nations. China and India stand out as the primary contributors in terms of overall citations, with China leading at 2795 and India following at 1939 (Figure 4 A). However, when considering the mean citations per article, a different picture emerges. The United States demonstrates the highest impact with 64.4 citations per article, trailed by Qatar (55.3) and Bangladesh (26.2), despite their lower publication counts (Figure 4 B). This indicates that whilst Asian nations like China and India generate a greater volume of research, certain countries with fewer publications achieve greater impact per article. Egypt and Pakistan maintain consistent positions across both metrics, while Australia exhibits a balanced performance with moderate total citations (421) and above-average citations per article (23.4). Iran, despite ranking in the top 10 for total citations, shows the lowest average citations per article (9.8), suggesting a possible emphasis on quantity over impact in their research output (Figure 4 A, B).
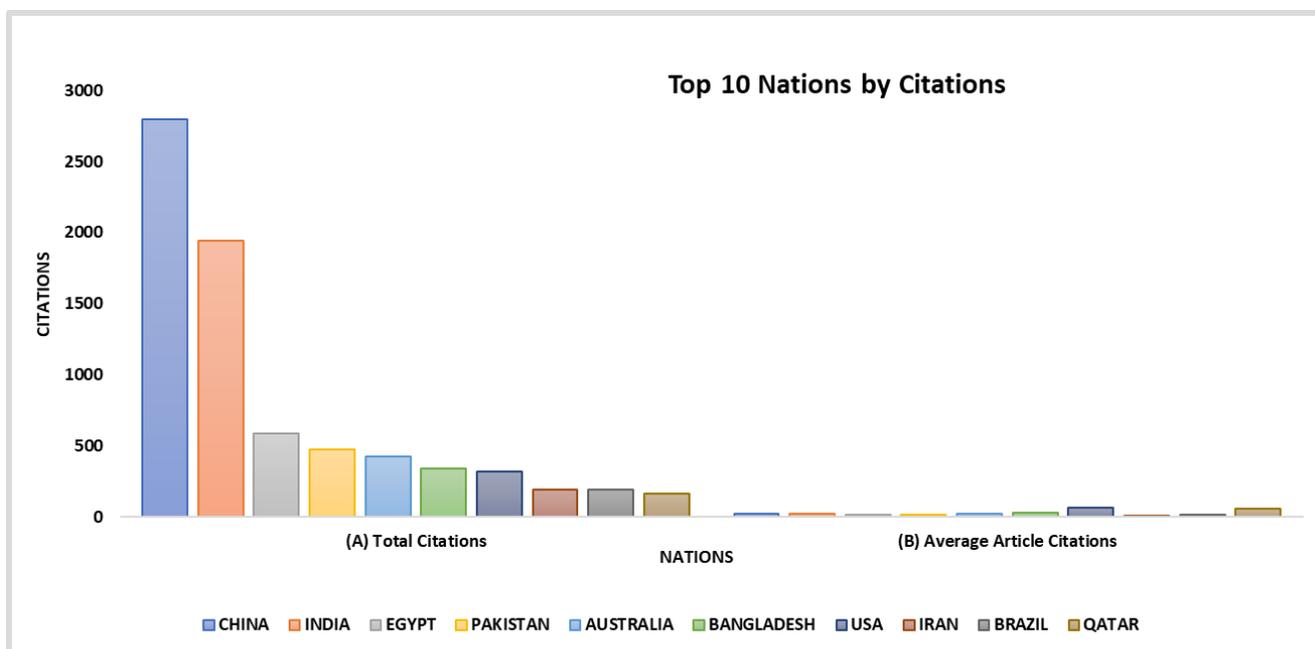
Figure 4. Topmost nations citations viz listed

2.3. Top Most Journals

From the analysis of publications regarding salinity stress and nanoparticles (NPs) from 2021 to 2024 (Figure 2 supplymentry), it shows that MDPI's Plants is in charge in the field (27.6%), and afterwards Frontiers in Plant Science (21.1%). Some of the significant contributors include Plant Physiology and Biochemistry (8.76 %), Science of The Total Environment (8.36 %), Environmental Science and Pollution Research (8%), and BMC Plant Biology (5.82 %). The top publishers of the four journals are Heliyon (5.45%), Scientific Reports (5.05%), Chemosphere (4.73%), and Environmental Research (4.73%). The preponderance of Q1 journals highlights the rising interdisciplinary interest in NPs-mediated salinity stress tolerance among the fields of plant sciences and environmental chemistry, respectively (Figure 2 supplymentry).

