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A bibliometric review of studies on PG utilization by using CiteSpace

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Abstract: The utilization of phosphogypsum (PG) plays a critical role in promoting the high-quality development of the phosphorus chemical industry. To achieve large-scale, systemic and effective use of PG, researchers worldwide have conducted extensive studies. In this work, 263 articles related to PG utilization published between 1993 and 2023 were retrieved from the Web of Science Core Collection database. Using bibliometric methods and large-scale statistical analysis, a knowledge map of research on PG utilization was generated with the aid of CiteSpace visualization software. This analysis identified the most influential regions, institutions, authors, journals, keywords, and references within the field. Cluster analysis revealed that research primarily focuses on "fly ash", "hemihydrate phosphogypsum", "resource efficiency", and "carbonization products". Current research hotspots, identified through co-citation analysis, include: (1) the preparation of calcium sulfoaluminate cement, (2) the production of carbonation products, and (3) the synthesis of hemihydrate phosphogypsum. Future research directions are proposed in the following areas: (1) cement and retardants, (2) construction and filling materials, (3) soil improvement and ecological restoration, and (4) phosphorus fertilizer production. The results of this review may provide valuable guidance for researchers and practitioners in this field.The adsorption kinetics of sulfamethoxazole on the most effective adsorbent, CHS1a, was described using the pseudo-second-order kinetic model and the multi-center Langmuir adsorption model. CHS1a composite can be considered a promising adsorbent for the removal of sulfamethoxazole from water.

Highlights

(1) Building materials and soil improvement are current research hotspots for PG utilization.
(2) PG is discussed in detail for building materials and environmental applications.
(3) The directions and challenges of comprehensive utilization of PG are presented.

Introduction

Phosphogypsum (PG) is a by-product generated during the production of phosphoric acid via the wet process, in which sulfuric acid reacts with phosphate rock. Chemically, it consists primarily of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) and typically contains impurities such as calcium phosphate compounds (e.g., $Ca(H_2PO_4)_2 \cdot H_2O$, $CaHPO_4 \cdot 2H_2O$), fluoride, heavy metals, rare earth elements, and residual acids (Ding et al., 2019; Sabrina et al., 2022). In recent years, the growing global agricultural demand for phosphate fertilizers has led to a continuous increase in PG production. As of 2023, the global stockpile of PG was approximately 7 billion tons (Yang et al., 2024), and is projected to reach around 11 billion tons by 2050 (Akfas et al., 2024). According to Yang (2024), China's utilization rate of PG reached 48% of its annual production in 2022. Nevertheless, the remaining portion continues to be stored in stockpiles, which not only occupy significant land resources but also pose risks of pollution to surrounding soils, surface water, groundwater, and the atmosphere.

PG possesses dual characteristics as both a resource and waste material. Its extensive accumulation not only consumes land resources but also represents a loss of valuable calcium and phosphorus components (Agrawal et al., 2023). Since the 1990s, researchers have gradually explored the resource potential of PG. Rich in calcium and phosphorus, PG can be utilized across industrial, agricultural, and construction sectors (Tayibi et al., 2009; Potgieter et al., 2003; Degirmenci et al., 2008; Abu-Eishah et al., 2000; Mun et al., 2007). In the EU, approximately 2 billion tons of PG are processed into gypsum annually (Nils et al., 2022). Furthermore, PG has been found to contain trace amounts of rare earth elements, up to 90% of which can be recovered through acid leaching (Sabrina et al., 2024; Maina et al., 2024). Consequently, many scholars argue that PG is a misplaced resource-especially on a resource-limited planet, making its recycling critically important (Jarosiński 1994; Degirmenci et al., 2007; Cui et al., 2024).

Current utilization pathways for PG are diversifying and include soil improvement and remediation, building materials, backfilling, cement production, non-insulating materials, and fertilizers (Ding et al., 2019; Zhou et al., 2024b). Particularly notable is its application in building materials such as cement, gypsum products, and road base layers, which offer significant advantages, including high consumption capacity, low cost, and minimal pollution (Rashad, 2017; Zhang et al., 2024a). In construction applications, PG is often blended with other materials, partially replacing conventional raw materials. Common uses include mixing PG with sand and cement to produce concrete for partition walls, or substituting natural gypsum in plasterboards and wall coatings (Murali et al., 2023). The use of gypsum in cement production dates to the early 19th century, a process pioneered by Müller and Kuhne in Germany, who decomposed gypsum to co-produce sulfuric acid and cement (Reijnders, 2014). Subsequently, countries including China, the United Kingdom, and France adopted PG as a raw material for co-producing sulfuric acid and cement (Ding et al., 2019). However, due to its complex composition, most utilization approaches remain at the laboratory stage, hindering large-scale implementation.

