



REVIEW ARTICLE

Agricultural nanotechnology for sustainable crop production: A systematic literature review

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Abstract

Sustainability in agriculture has gained immense importance worldwide due to population growth, global warming, declining soil fertility, excessive use of agrochemicals, water shortages and environmental pollution. Agricultural nanotechnology is an emerging technology capable of addressing these issues through enhanced crop productivity, efficient resource utilisation and environment-friendly practices. The main objective of this systematic literature review is to examine current trends, applications, limitations and future scope of agricultural nanotechnology as an innovative approach to sustainable agriculture. This review followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework to conduct a rigorous search and evaluation. Scientific publication published between 2015 and 2026 related to nanotechnology, nano-fertiliser, nano-pesticides, nanosensors, precision agriculture and sustainable agriculture were retrieved from the Scopus database. Out of these studies, a total of 398 were included in this systematic literature review based on predetermined selection criteria. From the results, it is evident that nanotechnology has great potential in improving nutrient use efficiency, crop growth, plant tolerance to abiotic stresses, reducing agrochemical waste and promoting precision agriculture. nano-fertilisers, nano-pesticides, nanosensors and smart delivery devices were found among major fields of research that contributed to sustainable agriculture. It was observed from bibliometric analysis that there is strong cooperation between countries with respect to studying agricultural nanotechnology, wherein some of the countries leading this front include India, China, Saudi Arabia, USA and UK. However, toxicity of nanoparticles, environment concerns, regulation problems, high costs associated with manufacturing and validation challenges at field level still remain significant barriers to adoption.

Keywords: agricultural nanotechnology; nanoparticles; precision agriculture; sustainable agriculture; sustainable crop production

Introduction

Agriculture is an important sector responsible for global food security, livelihoods and economic growth. Unfortunately, the agricultural sector faces several contemporary challenges, such as rapidly growing population, climate change, declining soil fertility, over-reliance on chemical fertilisers and pesticides, water scarcity and environmental degradation. The global population is projected to reach approximately 9.7 billion by 2050. Traditional agricultural methods have contributed significantly to improving the productivity of crops in the past few decades; however, intensive agricultural practices have led to soil depletion, loss of biodiversity, emission of greenhouse gases and pollution of water bodies. Consider specifying sustainable technologies and linking directly to nanotechnology (1–4).

Nanotechnology is regarded as one of the most significant technological breakthroughs in the field of science to revolutionise contemporary agriculture. The term nanotechnology refers to the manipulation and use of nanoparticles in the nanoscale range from 1 to 100 nm. These nanoparticles are characterised by unique physical, chemical and biological properties like high surface area, high reactivity, solubility and controlled release among others.

As a result, the use of nanoparticles in agriculture has become more attractive since they have been found to be useful for the delivery of nutrients, pest control, plant disease diagnostics, soil enrichment and precision agriculture among other applications (5–8).

One of the important applications of nanotechnology in agriculture is in the design of nano-fertilisers. In most cases, the efficacy of conventional fertilisers is low due to losses that arise through the volatilisation, leaching, runoff and fixation of nutrients in soils. These nutrient losses not only impose economic constraints on production but also drive environmental degradation. Nano-fertilisers represent an alternative technology developed to solve these problems via slow release mechanisms of nutrients. Recent research indicates that these novel formulations enhance nutrient utilisation, promote plant growth and reduce the loss of nutrients in the environment. It has also been shown that the utilisation of nano-fertilisers enhances the nutrient use efficiency and crop yield while reducing the amount of fertiliser needed for production (9–12). In a similar manner, pest and disease management practices are being revolutionised by the development of nano-pesticides, nano-herbicides and nano-

carrying systems. Pesticides pose numerous risks to the environment and human health due to their lack of specificity in action, excessive use and persistence in ecosystems. Nanopesticides enable more efficient and selective application of pesticides and minimise their use, resulting in minimal contamination and improved efficiency of pest elimination. Moreover, the use of nanomaterials makes agrochemicals stable and more easily available to plants even in small amounts. All of these developments make a significant contribution to sustainable agriculture (2, 13–15).

Nanotechnology has made another significant contribution in terms of playing a crucial role in precision agriculture and smart farming. The concept of precision agriculture refers to optimising the input of water, fertilisers, pesticides, etc. in agriculture through real-time monitoring and site-specific management of the land. With the help of nanotechnology, scientists have developed nanosensors to detect soil moisture, soil nutrients, pathogens, heavy metals and environmental stresses. Such nanosensors can provide real-time data to farmers to guide them in making informed decisions related to irrigation management, fertiliser management and pest management, respectively (16–18). Moreover, nanotechnology is highly effective in making plants more resilient against various types of biotic and abiotic stresses. Climate-induced abiotic stresses such as drought, salinity, high temperature, floods and heavy metal toxicity are affecting the growth and productivity of crops. Nanoparticles have exhibited great potential in increasing plant tolerance to stress via optimising the physiological, biochemical and antioxidant defense mechanisms. Silicon nanoparticles, metal oxide nanoparticles and carbon-based nanomaterials are extensively used to improve plant growth, increase the photosynthetic rate and optimise the stress responsive signalling pathways. It has been found that nanoparticle formulations increase seed germination rate, root growth, nutrient absorption capacity and plant tolerance to stress factors. For example, zinc oxide nanoparticles have been reported to enhance seed germination and seedling vigour in wheat, while silicon nanoparticles improved drought tolerance and growth performance in rice. Similarly, iron oxide nanoparticles have been shown to enhance nutrient uptake and biomass production in maize (19–22). Apart from crop production, nanotechnology has various other applications such as in soil remediation, post-harvesting process and food preservation. Nanomaterials have been widely employed in the field of soil remediation to remove heavy metals, pesticide residues and other soil-borne contaminants. Moreover, nano-technology-based packages and coatings that help in improving food quality, shelf life and reducing post-harvesting food losses have been developed. These developments are critical in providing food security and reducing food waste within the agricultural supply chain. Green nanotechnology techniques based on biologically synthesised nanoparticles have also gained interest due to their eco-friendly profile and lower toxicity compared to their chemical counterparts (23–26).