This distribution across both plant and environmental science publications emphasizes the interdisciplinary nature of NPs research in tackling salinity stress challenges. The most frequently cited publications in the field of agricultural nanotechnology emphasize sustainable applications, including advanced nanomaterials for enhanced efficiency, resistance to heavy metal contamination, and improved nutrient delivery via nonfertilizer (Beig *et al.,* 2022; Monreal *et al.,* 2015; Rahman and Zhang*,* 2018). The central themes encompass environmentally friendly nanotechnology for food security, nanomaterials that alleviate abiotic stress, environmental restoration, and nutrient management. These areas highlight the revolutionary impact of nanotechnology on the promotion of sustainable agricultural practices.

2.4. Top 10 Most Cited Publications

The top-cited article, *"Nano-enabled pesticides for sustainable agriculture and global food security,"* delves into cutting-edge nanomaterial advancements aimed at boosting agricultural

efficiency and productivity, garnering 306 citations (Table 1 supplymentry). Following this, *"Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices"* examines soil nutrient-microbe-plant interactions methods to enhance crop resilience against abiotic stress, supporting food security efforts, with 158 citations. The third study, *"Recent Trends in Nano-Fertilizers for Sustainable Agriculture under Climate Change for Global Food Security,"* accruing 156 citations, underscores the importance of nanofertilizers in optimizing nutrient delivery and promoting agricultural sustainability. *"Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives,"* cited 140 times, explores eco-conscious nanotechnological approaches to sustainable farming. With 132 citations, *"Regulation of photosynthesis under salt stress and associated tolerance mechanisms"* investigates the role of nanomaterials in alleviating plant salinity stress. The sixth paper, *"Metal/Metalloid-Based Nanomaterials for Plant Abiotic Stress Tolerance: An Overview of the Mechanisms"* offers a wide-ranging analysis of the transformative effects of nanotechnology on plant science for abiotic stresses management, cited 119 times. *"Nanofertilizers: A Smart and Sustainable Attribute to Modern Agriculture,"* article seven that have 113 citations. This article examines nanoparticles' dual impact on environmental pollution and remediation. Article eight, *"Nano-fertilizers: A sustainable technology for improving crop nutrition and food security"* cited 111 times and highlighted nanotechnology's contributions to environmentally sustainable agricultural practices. *"Plant Nutrition: An Effective Way to Alleviate Abiotic Stress in Agricultural Crops"* article nine explores the capacity of these innovative fertilizers to enhance nutrient utilization efficiency and reduce environmental impact, with 104 citations. The tenth article, *"Role of Silica Nanoparticles in Abiotic and Biotic Stress Tolerance in Plants: A Review,"* cited 99 times, discusses nanomaterials' dual application in addressing environmental challenges and improving agricultural yields (Table 1 supplymentry).

2.5 Authorship Network Analysis

2.5.1. Total Co-authorship Network Analysis

The relationships between academics on a certain topic are investigated using co-authorship analysis (Donthu *et al.*, 2021). It is crucial to comprehend the ways in which scholars engage with one another, including author qualities such affiliated institutions and nations, as co-authorship is a formal means of intellectual collaboration (Acedo *et al.,* 2006; Cisneros *et al.,* 2018). Collaboration among scholars is now prevalent due to the growing theoretical and methodological complexity of research (Acedo *et al.*, 2006). Collaboration among researchers can significantly improve research. When diverse researchers work together, it can lead to clearer and more insightful findings (Tahamtan *et al.*, 2016). A method for science mapping known as co-citation analysis presupposes subject similarity across frequently cited publications (Hjørland, 2013). The fundamental concepts and intellectual framework of a subject of study can be uncovered through this type of investigation (Liu *et al.,* 2015; Rossetto *et al.,* 2018). The bibliometric analysis is incomplete without an examination of authors resaerchs activites. In the current analysis, 2548 authors contributed to this topic, but not all of them are equally effective. The co-authorship networks of the most significant authors are shown in Figure 5. The overall strength of the author's links (degree of co-authorship) is indicated by the size of the letter and