In recent years, the stockpiling of PG has hindered the growth of phosphorus chemical industry and posed significant risks to human health and ecosystem stability (Qi et al., 2023; Wang et al., 2024b). In response, an increasing number of researchers have conducted studies on PG utilization (Akfas et al., 2024; Yang et al., 2022; Murali et al., 2023). For example, Chernysh (2021) reviewed literature on PG recycling from 1980 to 2020 using VOSviewer, outlining management trends and proposing biotechnological methods for recovering phosphorus raw materials. Cao (2021) analyzed both articles and patents from 1990 to 2020 using CiteSpace, showing that patents outnumber academic papers, with the former focusing on chemical materials and the latter emphasizing environmental issues . Wei (2022) identified research hotspots and trends from 1985 to 2020, highlighting future applications in rare earth element extraction, building materials, and soil conditioners. Bilal (2023) critically examined the physicochemical properties of PG at 65 global storage sites, concluding that its low radioactivity necessitates treatment. Murali (2023) reviewed the mechanical and microstructural properties of PG in construction, confirming its suitability for bricks, cement, and gypsum products. Qi (2023) summarized agricultural and soil remediation applications, noting its effectiveness in adjusting soil pH as a conditioner. Akfas (2024) reviewed the mineralogy and chemical composition of PG, suggesting potential pathways for trace element extraction. Cui (2024) surveyed recycling efforts in China, identifying uses in construction materials, retardants, and ecological restoration, although adoption remains limited by policy, market, and geographic factors. However, these reviews subjectively evaluated only a limited subset of the available literature, often up to 2020, and are therefore insufficient to capture current global research hotspots and emerging trends in PG utilization.

Bibliometrics provides a statistical and quantitative approach to analyzing literature. By examining literature systems and metadata characteristics through mathematical and statistical methods, it reveals patterns in publication distribution, structural evolution, and research dynamics (Zhang et al., 2024b; Azam et al., 2021). Among bibliometric tools, CiteSpace is one of the most widely used and influential visualization software packages (Chen et al., 2014). It enables the analysis of research progress, current trends, and emerging hotspots, thereby offering a macroscopic overview of a field and helping to reduce knowledge fragmentation. For instance, Cao (2021) reviewed PG-related articles and patents from 1990–2020; Li (2022b) analyzed green building literature from 2007–2021 from a stakeholder perspective; and Wang (2023) examined research progress on rhizosphere microbes of wetland plants from 1995–2022. However, few studies have systematically mapped the knowledge structure of PG research, and there remains a notable lack of bibliometric analysis on utilization trends beyond 2020. Therefore, this review employs bibliometric methods and CiteSpace to visualize and quantitatively analyze literature related to phosphogypsum utilization retrieved from the Web of Science (WoS) Core Collection database.

This study is based on literature published between 1993 and 2023 related to "phosphogypsum utilization." Using CiteSpace, it analyzes the knowledge base, intellectual structure, and research frontiers of the field. The main objectives are to: (1) identify significant national contributions to phosphogypsum utilization research; (2) examine the roles of core journals in the field; (3) classify major research themes and knowledge structures; and (4) identify research frontiers and emerging hotspots. Overall, this research aims to reveal the current knowledge structure, research hotspots, and future development directions in PG utilization. It provides a macroscopic understanding of the field and serves as a comprehensive reference for researchers, thereby promoting further progress in PG recycling and applications.

