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Magnesium in agricultural sustainability: mapping research priorities, emerging trends and thematic shifts between 2005 and 2024

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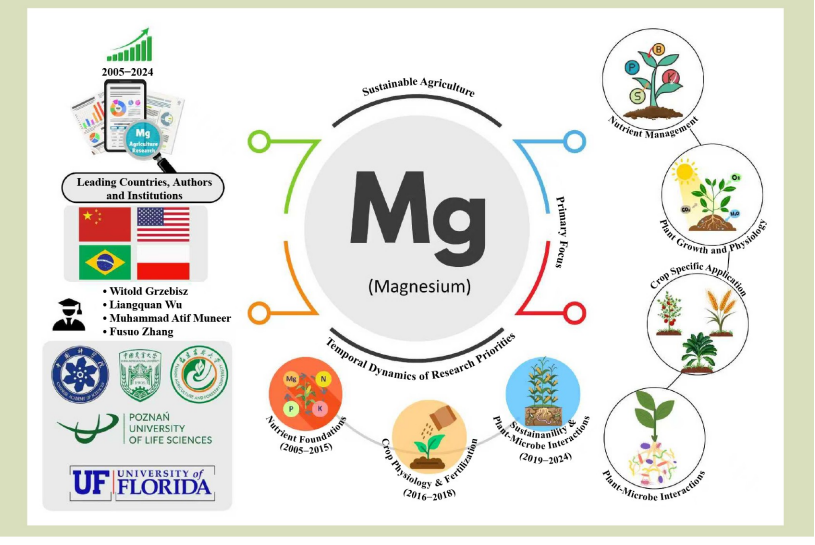
KEYWORDS

Agricultural sustainability, bibliometric analysis, CiteSpace, magnesium, nutrient management

HIGHLIGHTS

- Global Mg research in agricultural sustainability has grown rapidly from 2005 to 2024.
- China has surpassed the USA as the leading contributor in Mg research.
- Research priorities include nutrient management, plant physiology and plant-microbe interactions.
- Mg-research focus has shifted from fundamental nutrition to sustainable agroecosystems.
- Enhanced global collaboration is needed to advance Mg-research impact.

GRAPHICAL ABSTRACT



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ABSTRACT

Magnesium is an essential macronutrient for photosynthetic activity, metabolic functions, and stress tolerance, thus plays a vital role in crop production. Despite its agronomic significance, global Mg-research trends in agricultural systems have not been systematically characterized. In this study, CiteSpace was used to analyze 3318 articles from 2005–2024 to determine growth patterns, influence and thematic shifts in Mg research. The number of annual articles has increased substantially over the last 20 years, highlighting the growing scientific interest in Mg for agricultural sustainability. The top

contributors are China and the USA with a two-decade comparison revealing a clear transition towards China during 2015–2024 driven by leading Chinese institutions, such as China Agricultural University, the Chinese Academy of Sciences and Fujian Agriculture and Forestry University. Co-authorship networks were fragmented, reflecting limited international cooperation. Keyword co-occurrence and cluster analyses identified four dominant thematic research domains, including nutrient management and soil fertility, plant physiology and stress responses, crop specific applications focusing on yield and quality, and plant-microbe interactions. Temporal keyword changes revealed a shift from mineral nutrition and soil fertility (2005–2015) to crop physiology and nutrient use efficiency (2016–2018), followed by sustainability and plant-microbe interactions (2019–2024). These temporal shifts indicate that Mg research has gradually moved from fundamental nutrient studies toward system-level sustainability and multiscale biological integration. This study provides a comprehensive evolutionary view of Mg research and highlights the need for stronger interdisciplinary and international collaboration to promote resilient, Mg-driven sustainable agroecosystems.

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1 Introduction

Magnesium has gained recognition for its essential function in sustainable agriculture due to its diverse roles that extend far beyond its typical classification as a secondary plant nutrient[1]. As an essential macronutrient, Mg is required in physiological, biochemical and ecological processes that affect crop yield and environmental health[2,3]. With increasing global food demand, the intensifying climate change, resource depletion and especially optimization of Mg management in agricultural food system has become increasingly important. This focus aligns with the concepts of sustainable agriculture that encourage high production while ensuring environmental protection[4]. However, there is insufficient understanding of the diverse roles of Mg, so it has not yet been fully incorporated into sustainability models.

Mg is required for chlorophyll synthesis, therefore important for efficient photosynthesis to enhance plant growth, development and metabolic functions[1]. In soil, Mg is an essential nutrient that enhances the physicochemical characteristics of soil, including water retention, pH and nutrient availability[5]. Also, Mg is a cofactor for numerous enzymes, and is important in synthesis of DNA and RNA, as well as in the uptake of important nutrients such as nitrogen and phosphorus, and therefore supports protein synthesis and other important metabolic activities. Mg also directly impacts plant physiology, leads to the alleviation of abiotic stresses (drought and salinity) and the improvement of water use efficiency and stress resilience under adverse weather conditions[5–7]. Nevertheless, the integrative role of Mg in enhancing agroecosystem resilience has not been effectively emphasized in established agronomic practices and nutrient modeling frameworks.

Despite its significance, sustaining Mg balance in soil remains a major challenge, as both deficiency and excess can negatively affect plant growth and productivity[8]. Also, the diversity of soil types and climatic conditions further complicates the Mg availability in soil, thus region-specific management approaches are needed[9,10]. To overcome these challenges, innovative Mg management approaches are needed to enhance crop yield, nutritional value and overall sustainability of agricultural systems. Progress made in Mg research has significant potential for improving global food security and nutrition[1,8]. However, the lack of standardized recommending practices continues to limit the adoption of improved Mg management practices. Therefore, it is important to find the key knowledge gaps and innovative approaches to exploit the potential of Mg in agricultural sustainability.

Bibliometric analysis has been recognized as an efficient

method for assessing scientific advancement, enabling researchers to quantitatively assess article patterns, citation patterns, thematic research hotspots and collaboration networks within a specified research field[11]. CiteSpace, a bibliometric software, is primarily used to visualize and analyze citation networks, mapping intellectual structures, and identifying emerging research trends in scientific studies[12,13]. These analyses provide strategic insights into influential articles, core institutions and emerging subfields, thus guiding future research directions and prioritizing funding[14]. Although bibliometric reviews have been used in diverse areas of agricultural sciences, studies specifically focusing on the development and pattern of Mg-related agricultural research are still limited. This gap restricts a comprehensive understanding of how Mg research has contributed to agricultural sustainability over the last 20 years.

To date, various studies have examined the physiological essence of Mg in plants, its key role in photosynthesis, carbohydrate partitioning, nutrients interactions and stress tolerance[5,15,16]. A meta-analysis has also shown that Mg application enhances crop yield and quality regardless of the types of production systems and agro ecological settings[1]. However, the recent reviews have highlighted the emerging role of Mg in controlling nutrient use efficiency, antioxidant metabolism and plant-microbe interactions in sustainable agricultural systems[17–19]. Nonetheless, the majority of the available reviews concentrate on particular physiological processes, types of crops, or responses to fertilizer application, instead of critically assessing the overall structure of research, modes of collaboration, and development of thematic trends of Mg-related research. As a result, a comprehensive bibliometric evaluation that systematically maps research trends, knowledge structures, and emerging directions in Mg focused agricultural sustainability research is still lacking.

To fill this gap, the current study aims to systematically map the scientific landscape of Mg research regarding agricultural sustainability from 2005 to 2024. Using a bibliometric method powered by CiteSpace, this study identified key research trends, leading contributors, thematic shifts and overlooked areas in Mg-related studies. The current study also critically assessed the global research landscape of Mg using bibliometric techniques. The specific objectives were: (1) to determine global Mg-research trends during the last 20 years; (2) to identify the key contributors, collaboration patterns and thematic research areas; and (3) to highlight emerging research directions and knowledge gaps to guide studies on Mg and sustainable agriculture.

2 Materials and methods

2.1 Data extraction

The literature data used in this study were collected from the Web of Science core collection database, a leading source for performing bibliometric analyses[20]. To ensure the comprehensiveness and precision of the acquired data, the "Basic Searches" mode was used, setting the "Topic" search criteria to; ("magnesium") AND ("crop" OR "plant" OR "fruit"). The search period covered the last 20 years, beginning 1 January 2005 and ending on 31 December 2024. A total of 3318 valid research articles were acquired. Refinement filters were applied within the Web of Science platform to exclude early access items, publisher invited reviews, book chapters, retracted articles and non-English-language records. The information from these articles was extracted in "plain text format" according to requirements of the bibliometric software. To facilitate subsequent processing, the unformatted text files were labeled with "download_#" and saved with option "Full Record and Cited References". This dataset underwent additional screening and refinement for comparison at the author, institution, and country levels over two decades (i.e., 2005–2014 and 2015–2024) to evaluate changes in research productivity and collaboration trends over time.

2.2 Methodology

CiteSpace, a visualization tool, widely known for its ability to identify the research trends by depicting knowledge maps, highlight research hotspots for further in-depth research, and assisting in future trends prediction. In the current study, we used CiteSpace v6.4.R1 Advanced to thoroughly visualize and analyze the literature data on the role of Mg in agricultural sustainability. The time span was 2005–2024 with time slices of 1 year. Node types included authors, institutions, countries, keywords and references depending on the analysis type. The most frequent or most cited items were selected for each time slice. Algorithms like pathfinder and minimum spanning tree were used for network pruning to minimize redundant links and improve the clarity of the network. Betweenness centrality was used to determine the key nodes in collaboration and

citation networks. These parameters were used uniformly in all analyses to ensure methodological consistency and reliability. In addition, resulting metrics and knowledge graphs were assessed to identify key countries, institutions, temporal trends and leading research areas in Mg for agricultural sustainability. These analyses go beyond simply repeating facts to provide a new perspective on the significance of Mg in sustainable agriculture.