circle. Both circle and letter sizes are larger for writers with more co-authorship. Following the co-occurrence link, the distance between the aurthors (circle) shows how linked they are in matter of co-authorship; selected 100 top researchers who were closely related to the topic among all 92 researchers who closely shared the work related to salinity stress and NPs. In the co-authorship network analyzed ten cluster based on co-authorship. Cluster 1 (red color) has the highest number of co-authors, totaling 20, with 365 publications and the highest total link strength (Figure 5). Cluster 2 (green color) follows with 14 co-authors and 217 publications, demonstrating significant collaborative efforts. Similarly, Cluster 3 (blue color) includes 12 co-authors contributing 201 publications, while Cluster 4 (acid green color) also comprises 12 co-authors but with a slightly lower output of 173 publications. Cluster 5 (amethyst color) involves 10 co-authors with 230 publications, reflecting active research engagement, and Cluster 6 (aqua color) also has 10 co-authors but with 136 publications, indicating moderate collaboration. Smaller yet productive groups include Cluster 7 (orange color) with 6 co-authors and 88 publications, and Cluster 8 (brown color) with four co-authors producing 108 publications. Lastly, Cluster 9 (violet color) and Cluster 10 (pink color) both feature 2 co-authors, contributing 28 and 33 publications, respectively, reflecting minimal but steady collaborative efforts (Figure 5).
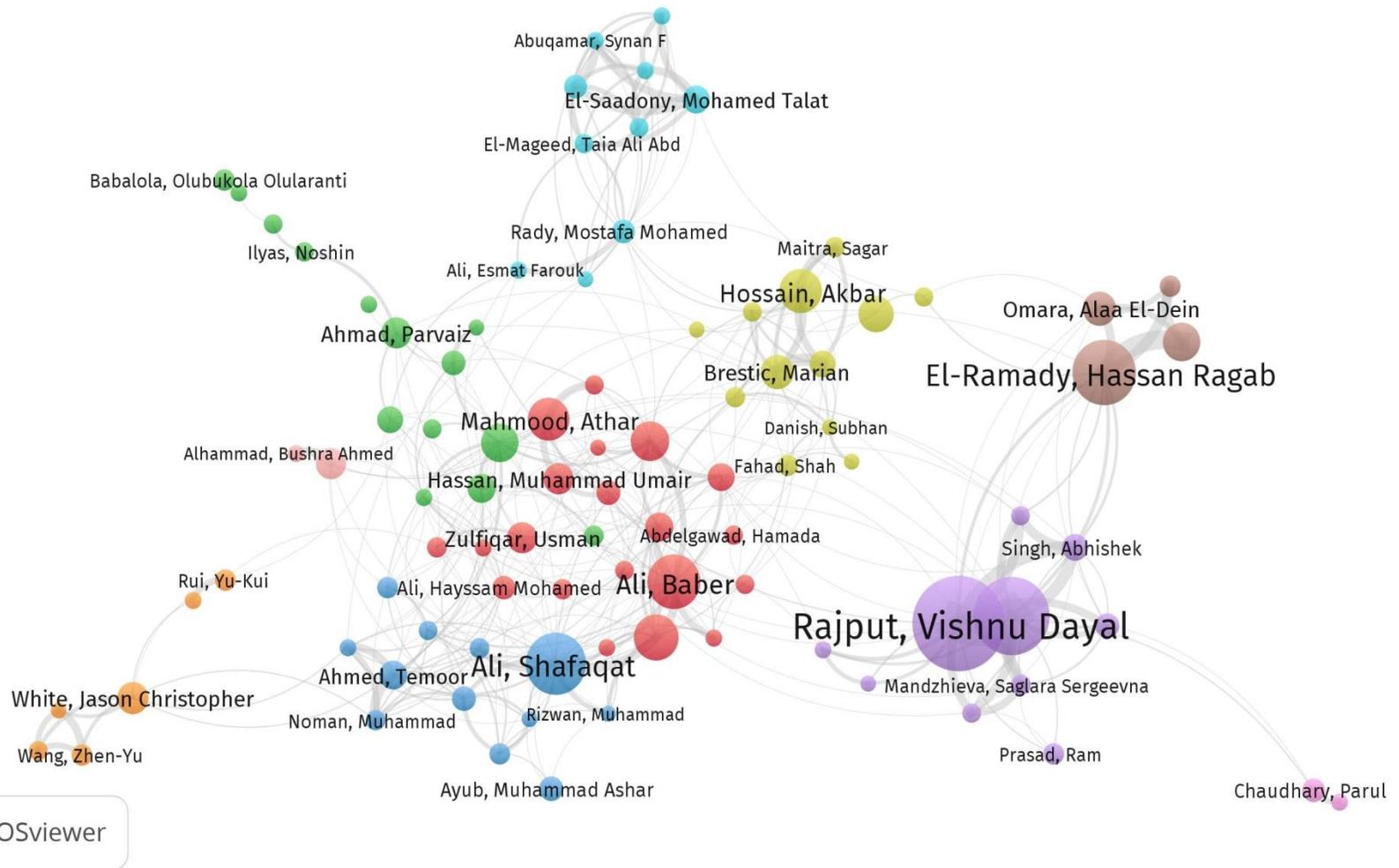
Figure 5. Using Dimensions database and VOSviewer software, a co-authorship network analysis identified the top 100 researchers contributing to nanotechnology and agriculture-related salinity stress in environmental contexts