However, despite all the benefits of nanotechnology in agriculture, there exist certain concerns related to the environmental safety, toxicity and ecological consequences of using nanotechnology in agricultural systems. Specifically, the widespread application of nanoparticles in agriculture introduces risks of bioaccumulation, toxicity to beneficial microorganisms,

entry into the food chain and risks for human health. The behaviour and transformations of nanoparticles in agricultural ecosystems depend on certain aspects such as particle size, chemical structure and surrounding environmental conditions. In recent years, scientists have underlined the significance of performing comprehensive risk assessment and developing regulations concerning the safe application of nanotechnology within agricultural production processes (27–30). Furthermore, the use of nanotechnology in the agricultural sector is influenced by various aspects, including costs of production, low awareness levels, low rates of commercialisation, lack of infrastructure and uncertain regulation. Although numerous nano-based agrochemicals have demonstrated promising results in laboratory and greenhouse studies, their implementation at an industrial level is still minimal in many developing nations. Thus, research and policy efforts are geared towards creating efficient, environmentally friendly and easy-to-use agricultural practices to enhance agricultural development sustainably (1, 31–33).

Given the growing importance of sustainable agriculture, agricultural nanotechnology has emerged as a key research area. Nanotechnology in agriculture has the potential to offer improvements in the area of increasing agricultural output, enhancing the efficiency in the utilisation of nutrients and water resources, reducing pollution and climate resilience. Nonetheless, it is imperative to develop a better understanding of what agricultural nanotechnology entails in terms of applications, advantages, disadvantages, environmental impacts and future prospects. This literature review is therefore intended to critically assess recent research on agricultural nanotechnology in sustainable crop production (3, 4, 8).

Problem focus

Despite the rapid progress made in agricultural nanotechnology, a number of problems persist and restrict its practical application to crop production in a sustainable manner. traditional agricultural approaches are increasingly inadequate to meet the growing food requirements worldwide owing to factors such as climate change, soil infertility, excessive reliance on chemical fertilisers and pesticides, shortage of water resources and other environmental problems. However, nanotechnology can be considered one of the solutions for increasing fertiliser efficacy, crop yield, stress resistance and smart farming techniques, research efforts in this field are still fragmented.

Moreover, many past studies have focused primarily on the benefits of nanotechnology without considering environmental hazards, nanoparticle toxicity, ecological consequences, regulatory difficulties and large scale field application of nanoparticles. Long term implications of nanoparticles for soil microorganisms and the environment, human health and food safety have yet to be poorly understood. Moreover, the lack of regulatory mechanisms, variations in methodology for experiments and formulation differences of nanoparticles make it difficult to determine the safe use of nanotechnology in agriculture. An important problem is also the lack of commercialisation and field-scale implementation of nano agricultural technology, especially in developing countries. Many nanotechnologies that are being used in agricultural applications and show promising results in laboratory settings fail to be implemented on farms because of several factors such as cost of manufacturing, lack of infrastructure and lack of awareness

among farmers.

In addition to this, the rapid increase in the number of scientific publications concerning agricultural nanotechnology necessitates a thorough and systematic synthesis of all past researches carried out in this field. Earlier research reviews were limited to examining specific applications or features of nanotechnology in agriculture, often overlooking important aspects such as risk assessment, field-scale applications, regulatory frameworks and its role in promoting sustainable agricultural practices. As a result, there is still a deficiency of such systematic synthesis of technology, environment, trends of research and future research areas in agricultural nanotechnology. Thus, a systematic literature review has been conducted for the assessment of agricultural nanotechnology.

Methodology

This systematic literature review (SLR) on agricultural nanotechnology in sustainable crop production was conducted using a structured and transparent review methodology to comprehensively evaluate the existing scientific literature. The study adopted the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines to ensure the systematic identification, screening, eligibility assessment and inclusion of relevant research articles. The PRISMA framework is widely recognised for enhancing the transparency, consistency and reliability of systematic review studies in scientific research. The Scopus database was selected as the primary source for literature retrieval because of its extensive coverage of peer-reviewed scientific publications across multidisciplinary research fields, including agriculture, plant science, nanotechnology, biotechnology and environmental science. Scopus was considered suitable for this review due to its high-quality indexing standards and comprehensive collection of recent scholarly publications. The inclusion and exclusion criteria employed during the review process are presented in Table 1.

Studies associated with the application of agricultural nanotechnology have become abundant since 2015 owing to growing concerns about food security, environmental sustainability, climate change, declining soil fertility, dependency on chemical fertilisers and pesticides and sustainable agriculture practices.

Recently published literature has highlighted the significance of nanotechnology in enhancing nutrient use efficiency, crop productivity, stress tolerance of plants, pest control and precision agriculture. Hence, the current review was carried out on scientific research articles published from 2015 until 2026 to reflect new developments and research trends in the field of agricultural nanotechnology.

A comprehensive search strategy was developed to identify relevant scientific studies related to nanotechnology applications in sustainable crop production. The search strategy incorporated multiple keywords associated with agricultural nanotechnology, sustainable agriculture, crop productivity, plant growth, soil health, precision farming and environmental sustainability. The search query included terms such as "Nanotechnology," "Agricultural Nanotechnology," "Nano-enabled Agriculture," "Nanomaterials," "Nanoparticles," "Nano-fertilisers," "Nano-pesticides," "Nanoherbicides," "Nanoformulations," "Sustainable Agriculture," "Climate-smart Agriculture," "Precision Agriculture," "Smart Farming," "Crop Production," "Plant Growth," "Soil Health," "Food Security," and "Environmental Sustainability." Boolean operators such as AND and OR were used to broaden the scope of literature retrieval and improve the identification of relevant studies. The complete list of keywords used during the database search process is presented in Table 2.

The literature search was conducted in the Scopus database on 15 January 2026, initially yielding 1812 research publications related to agricultural nanotechnology and sustainable agriculture. Subsequently, a systematic screening process was carried out following the PRISMA framework to refine and filter the retrieved studies. The PRISMA flow diagram presented in Fig. 1 illustrates the stages involved in the identification, screening, eligibility assessment and inclusion of studies in the review process.