Data and methodology

Data sources

The WoS Core Collection database was used as the source of data analysis. The search topic was "phosphogypsum utilization", and the literature time span was set from January 1, 1993 to December 31, 2023. By restricting the publication type to articles and reviews, a total of 390 records were obtained. After removing duplicates and papers unrelated to the research

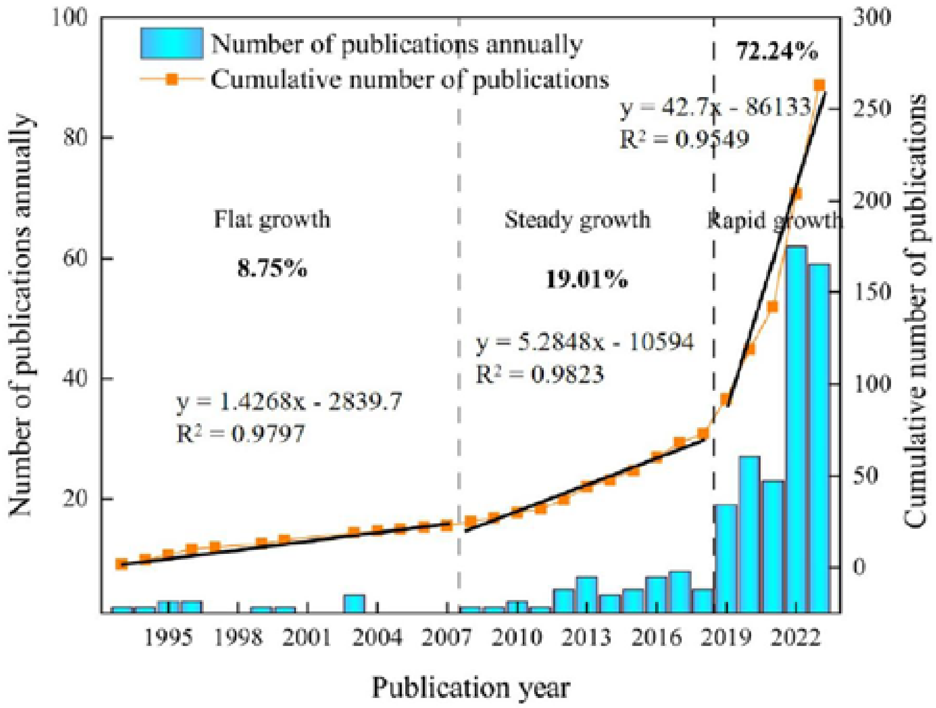

Fig. 1. Trends in cumulative number of publications on PG resource utilization.

topic, 263 documents remained. . The selected records were downloaded in the "Full Record and Cited References" format and saved as plain text files for further analysis.

Analysis methods

CiteSpace is an analytical software based on mathematical and statistical methods for in-depth mining of literature data, developed by Chaomei Chen (Li et al., 2022a). When combined with bibliometric analysis, CiteSpace enables the visual exploration of relationships, structures, and patterns within the literature. It helps researchers quickly identify research hotspots, historical developments, and future directions in a particular field (Li et al., 2022a). In this study. CiteSpace 6.3.R1 Basic software and WoS Core Collection database were used to process and analyze literature related to PG utilization. The time slicing was set to one year, and node types included Country, Institution, Author, Keyword, Reference and Cited Author. CiteSpace was used to map these nodes in order to explore the evolution and research trends in PG utilization over the past 30 years.