2.5.2. Co-Citation Network Analysis

A co-citation network establishes a connection between two publications when they appear in the reference list for another publication. One advantage of co-citation analysis for business researchers during applications for different grant programs is that it helps them locate theme clusters, as well as the most influential publications. Current analyses are beneficial for charting the organization and evolution of nanotechnology and salinity stress-related fields of study, offering insights into seminal works and thematic groupings. In the co-citation network analytical approach, a co-citation pair is formed when two documents are referenced together by a third source. The frequency of co-citations between documents indicates the strength of their thematic, methodological, or conceptual links. Researchers can visualize and examine clusters of frequently co-cited documents by creating a co-citation network, where nodes symbolize documents and edges represent co-citation frequency (Figure 6) (Du *et al.*, 2022). Co-Citation Network Analysis is a technique employed to investigate the relationships between various documents, including scholarly articles, literary works, or intellectual property, by examining their joint citations in other sources. Our present investigation encompasses an analysis of 100 researchers, featuring 2529 citation connections and a total of 9985 citations, distributed across 7 clusters (Figure 6).

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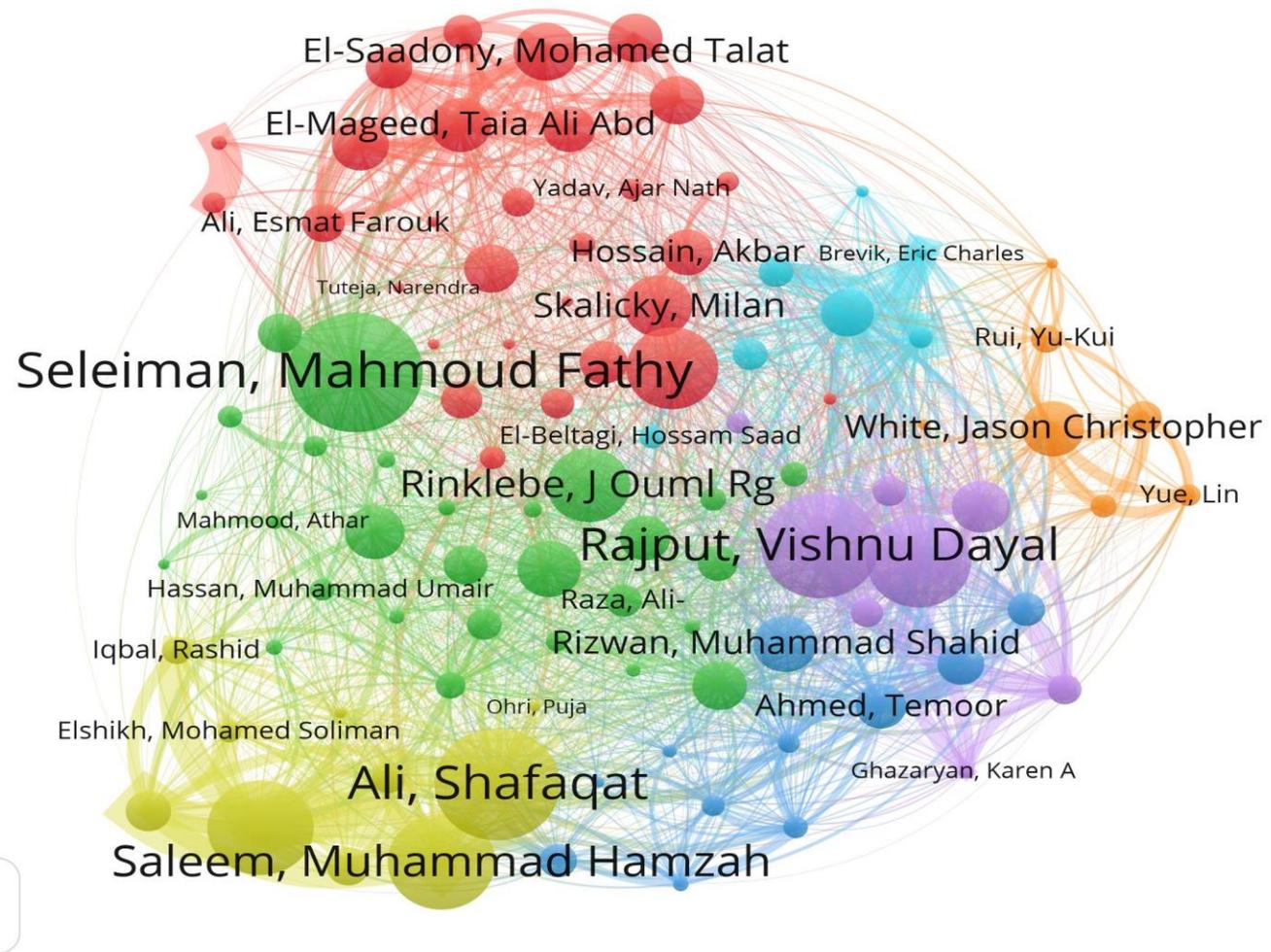
Figure 6. Using Dimensions database and VOSviewer software, a Co-Citation network analysis identified the 100 most influential researchers in nanotechnology and agriculture-related salinity stress in environmental contexts

2.5. 3. Top 10 Authors Network Analysis