During the screening stage, duplicate and irrelevant records were removed based on the predefined eligibility criteria. Only peer-reviewed journal articles and review articles published in English between 2015–26 and indexed in the Scopus database were included for analysis. Only final published, full-text open-access articles were considered to ensure accessibility for detailed evaluation and data extraction. Conference papers, conference reviews, editorials, books, book chapters, trade journals, conference proceedings, articles in press and publications not directly related to agricultural nanotechnology and sustainable

Table 1. Eligibility criteria adopted for the systematic literature review

Criterion	Inclusion criteria	Exclusion criteria
Database	Scopus database	Other databases
Publication period	2015–2026	Published before 2015
Document type	Original research articles and review articles	Conference papers, Book chapters, Books, Editorials, Conference reviews
Languages	English	Non-English publications
Source type	Peer-reviewed journals	Trade journals, conference proceedings, magazines and other non-peer-reviewed sources
Publication stage	Final published articles	Articles in press, early access or unpublished records
Accessibility	Full-text open-access articles	Publications without accessible full text

Table 2. The list of keywords employed during the database literature searches

Databases	Keywords	Total number of article
Scopus	"Nanotechnology" OR "Agricultural Nanotechnology" OR "Nano-enabled Agriculture" OR "Nanomaterials" OR "Nanoparticles" OR "Nano-fertilisers" OR "Nano pesticides" OR "Nanoherbicides" OR "Nanoformulations" AND "Sustainable Agriculture" OR "Sustainable Farming" OR "Climate-smart Agriculture" OR "Precision Agriculture" OR "Smart Farming" OR "Organic Agriculture" OR "Eco-friendly Agriculture" OR "Green Agriculture") AND "Crop Production" OR "Crop Yield" OR "Plant Growth" OR "Soil Health" OR "Nutrient Use Efficiency" OR "Pest Management" OR "Food Security" OR "Environmental Sustainability"	1812

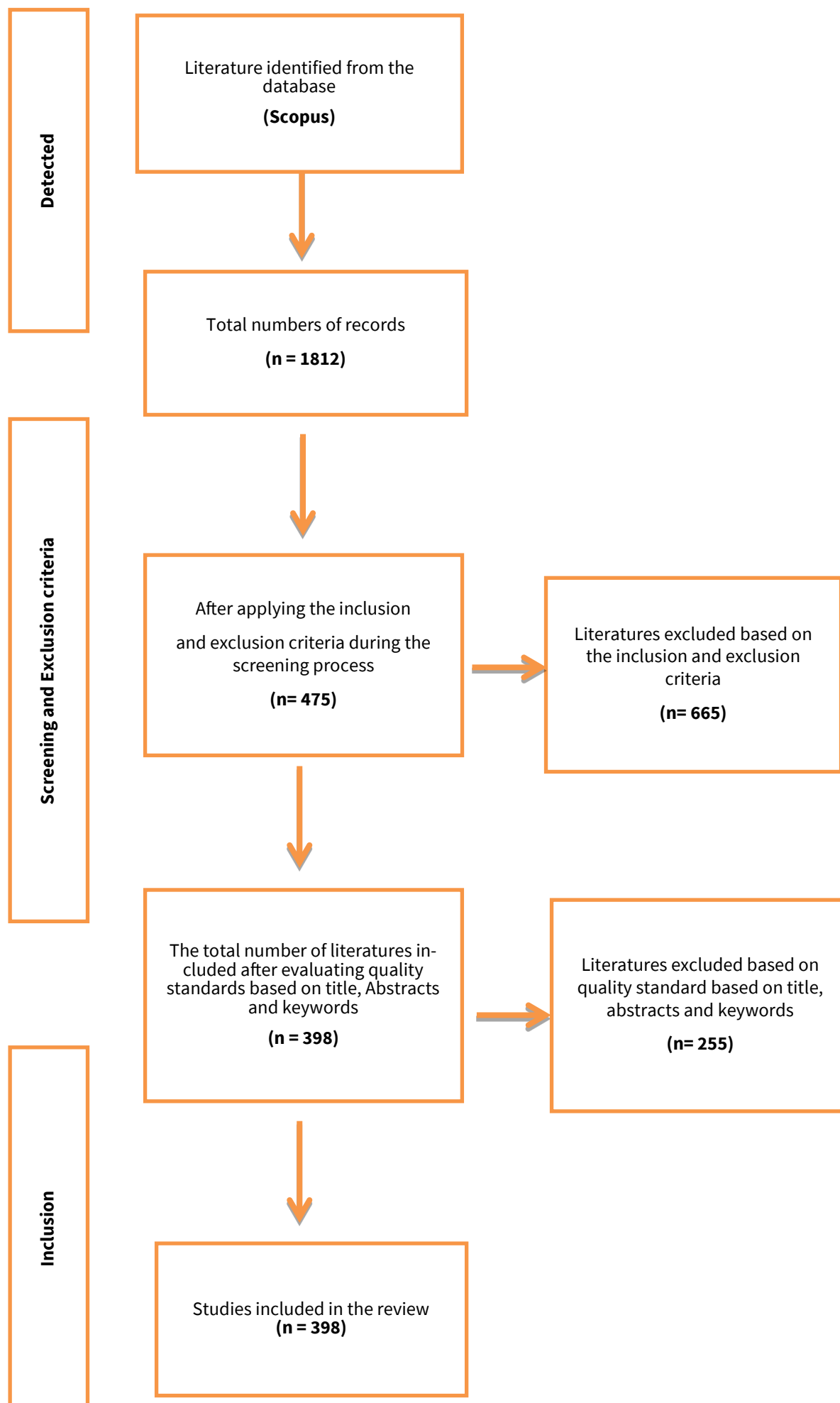


Fig. 1. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart.

crop production were excluded from the review. The detailed eligibility criteria are presented in Table 1.

After applying the screening criteria, the remaining articles were critically analysed on the basis of their title, abstract and keywords in order to establish their alignment with the research objectives. Specific attention was paid to those studies that deal with nano-fertilisers, nano-pesticides, nanosensors, smart delivery systems, plant stress management, precision agriculture, nutrient utilisation efficiency and environmental sustainability. Those studies that lack direct connection with agricultural nanotechnology and sustainable crop production have been excluded from the final stage of reviewing. Upon completion of the screening and selection criteria processes, 398 research articles were included for qualitative analysis and synthesis. Inclusion of these studies enabled the review to provide a comprehensive overview of agricultural nanotechnology in relation to its applications, advantages, environmental impacts, disadvantages and future outlook with regard to sustainable crop production. These studies covered a broad range of applications and emerging trends in agricultural nanotechnology related to sustainable crop production and resource management.

Justification for inclusion criteria

Peer-reviewed journal articles and review papers were included in this systematic literature review to ensure the scientific quality, credibility and reliability of the selected studies. Review papers were considered to provide comprehensive insights into research trends, knowledge gaps and thematic developments, while primary studies contributed original empirical evidence. To avoid duplication of evidence, review articles were used primarily for contextual understanding and synthesis of existing knowledge, whereas data extraction and analysis were based on original research findings. The Scopus database was chosen because of its extensive coverage of high-quality multidisciplinary research publications related to agriculture, plant science, nanotechnology and environmental science. Only English-language publications

published between 2015 and 2026 were considered, as this period reflects significant advancements in agricultural nanotechnology and sustainable crop production technologies. Furthermore, only final-stage open-access journal publications were included to ensure accessibility and availability of complete research articles for detailed analysis. Publications such as conference papers, conference reviews, editorials, books, book chapters, trade journals, proceedings papers and articles in press were excluded due to possible variations in peer-review standards, accessibility and scientific rigour. These inclusion and exclusion criteria helped maintain the consistency, transparency and reliability of the review process.