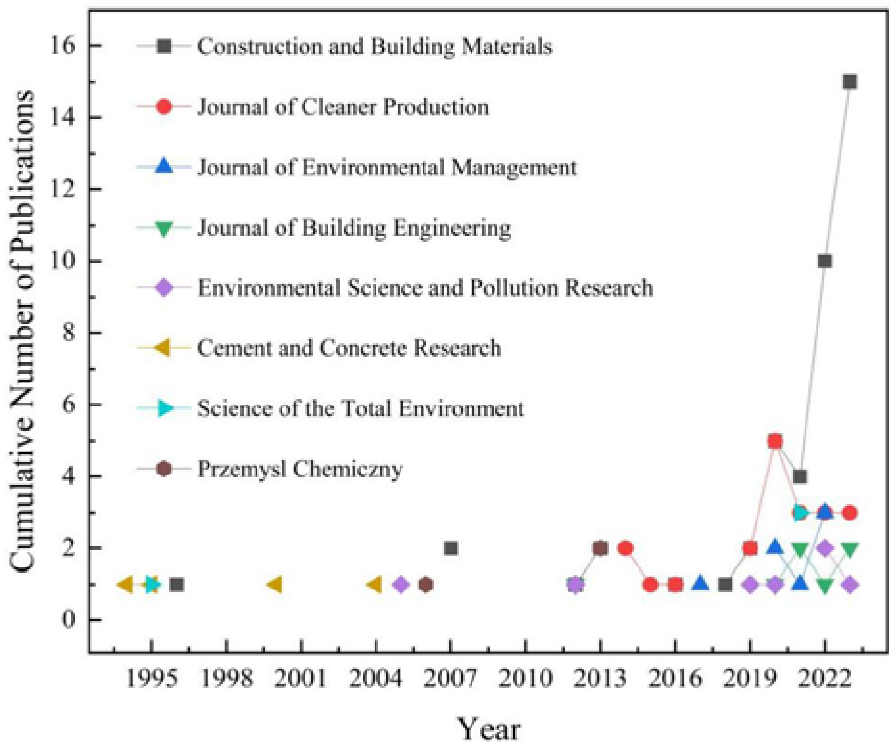

Fig.2. Number of journal publications related to research on PG utilization.

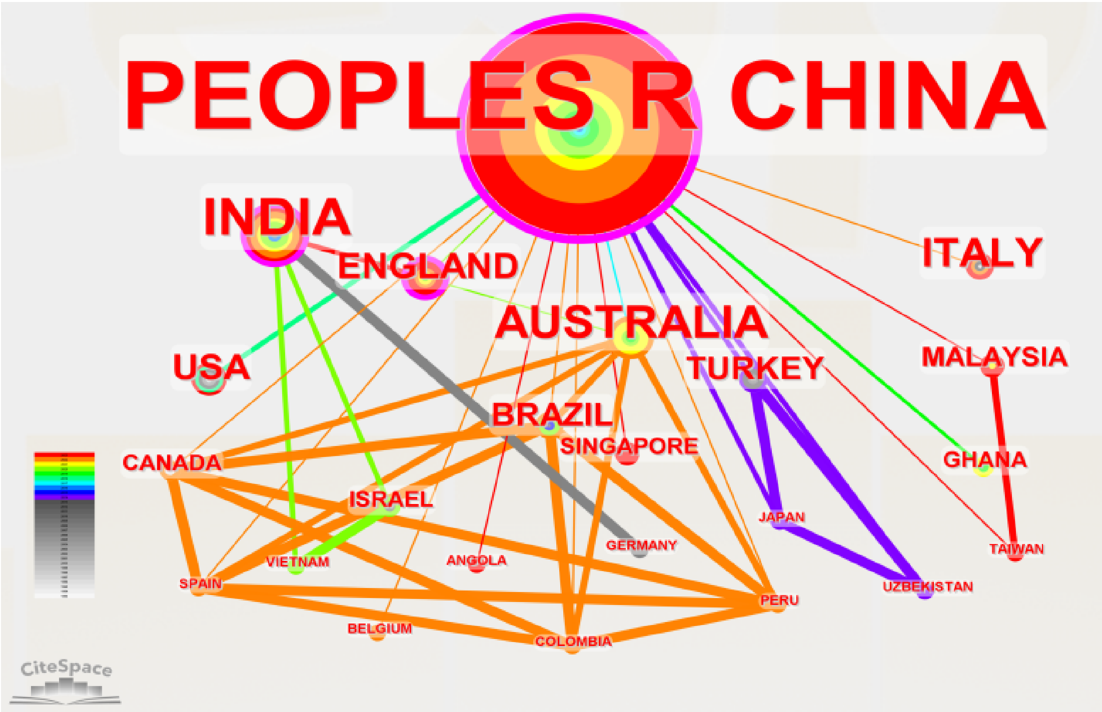

Fig.3. Country cooperation network of PG utilization.

Results and discussion

Publication trend analysis

The literature on PG and its statistical analysis from 1993 to 2023 is presented in Fig. 1. The results indicate that the number of publications on PG utilization can be divided into three distinct phases: flat growth, steady growth, and rapid growth. Overall, the publication count shows a gradual upward trend over time. The period from 1993 to 2007 represents a phase of flat growth, with a cumulative total of 23 publications. During this period, research primarily focused on the production of fertilizers from PG and the characterization of building materials, with limited attention given to large-scale resource utilization of PG. This limitation indirectly constrained its broader application (Jarosiński 1994; Stout et al., 2003; Smadi et al., 1999; Kwang-hyun 2003).

Over time, studies on PG utilization gradually expanded, entering a phase of steady growth between 2008 and 2018, during which the cumulative number of publications increased from 23 to 73. This decade marked a significant shift in PG utilization research – from studies focusing on individual material properties to diversified applications such as insulated wall materials, calcium sulfate hemihydrate, cementitious materials, element recovery, and soil conditioners (Li et al., 2018a; Mi et al., 2018; Garg et al., 2009; Fujimoto et al., 2013; Nisti et al., 2015).