The bibliometric data presented in the Figure 3-A (supplementary) and Table 2 (supplementary) offer insights into the scholarly achievements of the top ten researchers. At the forefront are *Ali S* and *Rizwan M*, both boasting an h-index of 12, g-index of 18, m-index of 4, and 18 publications each, demonstrating their significant academic influence. Rizwan M has garnered the most citations (544), closely followed by ALI S with 415. Kumar A secures the third position with an h-index of 9, g-index of 10, m-index of 3, 10 publications, and 449 citations, indicating a robust research presence. Ahmed T exhibits steady scholarly output, with an h-index of 8, g-index of 11, m-index of 2.6, 11 publications, and 243 citations. *Minkina T* and *Rajput VD* share identical metrics: an h-index of 8, g-index of 9, m-index of 2.6, and 9 publications. However, *Minkina T* edges ahead in total citations with 458, compared to *Rajput VD* 437. *Li Y* demonstrates noteworthy performance with an h-index of 7, g-index of 10, m-index of 2.3, 10 publications, and 317 citations. *Zia-Ur-Rehman M* shows consistent academic productivity, achieving an h-index of 7, g-index of 8, m-index of 2.3, 8 publications, and 204 citations. Rounding out the list are *Alharby HF* and *Ali B*, both with an h-index of 6 and m-index of 2. *Ali B* slightly outperforms *Alharby HF* with a g-index of 7 and 212 citations, compared to Alharby HF g-index of 6 and 185 citations. These bibliometric indicators underscore the varied contributions and scholarly impact of each researcher within their respective fields. The correlation matrix displayed in the heatmap showcases the relationships among five bibliometric measures: h-index, g-index, m-index, Total Citations (TC), and Number of Publications (NP), (Figure 3-B supplementary).