Results and Discussion

Co-authorship network of authors

The co-authorship network shown in Fig. 2 was generated using VOSviewer to analyse collaboration patterns among authors in the field of agricultural nanotechnology for sustainable crop production. Each node represents an author, while node size reflects the author's research influence and collaboration strength. The network consists of three major clusters, indicating the presence of active research groups in this domain. Among these, the red cluster was the largest, comprising 7 authors: Tatiana Minkina, Vishnu D Rajput, Abhishek Singh, Svetlana Sushkova, Saglara Mandzhieva, Karen Ghazaryan and Krishan K Verma. Within this cluster, Tatiana Minkina and Vishnu D Rajput emerged as the most influential authors, as indicated by their larger node sizes and stronger collaborative connections with other researchers. The prominence of this cluster highlights its significant contribution to the development of agricultural nanotechnology research and sustainable crop production.

Authors belonging to the blue cluster include Mohammad Faizan and Pravej Alam. These authors act as connecting authors between the red and green clusters and therefore, they help in the effective development of interdisciplinary cooperation and scientific interaction in research studies. Authors belonging to the green cluster

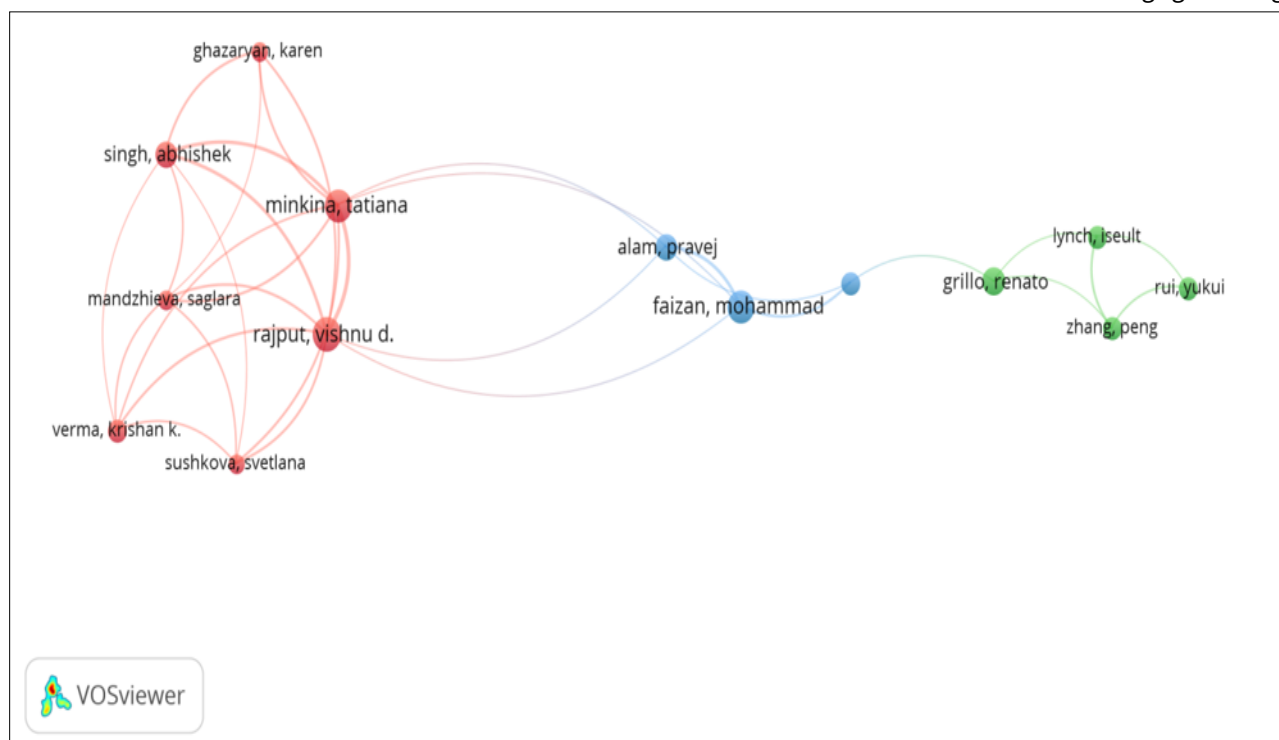


Fig. 2. Co-authorship analysis of authors in agricultural nanotechnology research.

cluster include Renato Grillo, Peng Zhang, Yukui Rui and Liseult Lynch. In this cluster, the most notable author is Renato Grillo owing to the stronger associations he has formed with other authors in this cluster. The associations formed within this cluster reflect an increase in the international collaboration of researchers and increased interests in using nano-agriculture technologies to promote sustainable crops. In summary, the co-authorship analysis shows that the studies carried out in agricultural nanotechnology for the production of sustainable crops involve extensive collaborations among researchers. The extensive linkages formed by the leading authors show that there is an increasing level of scientific collaboration across the globe to enhance the development of agricultural technology in order to improve crop production.

The findings of the present study are consistent with earlier review studies that described agricultural nanotechnology as a highly multidisciplinary research field requiring collaboration among experts in plant science, nanotechnology, environmental science and biotechnology (2, 4). Similar to previous studies, the present co-authorship analysis demonstrates that scientific collaboration has become increasingly important for addressing complex agricultural challenges through nano-enabled technologies. However, unlike earlier narrative reviews, the present bibliometric analysis provides an updated quantitative assessment of collaborative research networks and identifies Tatiana Minkina, Vishnu D. Rajput and Renato Grillo as major contributors during the 2015–26 study period. These findings highlight the evolving global research landscape and provide current evidence of leading collaborative research groups in agricultural nanotechnology.

Co-authorship network by countries

The network of co-authorship illustrated in Fig. 3 was constructed using VOSviewer to investigate the pattern of international research collaboration amongst countries in the area of agricultural nanotechnology for sustainable agriculture. Each country is indicated by nodes, where the size of the node denotes the relative contribution and collaboration of the country. Lines denote the connections of countries through co-authorship and each colour

represents different collaboration clusters. It is evident from the network that there exists a high level of international collaboration amongst all the countries in this area of study. India, China and Saudi Arabia can be seen as the leading The network of co-authorship illustrated in Fig. 3 was constructed using VOSviewer to investigate patterns of international research collaboration in agricultural nanotechnology for sustainable agriculture. The network revealed three major collaboration clusters, demonstrating a high degree of global scientific cooperation in this research area. India, China and Saudi Arabia emerged as the most influential countries in the network, as reflected by their larger node sizes and extensive collaborative linkages with other countries.