2.2.1 Co-authorship analysis

The importance of Mg in advancing agricultural sustainability has been acknowledged through enhanced collaboration among different organizations, universities and countries. Co-authorship analysis is crucial for a deeper understanding of the collaborative networks among researchers. An article with multiple authors indicates collaborative ties not only between the authors, but also among their affiliated institutions and countries. We evaluated cooperation networks from the perspectives of authors, countries and research institutes in the field of Mg for agricultural sustainability. Through our study, we explored the dynamic distribution of research influence as well as the strength of collaboration between diverse nodes within the global research network. In addition, we identified the central positions of nodes in the cooperation network by introducing the betweenness centrality measure, because nodes with high betweenness are major contributors.

2.2.2 Co-citation analysis

Co-citation analysis is a bibliometric method used to examine relationships between two documents based on their shared citations. In other words, if two academic articles are cited together by other articles, it indicates a conceptual or thematic connection between them. This approach helps to identify influential journals and literature, contributing to a deeper understanding of the scholarly landscape.

2.2.3 Keywords co-occurrence analysis

The co-occurrence analysis of keywords examines the frequency at which certain keywords appear together in scientific articles. The keywords used in an article are critical in summarizing its key content and focus. Keyword co-occurrence analysis can be used to determine which topics are popular in a particular field by examining the keywords used in relevant articles. Researchers can identify new trends and key areas of interest in their field by analyzing a network of frequently used keywords. We used CiteSpace to analyze 3318 research articles to create a map of keyword connections.

3 Results and discussion

3.1 Quantitative analysis of published articles

Quantitative analysis of articles reveals the advancement and maturity of a research field. An annual article count provides valuable insights into the depth and trajectory of research in a given field, offering a glimpse into the evolution of research. The number of published articles related to Mg in agricultural crop production is shown in Fig. 1. We found that during 2005–2012, annual articles remained below 100, with the lowest number in 2005 (41) and only moderate increases in subsequent years. However, over time, the number of articles increased to over 100 between 2013 and 2018, rising steadily, ranging from 118 to 167 articles annually. A major turning point was observed in 2019, with articles rising to 209 and further increasing to 261 in 2020, 321 in 2021, 328 in 2022, and 364 in 2023, peaking at 430 in 2024. This increasing trend indicates growing research interest in the role of Mg in agricultural sustainability. At present, research in this field is advancing rapidly, making a shift in focus to Mg which has been long considered a forgotten element[15]. Therefore, during the initial years (2005–2012), the annual articles were quite limited. The potential explanations could include the Mg role in crop production has not been thoroughly studied or has not been sufficiently acknowledged as a significant yield-limiting factor in agriculture. Nevertheless, a significant change in the number of annual article (over 100) indicates increased awareness and interest in the role of Mg in agriculture. Several factors might have contributed to this increase, such as technological advances, growing research findings and changing agricultural priorities[7,21]. In 2019, a significant change occurred as annual articles exceeded 200, reflecting global recognition of the role of Mg in agriculture. This significant rise in interest is likely a result of the emerging challenges in agricultural sustainability, which have encouraged researchers and scientists to show greater interest in this research field[7,22]. Overall, Mg-related agricultural research has undergone a transformation from an overlooked element to a focal point of global research. The growing volume of articles indicates that Mg is reaching a pivotal point in understanding and harnessing its potential for improving agricultural sustainability.

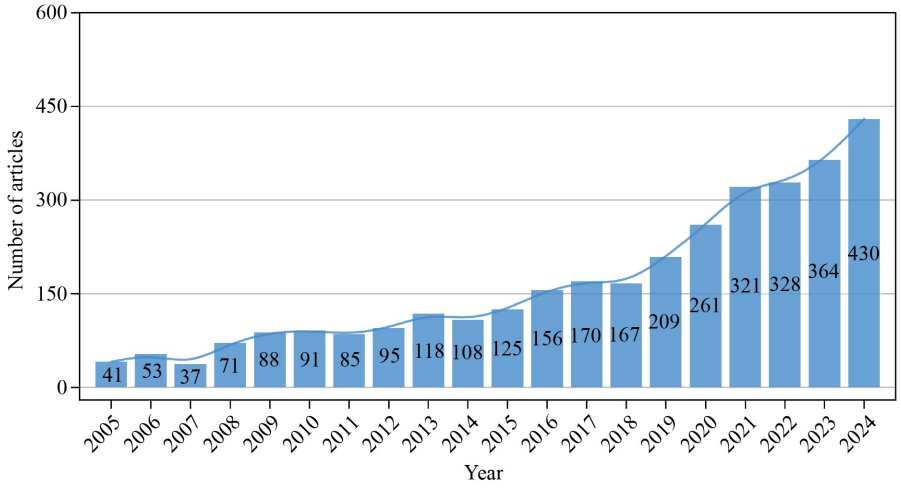


Fig. 1 Trends of articles during 2005–2024. The number in the bar chart indicates the number of articles.

3.2 Co-authorship analysis

Co-authorship analysis is valuable for visualizing and illustrating the collaboration patterns among researchers. In the current study, we examined the cooperation networks from the perspective of authors, countries, and research institutes. Global research networks are analyzed based on co-authorship to understand their structure and collaboration intensity.

3.2.1 Author co-authorship analysis

Author co-authorship analysis identifies the collaboration patterns and influential researchers in Mg-related agricultural sustainability studies. The mapping network resulted in 693 nodes and 585 edges (the connecting lines) (Fig. 2). Each node represents an author, with larger nodes representing more articles and connecting lines signifying cooperative relationships. The top productive authors are shown in Table 1. During the last 20 years, Grzebisz (15) is the leading author, followed by Wu (14) and Muneer (10). Other active authors include Zhang (8), Bossolani (8), and Jarosz (8). A decade-wise comparison (2005–2014 vs. 2015–2024) showed a significant contribution of authors, i.e., Wu, Muneer, Zhang and Chen from the International Magnesium Institute, Fujian Agriculture and Forestry University (FAFU), China, who emerged as leading contributors in the most recent decade (2015–2024). However, all top authors (2005–2024) had a centrality of 0, indicating limited direct collaboration within the global network. This fragmented pattern reveals that current studies on Mg in agricultural sustainability are scattered in small, localized groups instead of a unified global network. Wu, Muneer and Zhang are prominent researchers at International Magnesium Institute focusing on Mg nutrition and its physiological effects on crop yield and quality, including soil microbiota regulation and enhancing fruit nutrition[23–26]. Grzebisz has been making continuous contribution to nutrient management and soil fertility studies, especially in European agriculture[27,28]. Bossolani has been contributing to tropical soil fertility studies, with focus on Mg in nutrient management. His studies reveal that Mg improves nitrogen use efficiency, photosynthesis and crop yield, and that Mg-enriched fertilizers like thermomagnesium and lime-phosphogypsum improve soil health and sustainability[29,30]. Even though outstanding contributions have been made by the individuals, the lack of strong inter-author connections highlights that more cross-regional collaboration and data sharing are necessary to enhance the scientific integration of Mg-centered agricultural sustainability studies.

3.2.2 Country co-authorship analysis

The number of published articles from a country or region often reflects its research focus in a specific area. Therefore, a network map was created to explore the global collaboration initiatives among different countries in the field of Mg for improving agricultural sustainability from 2005 to 2024. This visual representation included 128 nodes and 544 edges,

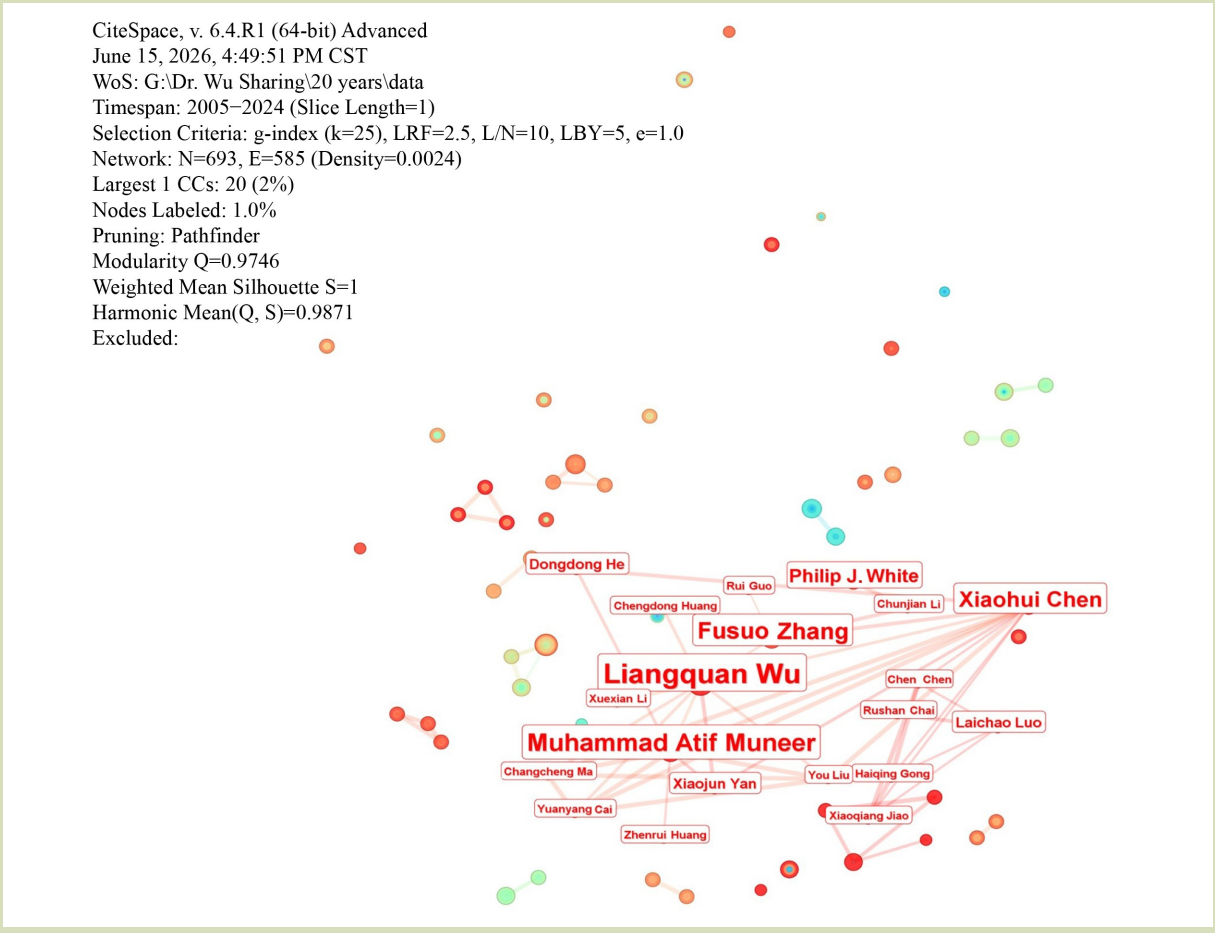


Fig. 2 Author cooperative map. Each node represents an author, and node size represents the number of published articles and the connection between nodes reflects the cooperative relationship. The color gradient shows the article time period from earlier to more recent years.