3. Analysis of Keywords

3.1 Most Frequent Keywords

The top 50 keywords associated with salinity stress and NP were presented in Table 3 (supplementary) to identify the hotspots in this field of research. The most common words-agriculture (84 papers), nanoparticles (75), soil (72), plants (55), and antioxidant (54)-professional in the know-how and exercise of using nanotechnology to enhance resilience. Subjects such as salt stress (49), salinity (47), fertilizers (27), nanostructures (26), and nanomaterials relate to soil health and stress tolerance. Physiological mechanisms are well-supported by research on photosynthesis (22), chlorophyll (19), salt tolerance (18), and oxidative stress (14). With broader concerns of climate change (12) and crop production (9), sustainability is a pressing matter that connects nanotechnology with environmental and agricultural (13) progress.

3.2. Tree Map Analysis

Keywords are extracted from abstracts to complete the keyword set. Figure 7 displays a treemap based on keyword dynamics, focusing solely on abstracts.
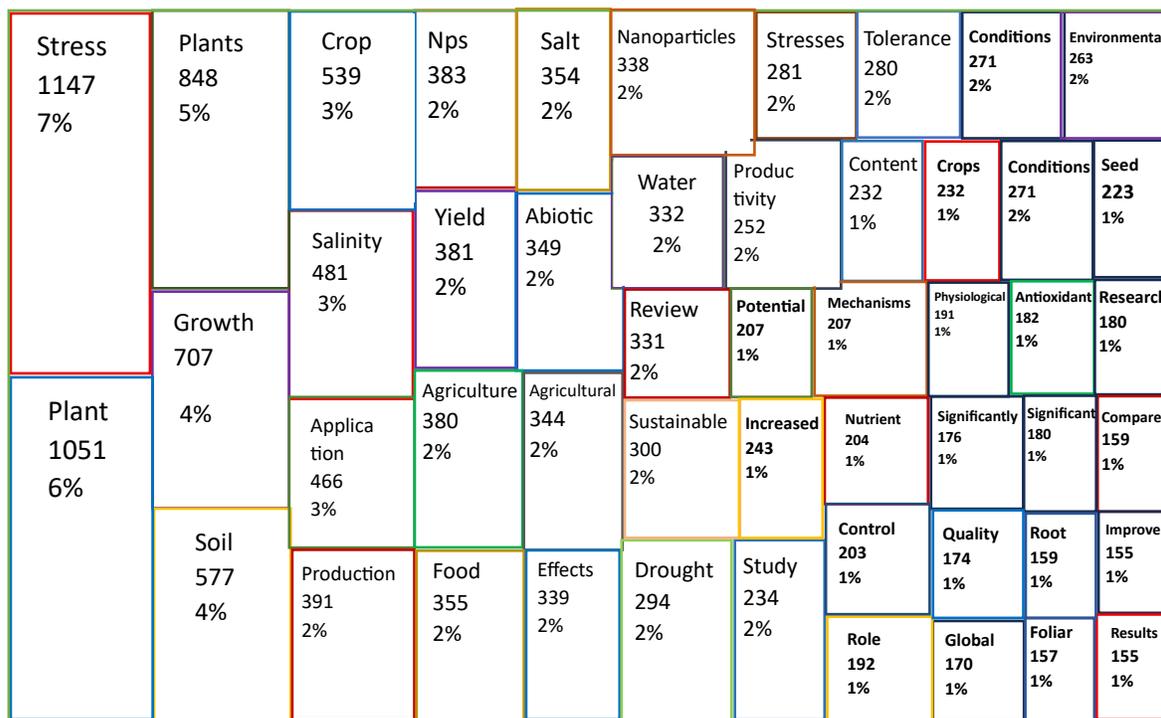
Figure 7. Tree Map Analysis using R-Studio examined abstract keywords from Dimensions database focusing on salinity stress and NPs mitigation

3.3. Word Cloud

Most of the words were found to be domain specific upon review of Figure 8. The word "agriculture" was used more than any other. "Nanoparticles" ranked as the number two most popular word. Following this, words such as "Salinity Stress," "Antioxidant," "Stress physiology," and "Soil" were introduced.