The blue cluster comprised 6 countries, namely India, South Korea, Germany, Australia, Poland and the Czech Republic. The strong interconnections among these countries indicate active research collaboration and knowledge exchange. India occupied a prominent position within this cluster, highlighting its growing contribution to agricultural nanotechnology research and international partnerships.

The green cluster consisted of 7 countries: China, Pakistan, Saudi Arabia, Egypt, Jordan, Mexico and Turkey. China served as the central country within this cluster, reflecting its significant research activity and strong collaborative relationships in the field of nano-enabled agriculture and sustainable crop production.

The red cluster included 7 countries, namely the United States, the United Kingdom, Brazil, Italy, Canada, Nigeria and Hungary. The United States and the United Kingdom exhibited strong collaborative connections with other countries in the cluster, indicating their important role in advancing multidisciplinary research related to sustainable agricultural technologies. In addition, countries such as Iran, Ethiopia and Iraq acted as bridging countries connecting different clusters and facilitating international scientific cooperation. Overall, the co-authorship network demonstrates that agricultural nanotechnology research is characterised by extensive international collaboration, which plays a crucial role in accelerating innovation, knowledge sharing and the development of sustainable

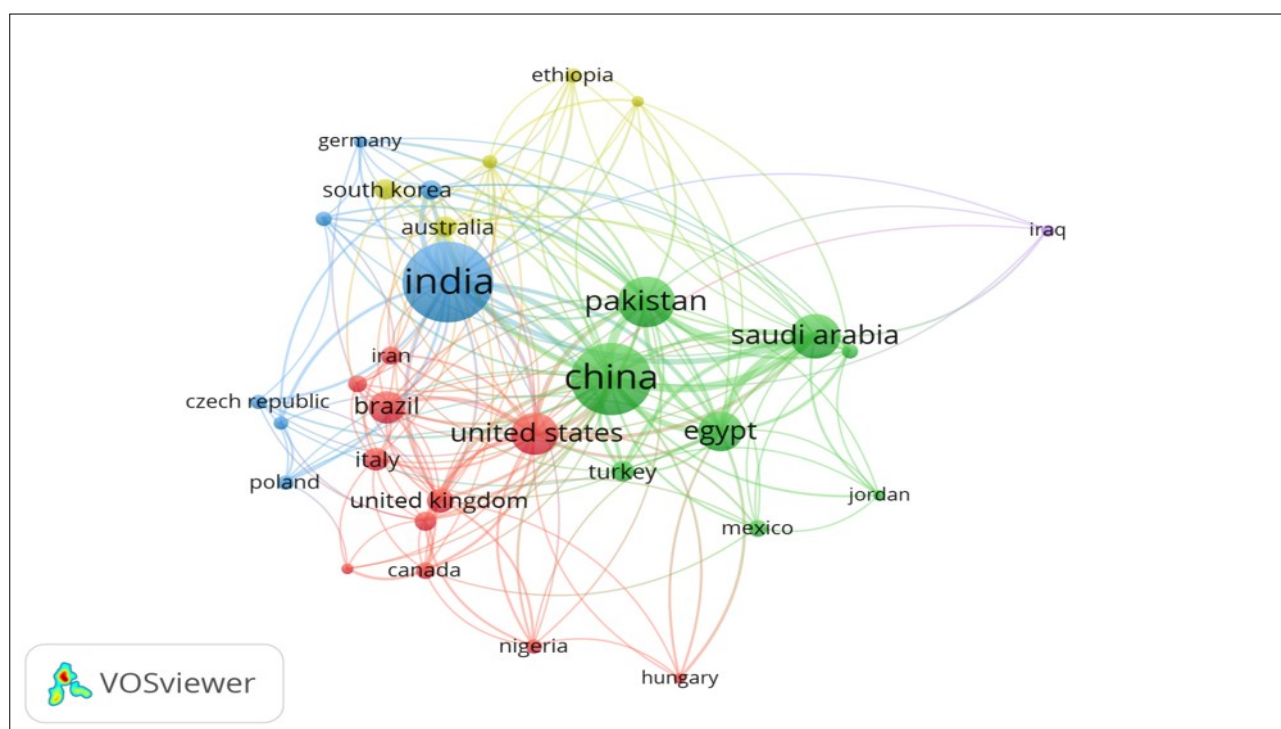


Fig. 3. Co-authorship analysis of countries in agricultural nanotechnology research.

agricultural solutions worldwide.

The international collaboration patterns observed in the present study agree with previous reviews, which reported that countries such as India, China and the United States play leading roles in advancing agricultural nanotechnology research (4, 5). The current findings further demonstrate the growing contribution of Saudi Arabia and other emerging research nations, reflecting the expansion of global scientific collaboration in sustainable agriculture. Compared with earlier reviews that primarily discussed technological applications, the present bibliometric analysis provides a more comprehensive understanding of international collaboration networks and knowledge exchange among countries.

Author keywords

The co-occurrence network presented in Fig. 4 was generated using VOSviewer to identify the major research themes and conceptual relationships in the field of agricultural nanotechnology for sustainable crop production. In this visualisation, each node represents an author keyword, while the size of the node indicates the frequency of keyword occurrence within the selected publications. The connecting lines represent the co-occurrence relationships between keywords and different colours indicate distinct thematic clusters. The network reveals that “sustainable agriculture” is the most dominant and central keyword in the study area, occupying a prominent position within the co-occurrence network and exhibiting strong connections with other major keywords such as “nanotechnology,” “nanomaterials,” “nano-fertilisers,” “nanoparticles,” and “crop yield.” This indicates that the primary focus of current research is on developing environmentally sustainable agricultural systems through nanotechnology-based approaches. The strong connections between “sustainable agriculture” and other keywords such as “nanotechnology,” “nanomaterials,” “nano-fertilisers,” “nanoparticles,” and “crop yield” demonstrate the increasing importance of nano-enabled

technologies in improving agricultural productivity and sustainability.

The red cluster primarily focuses on nanomaterials and agricultural productivity-related research themes. Keywords such as “nanomaterials,” “nano-fertilisers,” “crop yield,” and “pesticides” are strongly interconnected, indicating substantial research attention toward the application of nanotechnology for enhancing nutrient efficiency, improving crop productivity and reducing chemical input usage in agricultural systems.