illustrating the complex network of connections and interactions in this academic domain (Fig. 3). In the network, individual nodes represent different countries, and their sizes indicate the number of articles contributed by those countries. The connections between nodes show the collaborative efforts between different countries. Notably, the purple outer circle in the cooperative networks represents the mediation centrality, a measure that assesses the importance of intermediary nodes in facilitating connections and information flow. This index helps to identify key nodes within network[31]. For example, a node with an intermediary centrality exceeding 0.1 is regarded as key node[32]. Nonetheless, national betweenness centrality enables the evaluation of the extent to which a country influences global research. Consequently, visual analysis indicated limited collaboration among countries in this research field due to sparse network connections. This highlights the urgent need for enhanced global collaboration.

As evident in Table 2, China is at the forefront in terms of articles (507 articles and centrality of 0.16) followed by the USA (429 articles and centrality of 0.23) and Brazil (372 articles and centrality of 0.05). These three countries collectively represent about half of the total global research output in this research field. The USA has the highest centrality (0.23), reflecting its bridging role in global cooperation and frequent collaboration with other countries. In contrast, China, although having more articles, has a lower centrality, which restricts limited international collaboration. This indicates that Chinese research, although abundant, is mainly focused within the country and has a limited number of collaborative articles

Table 1 Top 10 authors in English-language literature published over the last 20 years (2005–2024) with a comparison between two decades, 2005–2014 and 2015–2024

Order number	2005–2024		2005–2014		2015–2024	
	Author	Articles	Author	Articles	Author	Articles
1	Witold Grzebisz	15	Zbigniew Jarosz	8	Liangquan Wu	14
2	Liangquan Wu	14	Piotr Szulc	6	Witold Grzebisz	13
3	Muhammad Atif Muneer	10	Katarzyna Dzida	6	Muhammad Atif Muneer	10
4	Fusuo Zhang	8	Renata Nurzynska-wierdak	3	Fusuo Zhang	8
5	Joao Willam Bossolani	8	Andrew D Cartmill	3	Joao William Bossolani	8
6	Zbigniew Jarosz	8	Zenia Michalojc	3	Xiaohui Chen	7
7	Shafaqat Ali	7	Ana M. Castillo-gonzalez	3	Renato de Mello Prado	7
8	Xiaohui Chen	7	Miroslaw Kobierski	3	Shafaqat Ali	6
9	Jadwiga Wierzbowska	7	Rashid Ahmad	3	Bernadine C. Strik	6
10	Renato de Mello Prado	7	Donita L. Cartmill	3	Davie M. Kadyampakeni	5

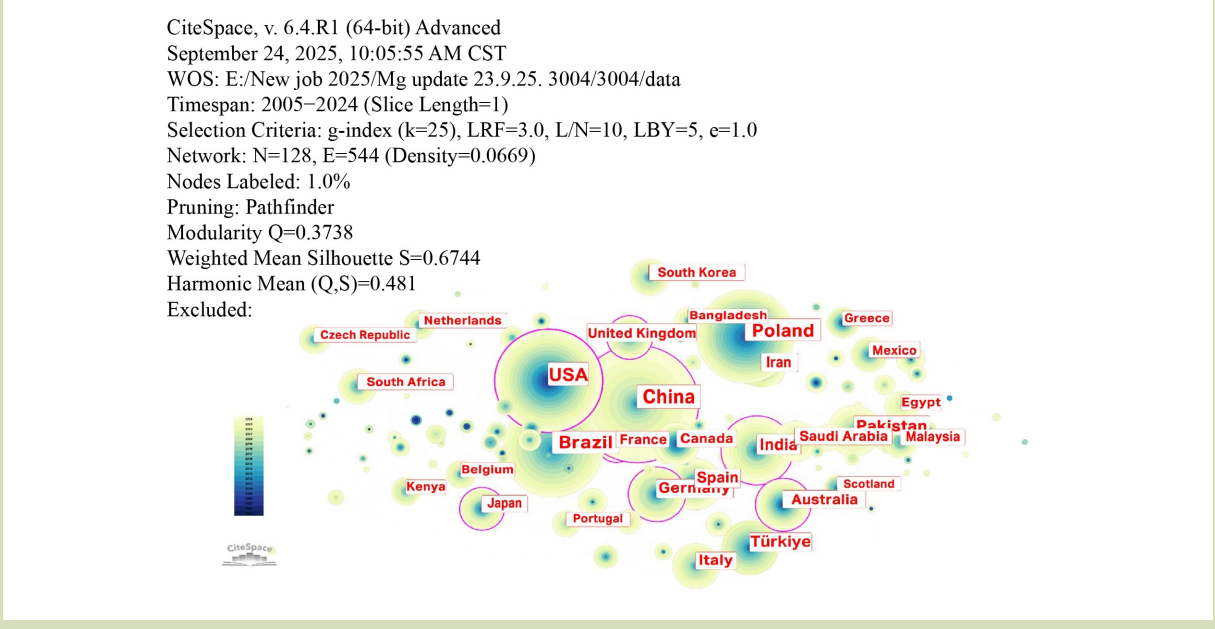


Fig. 3 International cooperative map. Each node represents a country, and node size represents the number of published articles. The purple outer ring represents the betweenness centrality, the ring color and thickness represent the year of occurrence, and the connection between nodes reflects the cooperative relationship.

with international groups. A comparison between two decades (2005–2014 and 2015–2024) highlighted a significant change, showing China as the global leader in the recent decade, along with strong growth from Brazil, India and Pakistan. In contrast, the USA and Poland, once leading, showed a relatively slower growth. It should also be noted that China's higher article could be related to structural agricultural problems, such as long-term intensive fertilizer application, soil acidification or Mg depletion in cropping systems. Additionally, the national policies supporting green agriculture

Table 2 Top 10 countries by number of English-language articles over the last 20 years (2005–2024) with a comparison between two decades, 2005–2014 and 2015–2024

Order number	2005–2024			2005–2014		2015–2024	
	Country	Articles	Centrality	Country	Articles	Country	Articles
1	China	507	0.16	USA	151	China	450
2	USA	429	0.23	Poland	115	Brazil	309
3	Brazil	372	0.05	Brazil	63	USA	278
4	Poland	331	0.06	China	57	Poland	216
5	India	209	0.1	Spain	39	India	176
6	Germany	130	0.05	Türkiye	37	Germany	100
7	Türkiye	128	0.11	Canada	34	Pakistan	99
8	Spain	118	0.06	India	33	Türkiye	91
9	Pakistan	118	0.06	Germany	30	Iran	83
10	Iran	111	0.06	Iran	28	Spain	79

and soil health restoration have also increased the research status in Mg management. These policy and agronomic measures contribute to the explanation of China's leading position in internationally indexed Mg research.

Poland (331 articles and centrality of 0.06), India (209 articles and centrality of 0.10), and Germany (130 articles and centrality of 0.05) had moderate levels of article volume and connectivity, reflecting an increasing involvement. Türkiye, Spain, Pakistan and Iran are making rising contribution with growing impact in regional networks. In general, global collaboration on Mg-based agricultural sustainability is limited, led primarily by a small number of research institutions. Strengthening collaboration among more countries in Asia, Europe and the Americas could promote wider data integration, multi-location studies and unified approaches to sustainable Mg management. This fragmented pattern could be a result of region-specific nature of Mg research, soil types, cropping systems and the patterns of Mg deficiency vary greatly across the geographical zones. Therefore, diverse studies have been conducted in localized conditions that restricts cross-regional integration and diminishes the development of globally connected research networks. Nevertheless, this kind of fragmentation limits the establishment of Mg management strategies that are universally applicable. Thus, future studies need to focus on the development of cross-regional collaborative platforms, such as long-term multi-location field experiments, standardized methodologies and common data systems to enhance global comparability and integration.

3.2.3 Institution co-authorship analysis

A collaboration map among institutions engaged in Mg for sustainable agriculture is shown in Fig. 4. Each node in the network represents an institute and its size denotes the number of articles published by the institute. There were total of 545 nodes (institutes) and 459 edges in the institutional collaboration network, which represents a diverse yet fragmented institutional network. According to Table 3, China Agricultural University (CAU) was ranked first with 60 articles and a centrality of 0.11, followed by the Chinese Academy of Sciences (CAS) with 59 articles and centrality of 0.10, and University of Florida with 59 articles and centrality of 0.02. The other well-known institutions are the Poznan University of Life Sciences (57 articles and centrality of 0.05) and FAFU (40 articles and centrality of 0.05). The two-decade (2005–2014 and 2015–2024) comparison revealed a substantial increase with a rapid rise in Chinese universities and research institutions. Specifically, FAFU has become one of the most influential global contributors in the last decade, along with CAU and CAS, signifying the increasing dominance of China in Mg-related agricultural sustainability research.