The period from 2019 to 2023 corresponds to a phase of rapid growth, with a cumulative total of 190 publications. In the past five years, the comprehensive utilization of PG has received increasing attention from researchers. Studies have focused on developing tailored utilization pathways based on PG's inherent properties. Overall, the continuous rise in publications on comprehensive PG utilization reflects growing policy support and government initiatives promoting sustainable use of industrial by-products

Publication trend analysis of journals

The temporal distribution of journals that have published more than three articles on PG resource utilization is shown in Fig. 2. The results indicate that *Construction and Building Materials* and the *Journal of Cleaner Production* published the highest number of articles on PG utilization between 1993 and 2023, which is consistent with the findings reported by Wei (2022). *Construction and Building Materials* (2023 Impact Factor: 7.4), classified as a Zone 1 journal in Engineering and Technology, focuses on construction materials such as cement, concrete, gypsum boards, bricks, mortar, polymers, non-conventional building materials, and road materials, as well as their applications. A total of 44 articles were published in this journal, with 10 in 2022 and 15 in 2023, accounting

Table 1. Top 10 countries publishing papers on PG utilization.

No.	Countries	Publications	Percentage (%)
1	PEOPLES R CHINA	188	71.48
2	INDIA	14	5.32
3	AUSTRALIA	9	3.42
4	ITALY	7	2.66
5	ENGLAND	5	1.90
6	USA	5	1.90
7	BRAZIL	4	1.52
8	TURKEY	4	1.52
9	MALAYSIA	3	1.14
10	CANADA	2	0.76

for 56.81% of its total publications in this field. The *Journal of Cleaner Production* (2023 Impact Factor: 9.7) ranked second, with a cumulative total of 20 articles on PG resource utilization, with a cumulative. Research on PG utilization appeared relatively late in this journal, with the earliest retrievable publication dating back to 2014, followed by a gradual increase in output. As a leading top-tier journal in the environmental sciences, it has consistently published studies on the development of new structures, systems, processes, materials, and products. This trend suggests that the use of PG in building materials represents an important and ongoing research direction in the mid- to late-stage development of the field, an observation further supported by the publication data presented in Section 3.1.

Furthermore, based on an analysis of 2023 journal impact factors, journals publishing research related to PG utilization generally possessed relatively high impact factors. *Cement and Concrete Research* (Impact Factor: 10.9), which published four articles on PG, had the highest impact factor among them. In total, six journals with an impact factor greater than 6.0 published studies on PG utilization, collectively contributing more than 86 articles, accounting for 32.70% of all publications. Notably, these high-impact journals primarily fall within the construction and environmental categories, indicating that PG research not only focuses on resource utilization but also emphasizes environmental sustainability.

Table 2. Top 10 author in studies related to PG utilization.

No.	Authors	Publications	Percentage (%)
1	Qu, Guangfei	8	3.04
2	Jin, Zihao	7	2.66
3	Wu, Fenghui	6	2.28
4	He, Xingyang	6	2.28
5	Ma, Liping	6	2.28
6	Li, Junyan	5	1.90
7	Chen, Bangjin	5	1.90
8	Wu, Lei	5	1.90
9	Yang, Jie	5	1.90
10	Liu,Shan	5	1.90

Cooperation network analysis

Country cooperation network analysis

The national collaboration network for literature on PG resource utilization is visualized and analyzed in Fig. 3, where nodes represent countries. As shown in Table 1, China published the