The green cluster, centered around “sustainable agriculture,” represents broader sustainability-oriented research themes, including “environmental impact,” “rice,” “biofortification,” and “salinity.” The close relationships among these keywords indicate growing research interest in using nanotechnology to address environmental challenges, improve crop resilience and enhance food security under stress conditions.

The blue cluster mainly represents research associated with plant stress physiology and crop protection. Keywords such as “oxidative stress,” “biostimulants,” and “crop protection” indicate increasing scientific attention toward improving plant tolerance against abiotic stress through nano-enabled agricultural interventions. Although “salinity” was also identified in the green cluster, its occurrence across multiple clusters suggests that it functions as a bridging keyword connecting sustainability-oriented research with plant stress management studies. This highlights the interdisciplinary nature of agricultural nanotechnology research, where salinity stress is addressed from both environmental sustainability and crop resilience perspectives.

The yellow cluster highlights emerging technological advancements in smart and precision agriculture. Keywords such as “artificial intelligence,” “nanosensors,” and “biochar” suggest the integration of nanotechnology with advanced digital technologies for real-time monitoring, precision nutrient management and

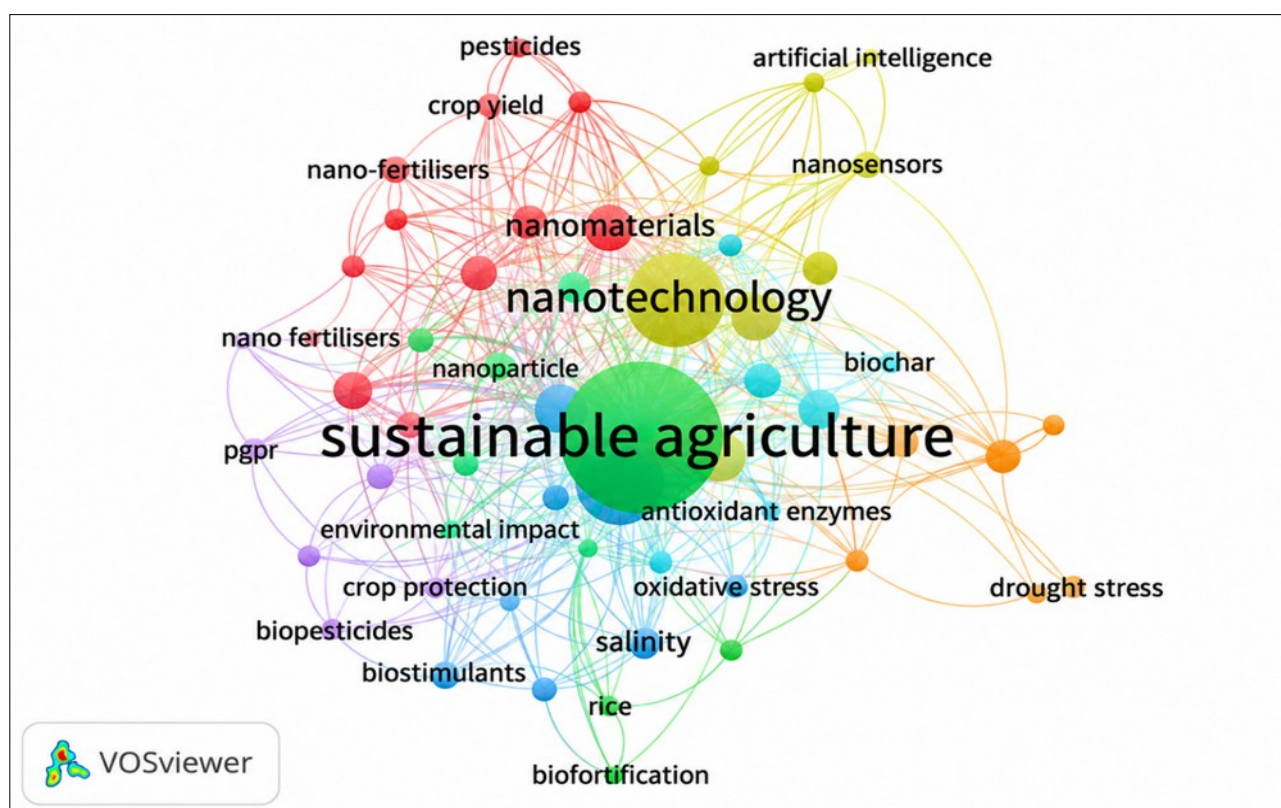


Fig. 4. Co-occurrence analysis of author keywords in agricultural nanotechnology research.

sustainable farming practices.

The purple cluster includes keywords such as “PGPR,” “biopesticides,” and “nano fertilisers,” reflecting the growing emphasis on biological and microbial approaches integrated with nanotechnology for environmentally friendly crop management strategies.

Additionally, keywords such as “drought stress,” “antioxidant enzymes,” and “biofortification” indicate that recent research is increasingly focused on enhancing plant stress tolerance, nutritional quality and climate resilience using nano-enabled agricultural technologies. Overall, the co-occurrence analysis demonstrates that research on agricultural nanotechnology for sustainable crop production is highly interdisciplinary and rapidly evolving. The strong interconnections among keywords indicate that current studies are increasingly integrating nanotechnology, environmental sustainability, stress management, precision agriculture and biological approaches to develop innovative and sustainable agricultural solutions.

The keyword analysis largely supports the findings of previous review studies, which identified nano-fertilisers, sustainable agriculture and precision farming as major research themes in agricultural nanotechnology (4, 9). However, the emergence of keywords such as artificial intelligence, nanosensors, biochar and oxidative stress indicates a recent shift towards digital agriculture, climate resilience and integrated smart farming approaches. These emerging themes demonstrate the continuous evolution of agricultural nanotechnology beyond conventional nutrient management towards intelligent and sustainable agricultural systems.

Documents of bibliometric coupling (Country wise)

The bibliographic coupling network presented in Fig. 5 was generated using VOSviewer to examine the intellectual relationships among countries based on shared references in publications related to agricultural nanotechnology for sustainable crop production. In

this visualisation, each node represents a country, while node size indicates the research influence and publication strength of the respective country. The connecting lines represent the strength of bibliographic coupling between countries, indicating the extent to which countries cite similar references in their research publications. Different colours represent distinct research clusters. The analysis identified three major bibliographic coupling clusters, demonstrating strong intellectual connectivity and shared research foundations among countries engaged in agricultural nanotechnology research. Among all countries, India, China and Saudi Arabia emerged as the most influential countries because of their larger node sizes and stronger bibliographic linkages with multiple nations. Their central positions within the network indicate substantial research productivity and significant contributions to knowledge development in this field.