The CAU and CAS are highly productive with substantial centrality values, making them central nodes that connect different regional research institutes. In North America, the University of Florida and USDA-ARS are more prominent in

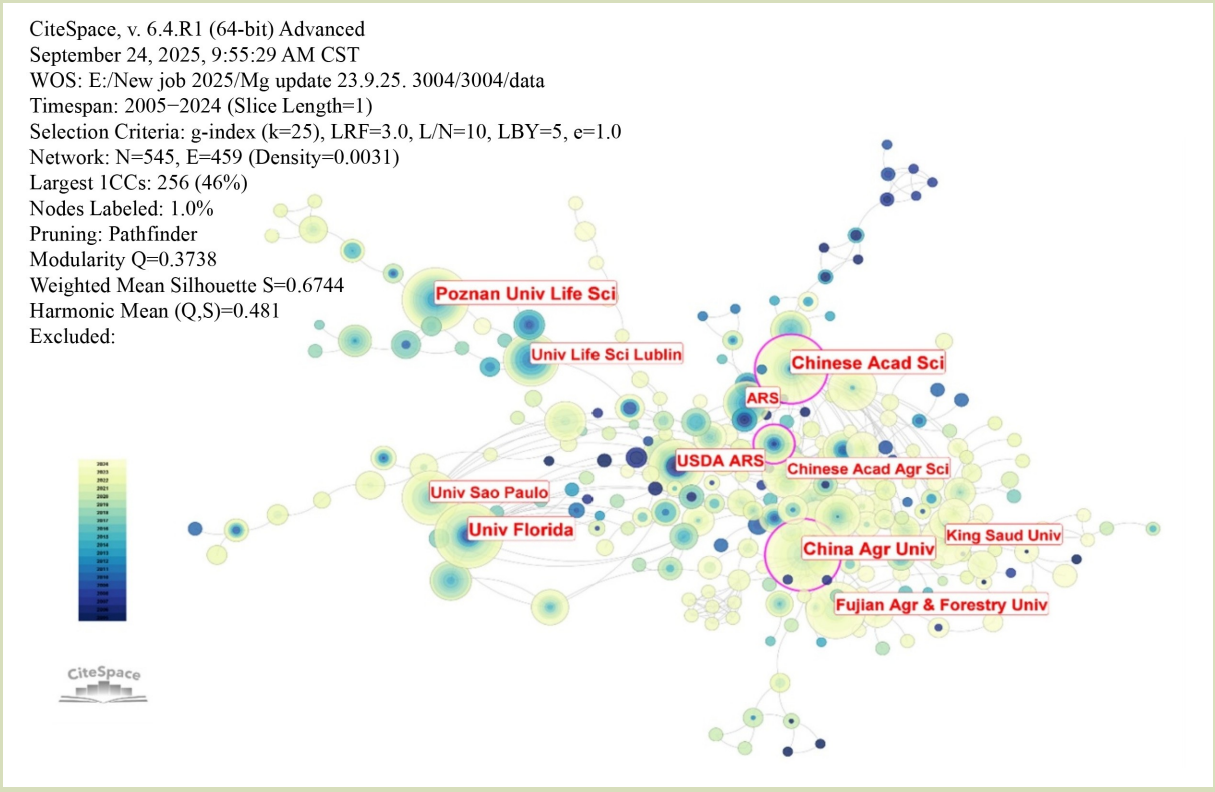


Fig. 4 Institutional cooperation map. Each node represents an institution, and the circle node size represents the number of published articles, the ring color and thickness represent the year of occurrence, and the connection between nodes reflects the cooperative relationship.

this Mg-research direction. European institutes such as Poznan University of Life Sciences (Poland) and University of Life Sciences Lublin (Poland) make substantial contributions but exhibit low network centrality. In general, although some top research institutes and universities lead in Mg-related agricultural research, the broader network remains loosely linked, highlighting the need for global institutional collaborations and interdisciplinary partnership to speed up the advancements in sustainable nutrient management.

3.3 Co-citation analysis

Co-citation analysis reveals relationships and links within scholarly literature. A co-citation occurs when two or more authors, journals or literary works are cited together in a third document[33]. Typically, when multiple works are cited together, there exists a thematic or conceptual link between them. For example, the frequent citation of two distinct articles by other scholars suggests that these articles explore a common idea or theme. In this study, we used the strength of co-citation analysis through two main approaches, journal and literature co-citation analysis.

3.3.1 Journal co-citation analysis

Journal co-citation analysis reveals the journals that are most frequently cited together, indicating intellectual connections and thematic foundations within a specified research domain. This approach offers insights for understanding the most influential journals and emphasizes their contribution in shaping the specific research field[34]. This analysis provides useful references and helps researchers to conduct more effective literature searches. It also indicates the influence of an article within a specific research area by the number of citations[35]. Co-citation network visualization produced a compact map of interconnected nodes, including 924 nodes, and 3779 links, illustrating journals frequently cited together in

Table 3 Top 10 institutions in English-language literature published over the last 20 years (2005–2024) with a comparison between two decades, 2005–2014 and 2015–2024

Order number	2005–2024			2005–2014		2015–2024	
	Institution	Articles	Centrality	Institution	Articles	Institution	Articles
1	China Agricultural University	60	0.11	University of Florida	22	China Agricultural University	55
2	Chinese Academy of Sciences	59	0.1	Poznan University of Life Sciences	20	Chinese Academy of Sciences	48
3	University of Florida	59	0.02	USDA-ARS	17	Fujian Agriculture and Forestry University	40
4	Poznan University of Life Sciences	57	0.05	University of Life Sciences Lublin	17	Poznan University of Life Sciences	37
5	University of Life Sciences Lublin	42	0.01	ARS	14	University of Florida	37
6	Fujian Agriculture and Forestry University	40	0.05	Chinese Academy of Sciences	11	University of Sao Paulo	36
7	USDA-ARS	39	0.06	Zhejiang University	9	King Saud University	32
8	University of Sao Paulo	38	0.02	EMBRAPA, Brazil	8	Chinese Academy of Agricultural Sciences	28
9	University of Warmia and Mazury	32	0	Agriculture & Agri-Food Canada	8	Huazhong Agricultural University	27
10	Chinese Academy of Agricultural Sciences	32	0.09	Cornell University	8	University of Warmia and Mazury	25

Mg-related research (Fig. 5). The bigger nodes represent journals with greater co-citation frequencies, which indicate their greater influence within the research landscape.

Table 4 lists the 10 most co-cited journals. *Plant and Soil* journal is recognized as the top leading journal with highest number of citations, i.e., 1390 with research focus mainly on soil science and nutrient management. Similarly, *Journal of Plant Nutrition* and *Communications in Soil Science and Plant Analysis* are also among the top journals based on citation frequencies, i.e., 956 and 855, respectively. These findings highlight that nutrient dynamics and analytical techniques are vital components in the advancement of Mg-related research.

Other highly influential journals include *Scientia Horticulturae* with 735 citations and *Plant Physiology* with 696 citations, which provide the critical insights into crop nutrition, plant metabolic functions, and physiological responses to nutrient inputs. The *Journal of Experimental Botany* (678 citations) and *Frontiers in Plant Science* (657 citations) have also published substantive contributions that link fundamental plant biology with applied agricultural research. Also, the increasing integration of ecological and environmental perspective in Mg studies is reflected in *New Phytologist* with 650 citations and *Science of the Total Environment* with 645 citations. *Agronomy Journal* is another highly influential journal that focuses on agronomic practices and crop productivity.

The co-citation map shows that although *Plant and Soil* and *Journal of Plant Nutrition* serve as core hubs, other journals such as *New Phytologist* and *Science of the Total Environment* expand research field to include plant ecology and environmental sustainability. This indicates that the Mg research involves multiple disciplines that link agronomy, plant physiology, soil science and environmental studies. These findings can serve as a guide to researchers in identifying important literature sources, possible article venues, and interdisciplinary possibilities of further Mg-related research.

3.3.2 Literature co-citation analysis

Similar to journal co-citation analysis, literature-based co-analysis examines the relationships among individual research articles, books or any other type of academic literature. This approach determines the influential works that have shaped the research on agricultural sustainability in relation to Mg and highlight the new knowledge clusters in the field. The co-citation network consisted of 950 nodes and 1600 edges, where nodes denote the individual documents and edges represent