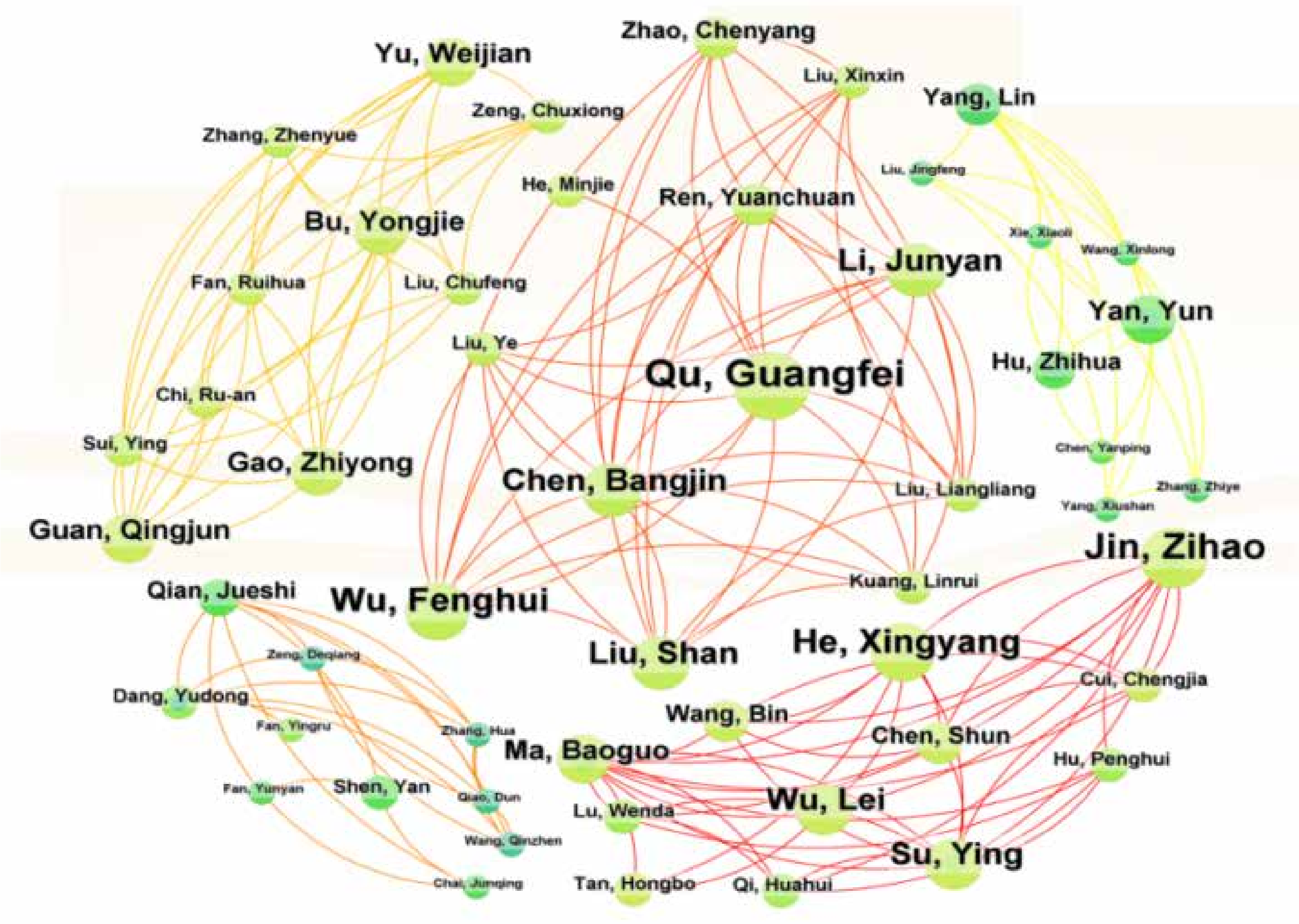

Fig.4. Author cooperation network of PG utilization.