Figure 8. A Word Cloud Analysis using R-Studio examined prominent keywords from Dimensions database on salinity stress and NPs mitigation

3.4. Co-occurrence of keywords Network Analysis

Two research clusters are suggested in Figure 9. *Cluster 1 (Red):* Agricultural Nanotechnology and Soil Interactions: The associated studies in this cluster are deal with nanotechnology and its role in soil health, crop productivity, and environmental management. Focusing on aspects such as *nanoparticles, fertilizers, soil pollutants (cadmium, zinc oxide), and metal nanoparticles effects, on roots and soil microbiology Keywords: nanoparticles, fertilizers, soil pollutants (cadmium, zinc oxide) and metal nanoparticles effects on roots and soil microbiology* (Table 4 supplementary). It also associates this issue of pesticide management, climate change, and commodity food crops, e.g., Oryza (rice), with nanotechnology. *Cluster 2 (Blue):* to Antioxidant Mechanisms and Stress Tolerance delves into plant responses to salt and oxidative stress, dominating in the areas of antioxidant mechanisms *(drought tolerance, biochemical pathway and salt), and chemicals (hydrogen peroxide, sodium chloride, ROS)* (Table 4 supplementary).

Collectively, these clusters underscore the interdisciplinary nature of studies at the convergence of nanotechnology, plant science, and environmental research. One cluster concentrates on utilizing nanomaterials to enhance agricultural output and reduce pollution, whilst the other focuses on physiological mechanisms for coping with abiotic stress through antioxidant responses. This network analysis emphasizes the requirement for novel, holistic approaches to bolster crop resilience, address environmental challenges, and foster sustainable farming practices in light of climate change.

Figure 9. Using R-Studio for Co-occurrence of Keywords Network Analysis, significant keywords related to salinity stress and NPs were identified from the Dimensions database

4. Analysis of Articles Achieving the SDGs (Sustainable Development Goals)

Nanotechnology is crucial in addressing agricultural salinity stress, significantly contributing to various Sustainable Development Goals (SDGs). SDG 2: Zero Hunger, aiming for sustainable food production, is supported by 444 papers emphasizing the need for innovative crop resilience solutions. Nanoparticles enhancing nutrient uptake and plant growth align with SDG 12: Responsible Consumption and Production (20 papers) by improving agricultural resource efficiency. These advancements also support SDG 13: Climate Action (16 papers) by enabling resilient crop varieties in saline environments, mitigating climate change impacts. Related SDGs include SDG 15: Life on Land (9 papers) focusing on sustainable land management, and SDG 6: Clean Water and Sanitation (8 papers) highlighting the importance of water quality in agriculture. Although SDG 3: Good Health and Well-Being, SDG 11: Sustainable Cities and Communities, and SDG 14: Life Below Water have minimal representation with 1 paper each, the integration of nanotechnology in combating salinity stress promotes sustainable agriculture and advances multiple SDGs, leading to a more resilient and food-secure future. The UN SDGs require a deeper knowledge of soil processes and qualities on a national and regional level (THE 17 GOALS | Sustainable Development, 2018) . A stronger feeling of duty and concern for soils is also inspired by the imperative to achieve SDGs by 2030. Multiple SDGs rely on the sustainable management of soil health. In current study we much more focus on following SDGs: *Goal 1 (End Poverty), Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-being), Goal 6 (Clean Water and Sanitation), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), and Goal 15 (Life on Land)* which are directly corelated to soil health, salinity stress or

saline soil related problems. Plant output is critical to achieving some of these SDGs, while soil processes are essential to achieving others (Bouma, 2018). The United Nations' SDGs 2, which focuses on eliminating hunger, is particularly crucial as soil salinity adversely affects crop productivity directly impacting food availability and access (Ussiri and Lal, 2018). Implementing sustainable soil management practices, such as utilizing soil amendments and nanotechnology, can enhance crop resilience to saline conditions, thereby ensuring stable yields and contributing to global food security. These approaches also support Goal 1, which aims to end poverty, by improving the productivity of small-scale farmers who are often disproportionately affected by soil degradation and salinity issues. Recent scientific articles from various databases demonstrate that nanoparticle-based approaches to managing saline soil effectively contribute to Sustainable Development Goal 2. By implementing sustainable agricultural practices that utilize nanoparticles for saline soil management, farmers can potentially stabilize their income and safeguard their livelihoods. Salinity in soils reduces agricultural nutritional value, which directly affects human health; hence, this issue relates to SDG 3 (Good Health and Wellbeing). Producing crops that are healthier and nutrient-rich leads to better nutritional outcomes and various experiments related to nanoparticles show that they help in maintaining of soil health under saline conditions (THE 17 GOALS | Sustainable Development, 2018; The State of Food Security and Nutrition in the World 2020; Ussiri and Lal, 2018). In addition, SDG 6 (Clean Water and Sanitation) is closely related to healthy soils because improper soil management can cause runoff and the leaching of salts and other contaminants to contaminate water sources (Brevik *et al.*, 2020).