The blue cluster consisted of 4 countries, namely India, Thailand, Ethiopia and Iraq. The close intellectual relationships among these countries indicate similarities in research interests, citation patterns and thematic focus areas. India occupied a highly central position within this cluster, highlighting its strong influence and extensive engagement with global research literature related to sustainable agricultural nanotechnology.

The green cluster comprised 7 countries, including China, Saudi Arabia, Egypt, Turkey, Jordan, Mexico and the United Arab Emirates. The strong bibliographic connections among these countries reflect shared scientific foundations and common research interests in nano-enabled agricultural technologies and sustainable crop management practices. China and Saudi Arabia emerged as the leading contributors within this cluster due to their extensive intellectual linkages with other countries.

The red cluster included 6 countries, namely the United Kingdom, Brazil, Italy, Canada, South Africa and Morocco. The dense interconnections within this cluster indicate a high degree of similarity in cited literature and research orientation. The United Kingdom and Brazil appeared as influential countries because of

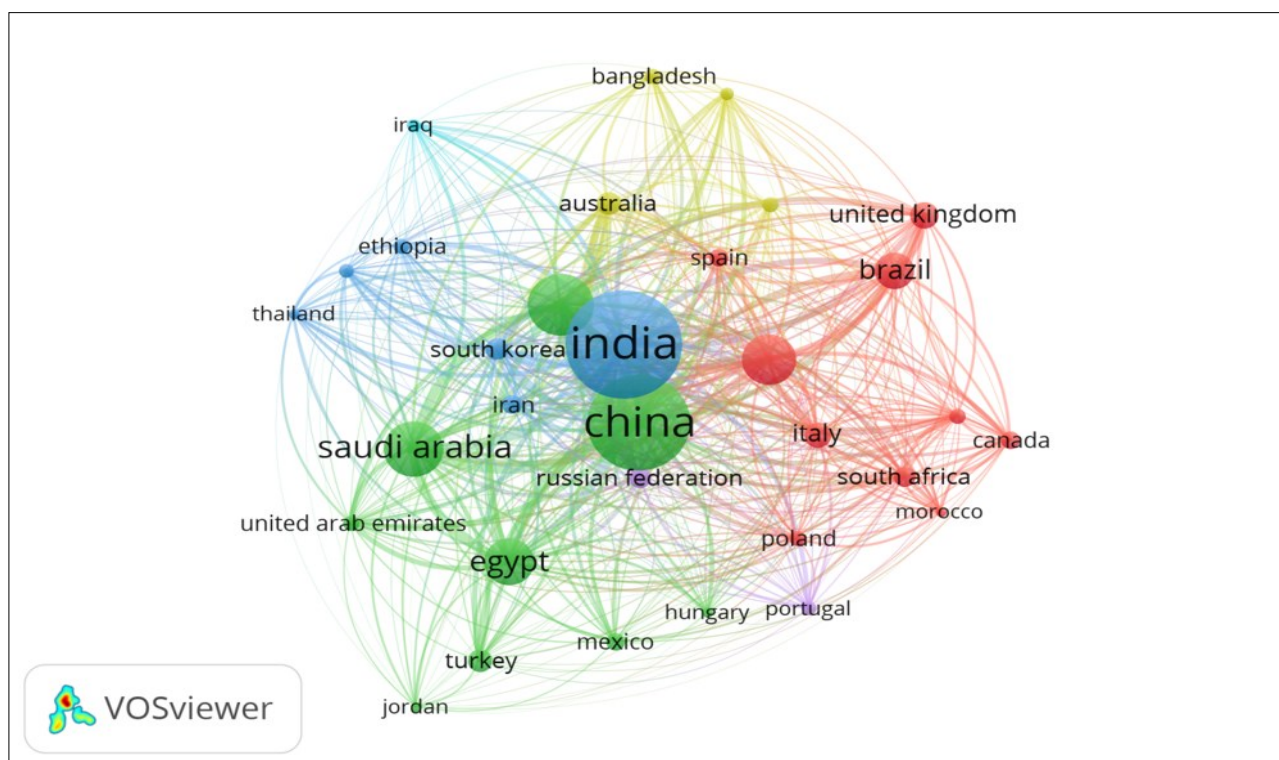


Fig. 5. Bibliographic coupling analysis of countries in agricultural nanotechnology research.

their relatively stronger bibliographic connections. Additionally, countries such as Australia, Spain, Bangladesh, South Korea, Iran, Poland, Portugal, Hungary and the Russian Federation occupied intermediary positions connecting multiple clusters and facilitating the exchange of scientific knowledge across the global research network.

The bibliographic coupling analysis confirms previous observations that India and China continue to serve as major centres of scientific knowledge in agricultural nanotechnology (2, 4). Nevertheless, the present study demonstrates stronger intellectual connections among countries than previously reported, indicating increasing international integration of research efforts. These findings suggest that agricultural nanotechnology has evolved into a globally collaborative research field supported by shared scientific foundations and multidisciplinary knowledge exchange.

Co-citation of cited references

The co-citation network presented in Fig. 6 was generated using VOSviewer to identify the intellectual structure and influential cited references in the field of agricultural nanotechnology for sustainable crop production. In this visualisation, each node represents a cited reference, while the node size represents the co-citation frequency of that reference within the selected publications. The connecting lines represent co-citation relationships between references and different colours indicate distinct thematic clusters. The network reveals several strongly interconnected clusters, indicating the presence of closely related research themes and shared scientific foundations within the field. The analysis highlights that studies related to nano-fertilisers, nanoparticle-based agricultural applications and nanotechnology-driven crop improvement form the core intellectual base of the research domain.

The red cluster represents a major research group within the network and includes highly co-cited references such as “Munne-Bosch S., Nanofertiliser”, “Shukla P., Effects of nanofertilisers”, “Torabian S., Nano-silicon” and “Do Espirito Santo Pereira A.” The strong interconnections among these references indicate that nano-fertiliser applications, nutrient efficiency and stress mitigation are major research themes in agricultural nanotechnology. The

relatively larger node size of Munne-Bosch S. suggests that this reference has substantial influence within the literature.

The green cluster primarily focuses on the broader applications of nanotechnology in sustainable agriculture. This cluster includes references such as “Lal R., Potentials of Engineered Nanomaterials”, “Zhou J., Applications of Nanotechnology”, “Panwar J., Nano-fertilisers” and “Nguyen Q D, Nanotechnology in Agriculture.” The close relationships among these references demonstrate strong conceptual similarity and indicate that these studies collectively contribute to the theoretical and applied foundations of nano-enabled agricultural technologies.