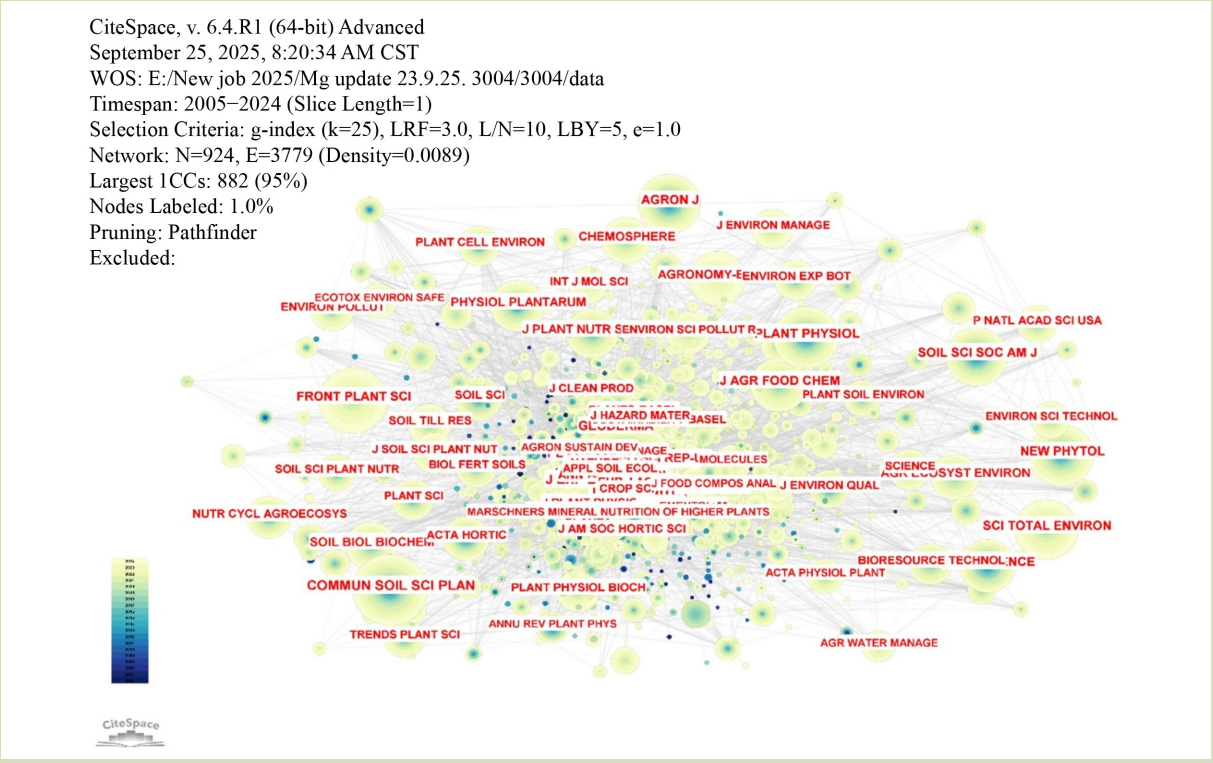


Fig. 5 Network map of co-occurring journals. Each node represents a journal; the larger the node, the more times it is referenced, and the connection between the nodes represents the co-citation relationship, and its thickness represents the co-citation strength. Colors from dark to light indicate the change of time from early to recent.

Table 4 Top 10 journals by citation frequency

Order number	Journal	Citation count	Centrality
1	*Plant and Soil*	1390	0
2	*Journal of Plant Nutrition*	956	0
3	*Communications in Soil Science and Plant Analysis*	855	0
4	*Scientia Horticulturae*	735	0
5	*Plant Physiology*	696	0
6	*Journal of Experimental Botany*	678	0
7	*Frontiers in Plant Science*	657	0
8	*New Phytologist*	650	0
9	*Science of the Total Environment*	645	0
10	*Agronomy Journal*	640	0

the links between them (Fig. 6). Large nodes depict the most influential articles that are key in advancing research in this area.

Table 5 lists the 10 most commonly co-cited references. The most cited article was Wang et al.[1], titled "Magnesium fertilization improves crop yield in most production systems: a

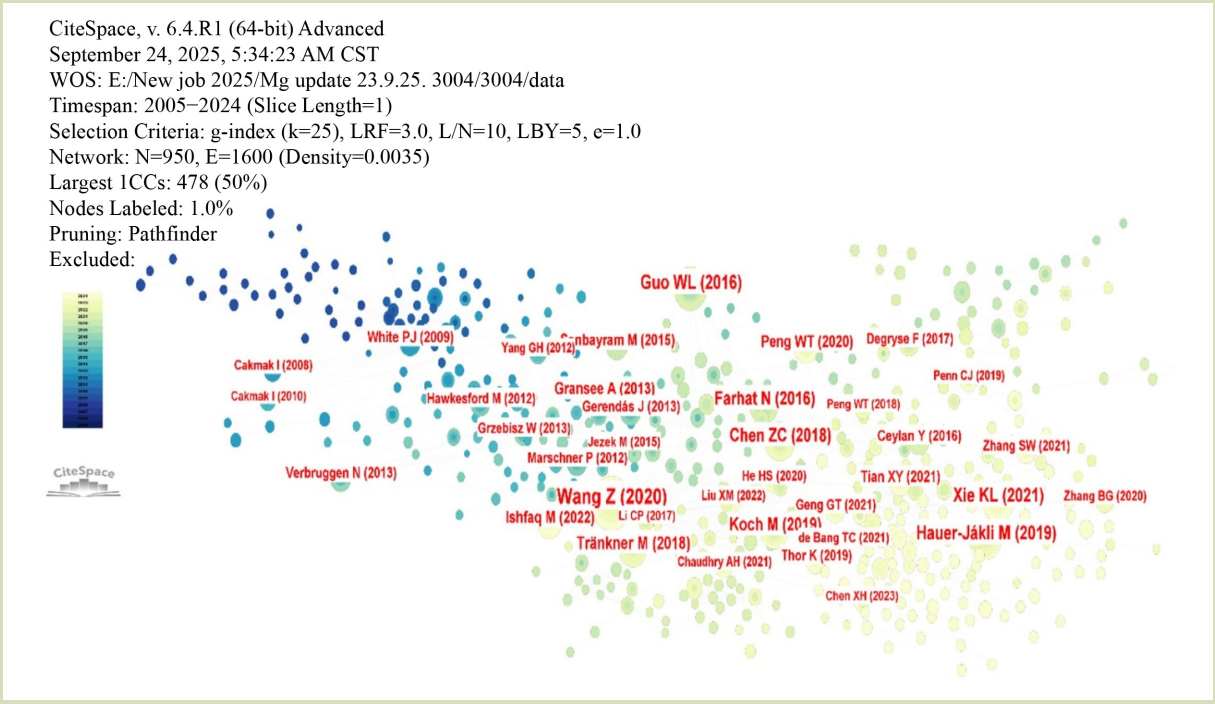


Fig. 6 Network map of co-occurring literature. Each node represents a piece of literature, with larger nodes indicating a higher number of co-citations, the connection between the nodes represents the co-citation relationship and its thickness represents the co-citation strength. Colors from dark to light indicate the change of time from early to recent.

meta-analysis", published in *Frontiers in Plant Science*, with 62 citations. This meta-analysis provided a strong quantitative data that Mg fertilizer application improves crop yield in different agroecosystems, offering solid justification for Mg use in modern agriculture. The second most cited reference with 40 citations, was published by Guo et al.[36] in *The Crop Journal*, which emphasized that Mg deficiency is a pressing issue of global agricultural systems. This article also highlighted how Mg deficiency has become a major problem in soils and has largely affected the plant health, productivity and nutritional value[36]. These highly cited articles represent a distinct shift in Mg research from problem identification to quantitative confirmation and mechanistic understanding. Another highly influential work by Hauer-Jákli and Tränkner[16], published in *Frontiers in Plant Science*, with 38 citations, examined Mg thresholds in plant leaves and their relationship with photo-oxidative defense. This research demonstrated that Mg is essential for maintaining photosynthetic efficiency and oxidative stress tolerance, thereby sustaining crop production under challenging environmental conditions[16]. Research on nutrient interactions was also among the most cited studies. Xie et al.[37] focused on synergy and antagonism relationships between K and Mg in plants and received 37 citations, highlighting the importance of nutrient balance in promoting plant performance[37]. Similarly, Koch et al.[38] and Tränkner et al.[39] focused on combined role K and Mg in photosynthate translocation, establishing a clear link between nutrient balance, productivity, and stress resistance. Collectively, these studies show that Mg research has evolved beyond defining the limits of deficiency to comprehending its integrative effect on plant physiology and nutrient relationships. These frequently cited studies highlight three major research domains: soil and nutrient management, plant physiology and photosynthesis, and molecular level nutrient interactions. This integration of the agronomic, physiological and molecular research underscores the complexity of Mg functions in agricultural systems. This change also implies that existing Mg studies are shifting toward a more systems-level approach, where nutrient interactions and physiological regulation are examined in an integrated, as opposed to isolated, fashion. The coexistence of meta-analysis and molecular studies indicates that this research area is shifting towards systems-level approaches. Collectively,

Table 5 Top 10 most cited references

Order	Title	Journal	Author	Frequency	Year
1	Magnesium fertilization improves crop yield in most production systems: A meta-analysis	*Frontiers in Plant Science*	Wang Z[1]	62	2020
2	Magnesium deficiency in plants: an urgent problem	*Crop Journal*	Guo W L[36]	40	2016
3	Critical leaf magnesium thresholds and the impact of magnesium on plant growth and photo-oxidative defense: a systematic review and meta-analysis from 70 years of research	*Frontiers in Plant Science*	Hauer-Jákli M[16]	38	2019
4	Synergistic and antagonistic interactions between potassium and magnesium in higher plants	*The Crop Journal*	Xie K L[37]	37	2021
5	Functional dissection and transport mechanism of magnesium in plants	*Seminars In Cell & Developmental Biology*	Chen Z C[17]	33	2018
6	Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning	*Acta Physiologiae Plantarum*	Farhat N[19]	32	2016
7	Differential effects of varied potassium and magnesium nutrition on production and partitioning of photoassimilates in potato plants	*Physiologia Plantarum*	Koch M[38]	30	2019
8	Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection	*Physiologia Plantarum*	Tränkner M[39]	28	2018
9	Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions	*Plant and Soil*	Gransee A[40]	22	2013
10	Magnesium supports nitrogen uptake through regulating NRT2.1/2.2 in soybean	*Plant and Soil*	Peng W T[41]	22	2020

these co-cited studies have established the intellectual foundation of Mg research, tracing its development through the identification Mg-deficiency issues to quantitative agronomic validation, and most recently, the mechanism of nutrient interactions at physiological and molecular scales. These accumulated studies support a modern, system-oriented and sustainability-focused paradigm of Mg management.

3.4 Hot research topics

3.4.1 Keywords co-occurrence network analysis

Generally, hot research topics are areas of study that are attracting significant interest and funding from the scientific community[42]. Thus, keywords are typically used to summarize the core content of an article, reflecting its value, objectives, and methodology[43]. Co-occurrence analysis of keywords is used to identify and analyze the patterns of keywords occurrence in scholarly articles. This analysis examines how often a pair or group of keywords occurs together within documents, indicating a thematic or conceptual connection. A frequent co-occurrence of keywords indicates that they are often found in the same context within the literature, highlighting the possibility of a relationship or connection between them. The co-occurrence of keywords could also indicate hot research topics or areas of high interest in academia. Therefore, keywords co-occurrence network analysis was performed to reveal the research hotspots of the Mg for agricultural sustainability.