5. Future research agenda

The suggested agenda summarizes the transformative potential and impact of the NPs and salinity stress in agriculture and advance this research field by highlighting ten major main themes: *(1) NPs for* Agriculture; (2) nanoparticles; (3) NPs for soil; (4) NPs for plants; (5) NPs for antioxidants; (6) NPs for stress physiological; (7) NPs for crops agricultural; (8) NPs for salinity Stress; (9) NPs for fertilizers; *and (10) NPs for seeds*. Future studies related to NPs and agriculture should redirect towards the context of crop production and protection under salinity stress. It is necessary to explore how NPs increase crop tolerance, especially their role in stress physiology at cellular and molecular levels. Soil health in the context of sustainable agriculture will require a long-term assessment of NPs on microbial communities under salt stress in soil research. Similarly, compiling research on the role of switch NPs in enhancing plant resistance across different organizational levels and species will strengthen protection and promote sustainable growth. In terms of biochemical responses, future research can focus on the role of NPs in inducing antioxidant pathways for salinity-induced stress mitigation. More research is needed to understand how or why NPs maximize nutrient uptake, increase crop production, and minimize the reliance on chemical inputs. It will be essential to understand their interplay in conferring additive advantages in the morphological and physiological traits under salinity stress. NP-based fertilizers also have a great potential as precision fertilizers due to their efficient nutrient release with less environmental pollution. They may assist the plants in overcoming ionic imbalance, facilitate the absorption of water, and ultimately bolster physiological vigour in saline environments. Finally, NP-based seed priming strategies are novel

possible signposting approaches that could be harnessed for transforming the performance of the crop by inducing better germination, growth, and stress tolerance under salinity stress.

6. Limitations of the Study

Although the researchers made extensive efforts to conduct a thorough search for relevant materials, this study has several limitations:

[1] The literature review was restricted to publications from the 2021-2024 timeframe.
[2] While the Dimensions database was utilized for the literature search, numerous journals remain uncatalogued, potentially leading to the exclusion of significant publications.
[3] As no search string can achieve absolute perfection, there remains a possibility of both false positive and false negative outcomes.
[4] The study's exclusive consideration of English-language articles may have introduced a slight bias towards anglophone nations.

Conclusions

From 2021 to 2024, this global research trend, key contributors, and thematic focuses of NPs-based strategies for salinity stress management in agriculture is profiled through a bibliometric analysis. Publication volume indicated that China and India were the top contributors, followed promptly by Egypt, Pakistan, Iran, and Bangladesh, as well, being highly internationally collaborative. Citation metrics further show that while higher output is concentrated in Asia and Africa, the USA, Qatar, and Australia have been responsible for producing some of the most heavily cited papers, indicating the global importance of this area of research. This topic overall represents an interdisciplinary area with 82% of research published in the agricultural sciences, but with contributions also from the environmental sciences and plant biology, as reflected in the top-20 key journals: Plants, Frontiers in Plant Science and Plant Physiology and Biochemistry. Well-cited publications are concentrated on sustainable nanomaterials, mechanisms for stress mitigation, nanofertilizers, and eco-friendly technologies. Domain-specific human network analyses revealed ten significant collaboration clusters and multiple key mega-researchers who have been nutrifying the intellectual growth of this field. Identified keywords analyses showed that the core themes like nanoparticles, agriculture, salinity, antioxidants, and mechanisms of plant tolerance, indicate that research is technologically (novel protocol) innovative and grounded on agronomic needs (pressure). This research therefore relates well with various Sustainable Development Goals (SDGs), namely, SDG 2 (Zero Hunger); SDG 12 (Responsible Consumption and Production); and, SDG 13 (Climate Action). Nanotechnology is of significant promise in agriculture to increase crop productivity, resource use efficiency and resilience to climate-induced stresses.

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Conflicts of interest

The authors declare that they have no conflict of interest in the publication.

Funding Declaration

Author contribution

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