The blue cluster contains references associated with nanoparticle-based systems and environmental applications of nanotechnology. References such as “Keswani C, Coping with the challenges” and “Ali S.A., nanoparticle-based Systems” show strong linkages with other clusters, indicating their role in connecting diverse research themes within the field.

The dense interactions between the clusters clearly show that research in the area of agricultural nanotechnology is very interdisciplinary. According to the co-citations, research that revolves around nano-fertilisers, engineered nanomaterials, crop stress management and sustainable agriculture is usually used collectively as a base for further advancements. In general, co-citation analysis proves that the area of agricultural nanotechnology as an approach towards sustainable crop production uses a rich array of sources that provide essential groundwork for developing knowledge, innovations and sustainable practices in the area.

The co-citation analysis is consistent with earlier review studies that recognised nano-fertilisers, engineered nanomaterials and sustainable agriculture as the principal knowledge base of agricultural nanotechnology (2, 4, 14). In addition, the present study identifies recent influential publications focusing on stress management, precision agriculture and sustainable crop production, demonstrating the changing research priorities of the field. Compared with previous reviews, this bibliometric analysis provides updated evidence regarding the intellectual structure and emerging directions of agricultural nanotechnology research.

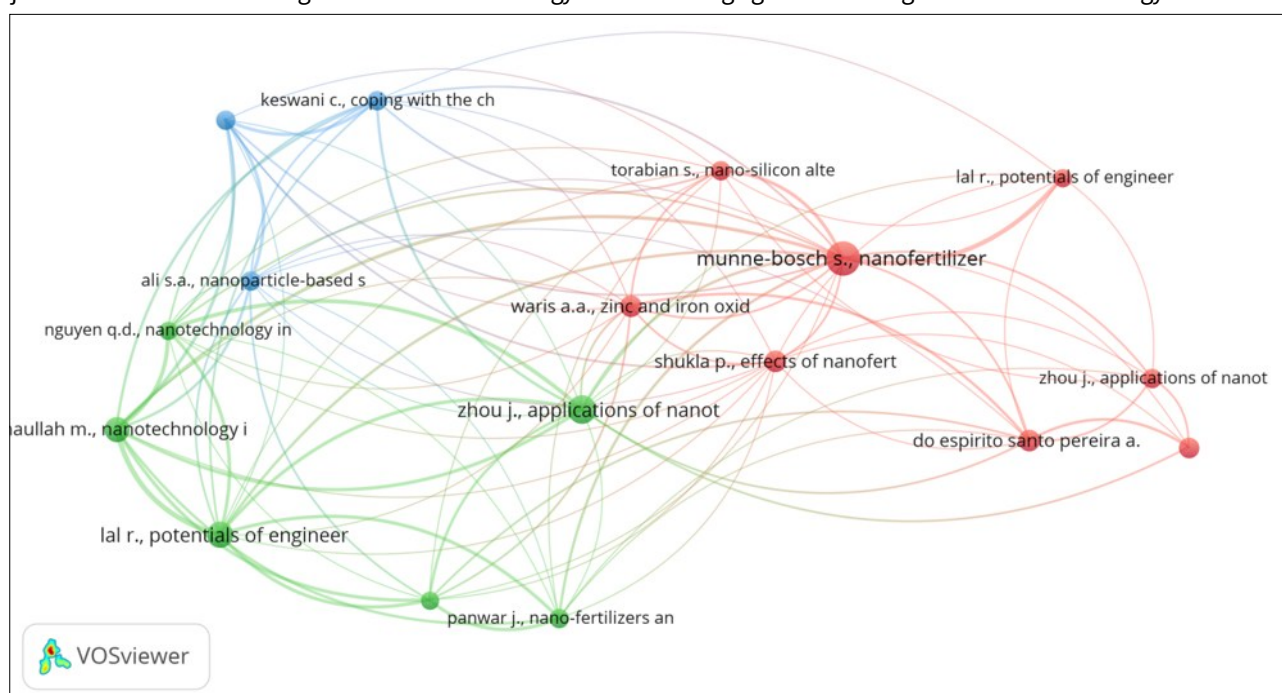


Fig. 6. Co-citation analysis of cited references in agricultural nanotechnology research.

Conclusion

Agricultural nanotechnology has emerged as a promising and innovative approach for addressing the growing challenges associated with sustainable crop production, food security, environmental degradation and climate change. This systematic literature review highlights that nanotechnology offers significant potential to improve agricultural productivity through applications such as nano-fertilisers, nano-pesticides, nanosensors, smart delivery systems and precision farming technologies. The reviewed studies demonstrate that nano-enabled agricultural technologies can enhance nutrient use efficiency, improve crop growth and stress tolerance, reduce agrochemical losses and support environmentally sustainable farming practices. The bibliometric and thematic analyses further reveal that research on agricultural nanotechnology has grown substantially in recent years and has become highly interdisciplinary and globally collaborative in nature. Countries such as India, China, Saudi Arabia, the United States and the United Kingdom play a major role in advancing scientific research and international collaboration in this field. Similarly, the co-occurrence and co-citation analyses indicate that sustainable agriculture, nano-fertilisers, nanomaterials, stress management, precision agriculture and environmental sustainability represent the major research themes and intellectual foundations of current studies.

Despite the numerous advantages associated with agricultural nanotechnology, the review also identifies several critical challenges that limit its large-scale adoption and commercialisation. Concerns related to nanoparticle toxicity, environmental safety, long-term ecological impacts, regulatory uncertainties, high production costs and limited field-level validation remain major barriers to the sustainable implementation of nano-enabled agricultural technologies. Furthermore, inconsistencies in research methodologies and the absence of standardised regulatory frameworks create uncertainty regarding the safe application of nanoparticles in agricultural systems. Overall, the evidence synthesised in this review indicates that agricultural nanotechnology has the potential to play a transformative role in future agricultural systems by enhancing productivity, resource-use efficiency and environmental sustainability. However realising this potential will require comprehensive long-term environmental risk assessment, large-scale field validation, development of cost-effective nanoformulations, alongside the establishment of comprehensive regulatory policies to ensure the safe and responsible integration of nanotechnology into sustainable agricultural practices worldwide. Greater collaboration among researchers, policymakers, industries and agricultural stakeholders will also be essential for promoting sustainable innovation and practical implementation of nano-enabled technologies in global agricultural systems.

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Authors' contributions

ARAK contributed to article collection analysis and interpretation. SS contributed to conceptualisation validation and manuscript review. ND contributed to drafting the manuscript. MP contributed to manuscript review. RV contributed to validation. All authors have read and approved the final manuscript.

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