Keywords co-occurrence network constructed in this study consisted of 612 nodes and 2036 edges (Fig. 7). Each node represents a keyword, with larger node sizes indicating higher frequency of occurrence, while the edges represent co-occurrence linkages between keywords. Thicker connections reflect stronger associations. The overall network density (0.0109) indicates a moderately connected research field with distinct clusters of interconnected terms.

Table 6 lists the 10 most frequently occurring keywords. The keyword "growth" (509 occurrences and centrality of 0.03) ranked first, followed by "yield" (423 occurrences and centrality of 0.02), "nitrogen" (405 occurrences and centrality of 0.03), and "quality" (321 occurrences and centrality of 0.04). The keyword "magnesium" appeared more often (309 occurrences), highlighting its key importance in the research field. Other keywords related to nutrient such as "phosphorus" (267 occurrences), and "potassium" (241 occurrences) were

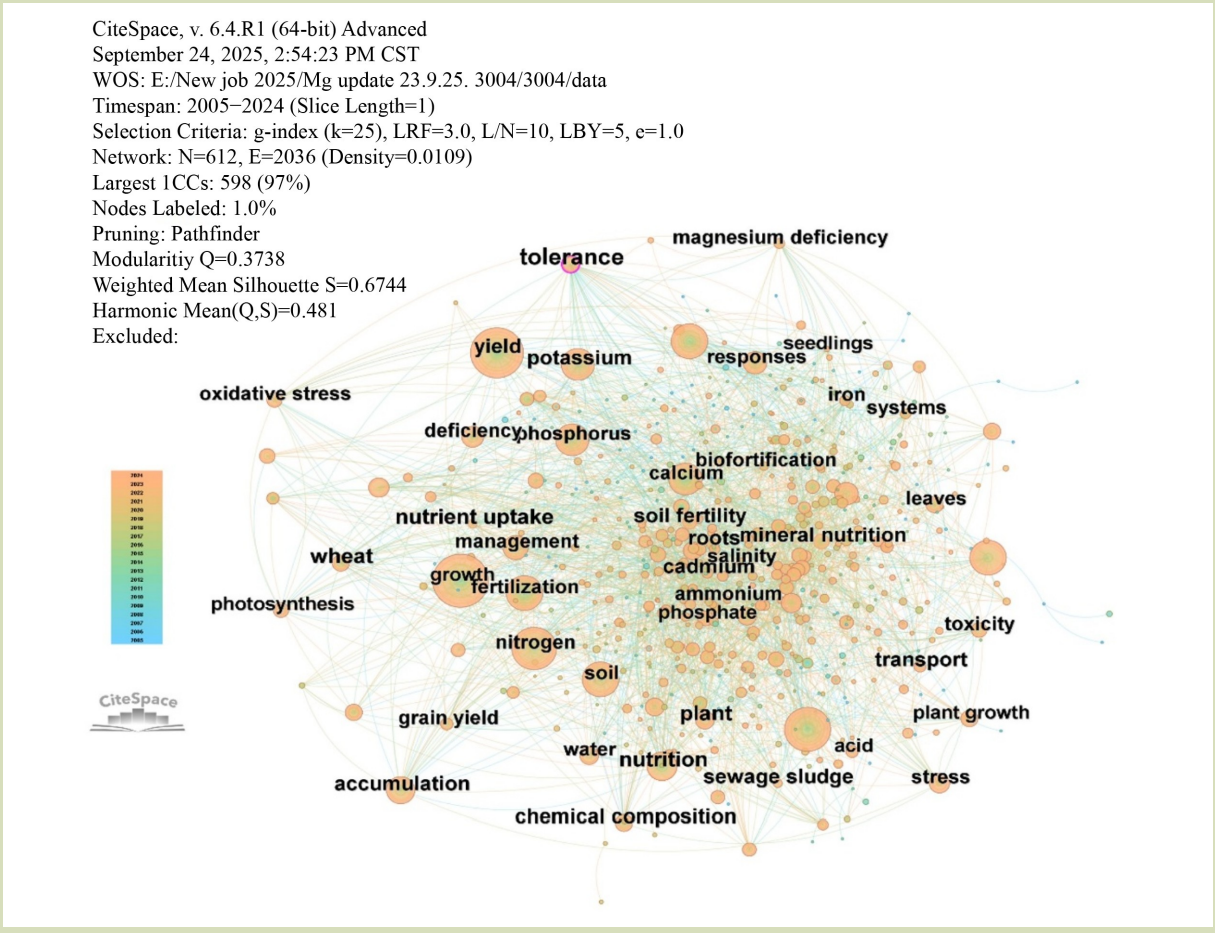


Fig. 7 Keyword co-occurrence network map. Each node represents a keyword and the size of the node circle means the rate of occurrence of the keyword. Connecting lines indicate co-occurence relationships between the keywords.

Table 6 Top 10 keywords by frequency

Order number	Frequency	Centrality	Year	Keyword
1	509	0.03	2005	Growth
2	423	0.02	2005	Yield
3	405	0.03	2005	Nitrogen
4	321	0.04	2005	Quality
5	309	0.02	2005	Magnesium
6	286	0.04	2005	Soil
7	267	0.02	2005	Phosphorus
8	250	0.01	2005	Plants
9	241	0.03	2006	Potassium
10	227	0.02	2005	Nutrition

also listed in the top keywords, showing how Mg research is closely linked to the broader nutrient management studies. Although "growth" and "yield" are the most common keywords, and are frequently used in agronomic research, and are not specific to Mg-based research. As the dataset was constructed on Mg-based search query, the keyword network primarily reflects Mg-related agricultural research. Therefore, Mg-related co-occurrence patterns provides a more detailed understanding of thematic relationship. The close association of Mg with "nitrogen", "photosynthesis", "stress" and "potassium" indicates that recent Mg studies have more focused on nutrient interactions, physiological control and stress alleviation, rather than the purely productivity outcomes.

The co-occurrence network depicted different thematic clusters. First, the importance of "growth" and "yield" is demonstrated, underscoring the importance of Mg in the biomass accumulation and crop productivity[44]. Strong co-occurrence of these keywords highlights their importance in research evaluating crop performance under varying levels of Mg. Second, nutrient interactions highlighted by co-occurrence of "nitrogen", "phosphorus", and "potassium" with "magnesium" signifies the essential role of Mg in these nutrient interactions[45,40]. This implies that Mg research is intricately linked to the studies of nutrient use efficiency and soil fertility. Third, soil and nutrient management highlights sustained interest in soil nutrient dynamics, Mg mobility and challenges of soil acidification, all of which are vital for long-term agricultural sustainability[46]. Fourth, the keyword "quality" implies a more recent research trajectory connecting Mg with the crop nutritional value and quality traits, like vitamin C contents and antioxidant compounds[15,47]. This signifies an expansion of the research focus from quantity (yield) to quality and sustainability.

Frequency indicates the number of keywords appears in the dataset. Centrality indicates the betweenness centrality of the keyword within the network, showing its importance in connecting different research topics. Year indicates the first tear in which the keyword appeared in the dataset.

3.4.2 Keywords cluster analysis

Keywords clustering offers a deeper understanding by grouping commonly co-occurring keywords into coherent research areas. A smaller cluster sequence number indicates a higher density of co-occurring keywords, thereby highlighting key areas of scientific interest in the research field. Keywords cluster network yielded 612 nodes and 3231 links, resulting in 11 separate clusters (Fig. 8 and Table 7). To improve interpretability, these clusters were combined into four main themes: (a) nutrient management and soil fertility ((#0, #3, #4 and #5), (b) plant growth, physiology and stress responses (#2 and #9), (c) crop and species-specific applications, and (d) plant-microbe interactions (#6).

Nutrient management and soil fertility (#0, #3, #4 and #5)

This cluster focuses on Mg deficiency, phosphorus recovery, soil fertility and nutritional status in agricultural sustainability. Mg deficiency has been identified as one of the frequent constraints in crop production, particularly in acidic soils where nutrient imbalances can result in the long-term soil degradation[40]. The excessive and unbalanced use of NPK fertilizers leads to an increase in soil acidification and nutrient leaching, which further worsen Mg depletion and disrupts nutrient cycling[46]. Recent research indicates that integrated management strategies combining Mg with lime or organic amendments can increase soil pH, reduce exchangeable acidity, and enhance root growth and development[49]. Additionally, Mg is important for other nutrient use efficiency, especially for N. Field experiments have shown that Mg application boosts nitrate uptake and assimilation, thus enhancing nutrient use efficiency and crop yield in various crops, including wheat[50], maize[51,52] and rice[53]. In soybeans, Mg application enhances N concentration and total N uptake, primarily by stimulating nitrate uptake by roots[41]. Recent findings indicate that Mg enhances the regulation of nitrate transporter 2 (NRT2) family genes, specifically NRT2.1 and NRT2.2, by facilitating sucrose distribution in soybeans roots[41].

Also, Mg application promotes carbohydrate distribution to underground plant parts, enhancing nodule development and N fixation, which enhances root nutrient uptake and improves N utilization[21,54]. Mg application enhances N assimilation in plants[41]. Various studies have shown that Mg deficiency results in reduced activity of nitrate reductase and glutathione synthetase, thereby affecting N assimilation in plants[55,56]. In addition, Mg application also enhances the P uptake in soybean by promoting mycorrhizal development[57]. Adequate Mg supply has a positive effect on mycorrhizal plant growth as it improves photosynthate metabolism and transportation in soybean grown under low P conditions[57]. Therefore, the sustainable and efficient use of Mg in crop production is

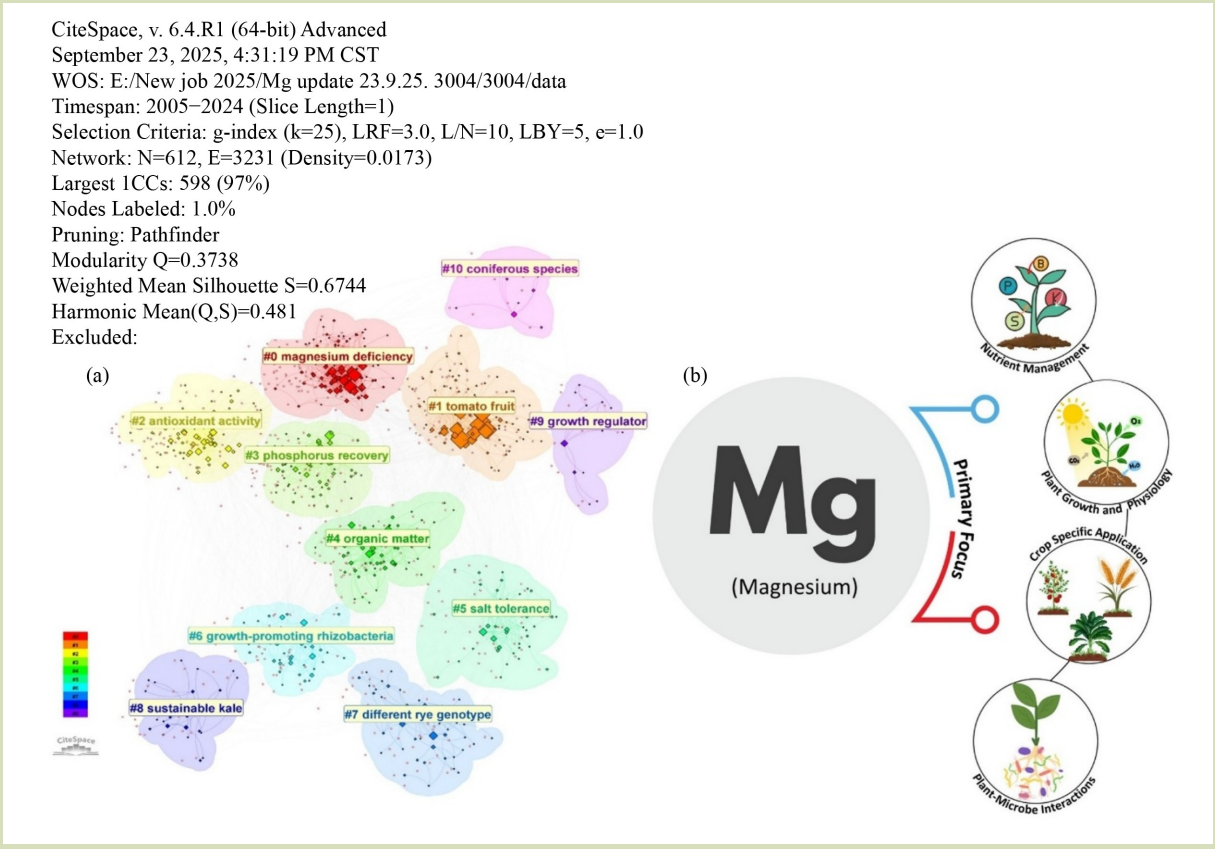


Fig. 8 Keyword co-occurrence cluster map. (a) The clustering criterion is guided by two indicators: a clustering modularity value (Q) exceeding 0.3 signifies significant clustering results, with larger values indicating better outcomes; also, a clustering profile index (S) surpassing 0.5 indicates reasonable clustering results. The values of Q and S were 0.374 and 0.674, respectively, affirming the ideal quality of the clustering results[48]. Different colors represent different clusters; the smaller the number, the more keywords are included in the cluster. (b) Derived primary research focus about role of Mg in agricultural sustainability.

critical, with careful consideration of soil health and balanced nutrient utilization.

Plant growth, physiology and stress responses (#2 and #9)

This cluster is related to antioxidant activity and growth regulators, and emphasizes the significance of Mg in plant physiological functions. Mg is also a structural component of chlorophyll and about 15% to 35% of leaf Mg is found in chloroplasts where it regulates photosynthetic electron transport and CO_2 assimilation[44]. Mg also controls major enzymatic activities involved in carbohydrate partitioning, N-assimilation, and reactive oxygen species removal[58,59]. Mg deficiency reduces the activity of nitrate reductase and glutathione synthase and reduces antioxidant capacity and increases oxidative stress in plants[59]. Recent reports reveal that Mg affects circadian activities of Rubisco in rice and that Mg homeostasis is linked to stable photosynthetic efficiency during day and night cycles[60]. Also, Mg is also sensitive to hormonal signaling pathways and growth regulators, reflecting its indirect role in developmental plasticity and stress adaptation[61]. Although significant improvements have been made in Mg research, still there are critical knowledge gaps that need to be addressed. For example, insufficient mechanistic knowledge about Mg-hormonal crosstalk, a lack of knowledge how Mg deficiency could alter the overall carbon distribution of whole plants during different developmental stages, and deficit in multi-stress research. Future studies should combine transcriptomic, proteomic and metabolomic approaches to determine Mg sensitive pathways, analyze Mg supplementation

Table 7 Top 10 clusters label information

Cluster ID	Cluster size	Contour value	Mean year	Cluster keywords (top three)
#0	109	0.607	2012	Magnesium deficiency; mineral nutrition; foliar application
#1	83	0.728	2009	Tomato fruit; nutrient concentration; nutrient status
#2	82	0.643	2014	Antioxidant activity; chemical composition; nutritional quality
#3	71	0.598	2015	Phosphorus recovery; slow-release fertilizer; Paddy soil
#4	64	0.629	2012	Soil fertility; organic carbon; organic matter
#5	48	0.725	2013	Nutritional status; acidic soil; nitrogen fertilizer
#6	46	0.707	2015	Growth-promoting rhizobacteria; nutrient uptake; plant growth
#7	45	0.699	2014	Different rye genotypes; grain yield; nutritional quality
#8	25	0.779	2016	Sustainable kale; nutritional composition; nitrogen fertilizer
#9	13	0.920	2011	Growth regulator; spring wheat; mineral nutrition;
#10	12	0.924	2012	Coniferous species; nitrogen fertilizer; nutrient status

during climatic stresses and include Mg physiology in predictive crop systems.

Crop and plant species-specific applications (#1, #7, #8 and #10)

These clusters include tomato, rye, kale and coniferous species that underscore the use of Mg research in different crops and managed plant systems. In tomato, Mg supply has a significant effect on fruit quality, such as sugar and vitamin C content[62]. Genetic variability of Mg uptake has been studied in rye genotypes and could play a potential role in breeding Mg-efficient cereal varieties[63]. Studies on kale have highlighted sustainable farming, showing that adequate Mg application enhances the nutritional quality and reduces susceptibility to abiotic stress[64]. In conifers, Mg deficiency has been associated with reduced growth and reduced carbon sequestration capacity of forest ecosystems[65]. Nevertheless, even with these advancements, several research gaps remain, including limited integration of Mg in crop biofortification programs, absence of comparative studies on different species and the absence of forestry applications. Future studies need to extend Mg biofortification research, identify genetic indicators of Mg deficiency and test Mg-based approaches to restore nutritional and ecological sustainability of forest systems.

Plant-microbe interactions (#6)

This cluster highlights the growing importance of Mg-mediated plant-microbe interactions and growth-promoting rhizobacteria. Optimal application of Mg improves root exudation and microbial colonization, resulting in improved nutrient uptake and tolerance to stress[66,67]. Mg is also shown to induce nodulation and symbiotic N-fixation in legumes, which confirms its dual effect on plant nutrition and microbiome recruitment[19,41]. Nevertheless, significant research gaps remain, including limited high-resolution studies on the role of Mg in influencing microbial communities, lack of mechanistic understanding of Mg-related signaling in plant-microbe interactions and minimal studies on the combination of Mg fertilizer application and microbial inoculants at field scales. Future studies should focus on integration of Mg with biofertilizer and plant growth-promoting rhizobacteria using metagenomics and metabolomics to elucidate the Mg-stimulated signaling pathways in the rhizosphere.

The keywords cluster analysis groups the 11 clusters into the four larger groups. Nutrient management and soil fertility form the foundation of Mg research, while plant physiology and stress responses provide deeper mechanistic explanations of Mg functions. Crop-specific applications turn these findings into practical solutions that farmers and producers can apply in real field conditions. In addition, plant-microbe interactions represent an emerging direction in sustainable agriculture. Overall, this thematic structure signifies the change from soil level management approaches towards integrated molecular, physiological and ecological perspectives in Mg research. It also shows the clear research gaps that define the future directions.

3.4.3 Keywords burst analysis

Keyword burst analysis identifies the sharp rise in frequency of

specific keywords over a period of time, revealing emergent topics and shifting research interest in a scientific field. CiteSpace was used in the present study to identify the keywords with the strongest citation bursts in Mg research related to agricultural sustainability from 2005–2024 (Fig. 9). In the timeline, the red bars indicate the time period during which a keyword had a significant increase in citations and the value of burst strength indicates the intensity of this increase.

Early phase: nutrient foundations (2005–2015). During this phase, the strongest bursts included nutrition (2005–2015, strength of 14.4), calcium (2005–2012, strength of 8.15), mineral nutrition (2005–2011), corn (2005–2014) and phosphorus (2005–2010). These keywords reflect the primary focus on the fundamental role of Mg and other mineral nutrients in plant nutrition, soil fertility and crop productivity. Research in this period primarily examined the interaction among Mg, Ca and P and their impact on crop physiology and

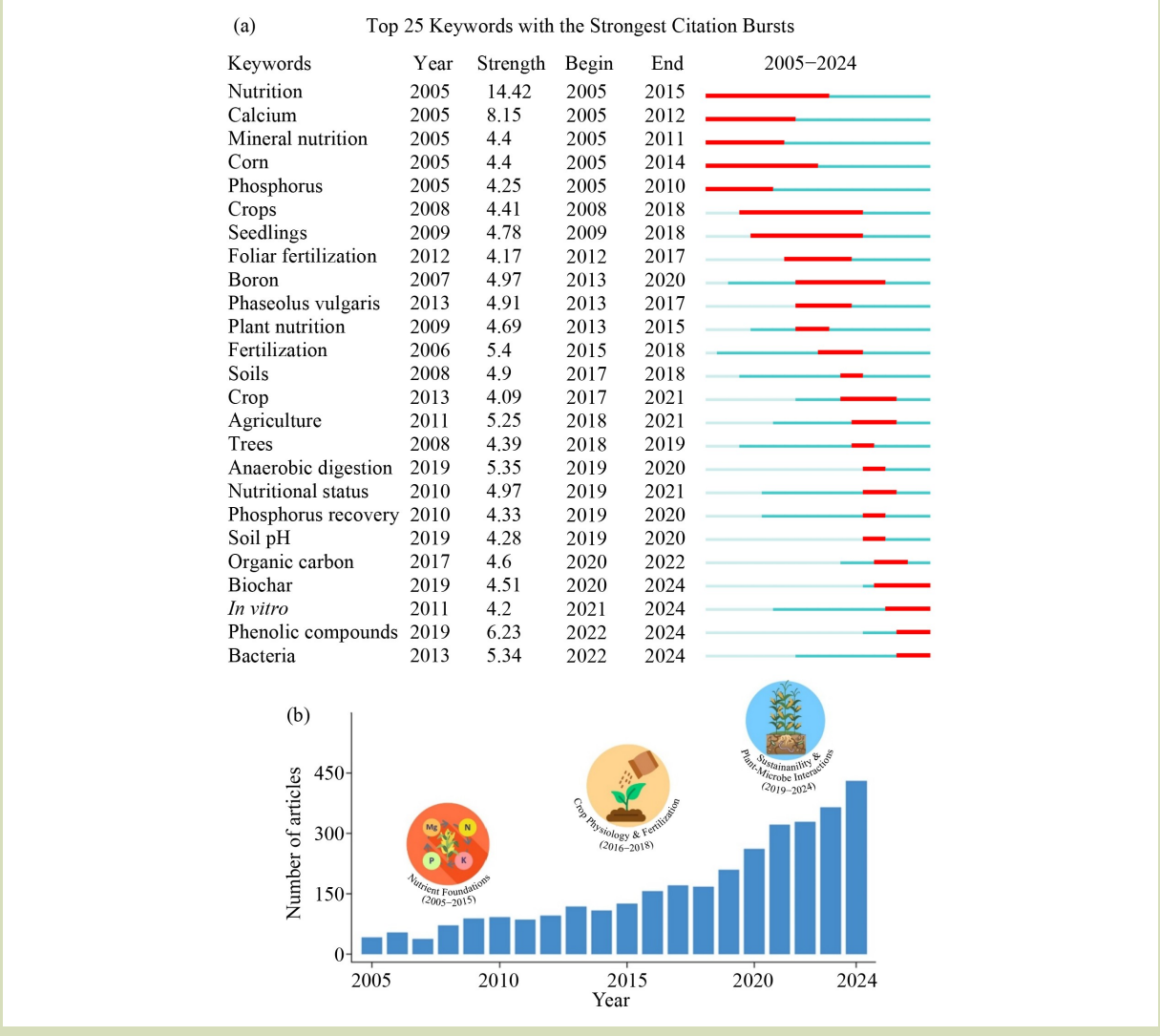


Fig. 9 Top 25 keywords with the strongest citation bursts. (a) Year represents the year in which the keyword appears for the first time, Begin and end represent the starting and ending years of the keyword as the frontier, and strength represents the burst strength. Red lines represent the specific diachronic stage when the keyword becomes a hot topic of academic research. Light blue indicates that the node has not yet appeared and dark blue that the node has begun to appear. (b) Temporal dynamics of research priorities.

productivity, e.g., maize[44,54]. This period marked by increased in research interest in mineral nutrition and maize, is an indicator of the significance of maize as a major model crop in the study of nutrient use efficiency[45]. Overall, this phase highlights the foundation of Mg research, with a focus on soil fertility and mineral nutrition in important crop plants.

Mid phase: crop physiology and fertilizer application strategies (2016–2018). Between 2016 and 2018, keyword trends changed to crop specific studies and optimized fertilizer application strategies. High burst keywords included foliar fertilizer application, *Phaseolus vulgaris*, fertilization and soils. This phase reflects growing interest in Mg application methods and physiological responses of plant to different nutrient conditions. Foliar Mg application gained a tremendous attention as a rapid method to correct Mg deficiency and enhance crop production[15]. The burst of *Phaseolus vulgaris* (common beans) highlights the growing use of legumes to study Mg-N interactions to control nodulation and nutrient use efficiency[41]. The inclusion of soil towards the end of this period signals renewed interest in integrated soil nutrient management. The overall research during this stage changed from general nutrient uptake to a specific fertilizer application strategy and crop specific physiological responses to improve nutrient uptake efficiency and productivity.

Recent phase: sustainability and plant-microbe interaction (2019–2024). During this time, the research scope expanded to sustainability science, soil quality and microbial processes. Burst keywords included crop, agriculture, trees, anaerobic digestion, phosphorus recovery, soil pH, organic carbon and nutritional status. The development of biochar reflects growing interest in biochar-Mg systems to enhance physicochemical properties of soil and nutrient retention[68]. This stage shows a clear transition towards sustainable nutrient management practices and principles of a circular nutrient economy, where Mg is important in soil health and ecosystem functionality. Also, the bursts of phenolic compounds and bacteria (2022–2024) highlight further expansion into biochemical and ecological perspectives. The term bacteria show increasing attention to Mg effects on rhizosphere microbial communities and plant-microbe interactions[67,69]. Although the interaction between Mg and plant-microbe systems has been a growing concern, insufficient is known about its mechanistic aspects. Future research directions should explore the effects of Mg supply to the rhizosphere microbial community, signaling pathways and nutrient cycling under the field conditions. Integrating microbiome analysis and precise nutrient management can strengthen the sustainable agricultural systems. Meanwhile, the burst of phenolic compounds indicates that more attention should be paid to the direct regulatory role of Mg in the secondary metabolism, antioxidant defense, and stress resistance. These trends illustrate the shift of Mg research toward multiscale systems biology and sustainability-focused agricultural design.

This three-phase progression reflects the broader development of global agricultural priorities and scientific progress. The growing concerns about soil erosion, nutrient imbalance, and climate related sustainability issues have gradually shifted research focus from individual-nutrient physiological research toward integrated soil-plant system approaches. The growing global interest in soil health, ecological production systems and carbon-neutral production systems has also served as an additional research stimulus on the importance of Mg in nutrient cycling and environmental resilience. Meanwhile, advances in high-throughput sequencing and omics technologies now allow detailed analysis of nutrient interaction networks and plant-microbe interaction networks. Collectively, these scientific, technological and policy drivers have shifted Mg research toward system-oriented and sustainability-focused frameworks.

4 Conclusions

This bibliometric analysis of 3318 articles from 2005–2024 indicates that Mg research related to agricultural sustainability has grown at an accelerated rate, and the number of articles in this field has reached annually over 300 annually since 2021. The leading countries are China and the USA with the major institutions being CAU, CAS, Poznań University of Life Sciences, University of Florida, and FAFU. Productive authors include Grzebisz, Wu, Muneer and Zhang. However, global collaboration is still fragmented. The major research themes include Mg in nutrient management, photosynthesis and plant physiology, crop quality and molecular regulations. Recent research interest has shifted toward Mg-microbiome interaction and soil fertility, as well as antioxidant mechanism, showing a system-level integration of Mg into sustainability research. Strengthening interdisciplinary and global cooperation will be required to advance Mg-based innovations in resilient, resource-efficient and sustainable agroecosystems.

Limitations and future perspectives

Despite this development, the low centrality values of the

international collaboration network suggest limited global integration. This pattern could be a result of the region-specific nature of Mg research, as soil types, cropping systems and the patterns of Mg deficiency vary greatly across the geographical zones. Additionally, Mg-specific initiatives lack international coordination as compared to other key nutrients, such as nitrogen and phosphorus, probably because of lower global funding priority. Poor cooperation may lead to repeated localized experiments, fragmented datasets, as well as reduced comparability across agroecological areas. The development of globally applicable Mg management strategies may require stronger transnational cooperation, including standardized methodology, common long-term field trials, open data platforms and strategic research alliances.

Beyond summarizing the current research trends, various strategic research directions emerge from this bibliometric study. First, there is a need for deeper mechanistic investigation by which Mg controls carbon-nitrogen metabolism, signaling pathways and plant-microbe interactions at both molecular and systems levels. Second, Mg management in a framework of precision agriculture and carbon-neutral production approaches should be implemented in future research, especially concerning the carbon dynamics of soils and efficiency of nutrient use. Third, it is also important to scale the findings from pot and field experiments to region-scale and global nutrient cycling model. Lastly, enhancing international cooperation by connecting long-term experimental networks in different climate-soil areas would enhance comparability, minimize research fragmentation and increase global knowledge sharing of sustainable magnesium management.

It is important to note that current bibliometric analysis is limited to articles indexed in the Web of Science Core Collection, which primarily represents international English-language journals. Hence, identification of China as leading contributor reflects its dominance within internationally indexed literature rather than domestic Chinese-language research. A substantial volume of Mg agricultural research has been published in Chinese core journals and national databases such as CNKI (China National Knowledge Infrastructure), which were not included in the present analysis. Future studies incorporating Chinese-language databases will provide more detailed consideration of the overall research contribution and thematic priorities of China.

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Compliance with ethics guidelines

Muhammad Atif Muneer, Xiaohui Chen, Xiaojun Yan, Dongdong He, Jiajie Chen, and Liangquan Wu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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