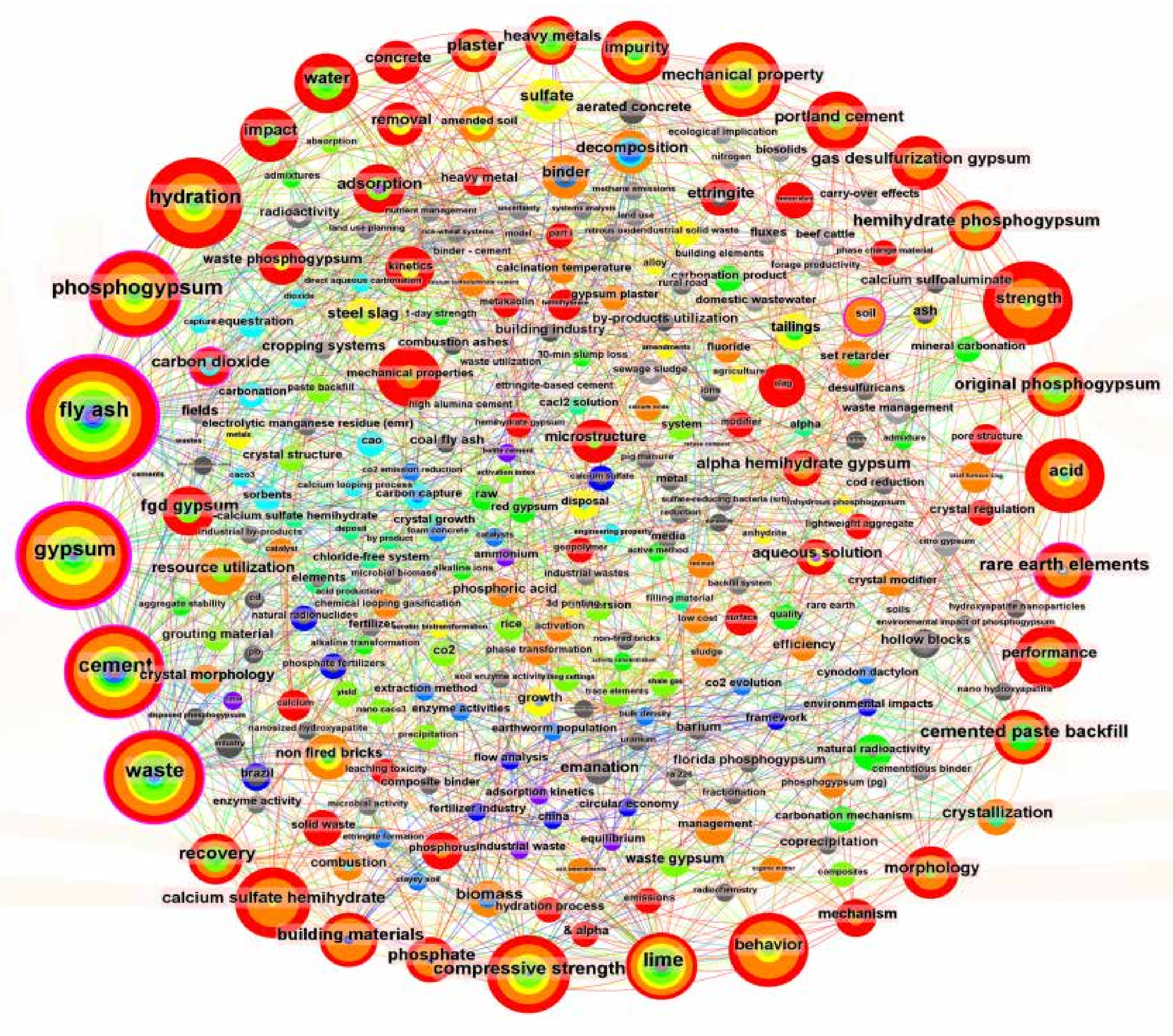

Fig.5. Keyword co-occurrence network of PG utilization.

highest number of articles on PG utilization (188), followed by India (14), Australia (9), Italy (7), the United Kingdom (5), and the United States (5). The analysis indicates that China's research output in this field significantly exceeds that of other countries, highlighting the nation's leading role and strong research interest in PG utilization. As reflected by the connecting lines between nodes, China has maintained close collaborative relationships with numerous countries. In the earlier stages, cooperation was primarily observed with Australia, the United States, the United Kingdom, and Turkey. In recent years, however, partnerships have expanded to include Italy, Brazil, and Malaysia, among others. Node centrality metrics further demonstrate that China (centrality = 0.41) far surpasses Italy (centrality = 0.13) and Australia (centrality = 0.03), underscoring China's high level of international influence in this research area. Additionally, countries such as India, Australia, and Malaysia began research on PG resource utilization relatively late. In recent years, collaborative links have strengthened, particularly between India and the United Kingdom, as well as between Australia and Brazil.

Author cooperation network analysis

To further elucidate the collaborative relationships in PG utilization research, a co-authorship network analysis was conducted among authors and researchers, as illustrated in Fig. 4 and Table 2. The results indicate that the most prolific authors are Qu Guangfei (8), Jin Zihao (7), Wu Fenghui (6), and He Xingyang (6). Among them, Qu Guangfei and He Xingyang are recognized experts in the field of solid waste resource utilization, underscoring the significant role of PG within this research area. Although Jin Zihao and Wu Fenghui entered the field of PG research more recently, they have published extensively in recent years and maintain close collaborations within their research team. Notably, all four of the top-publishing authors are affiliated with Chinese institutions, consistent with China's prominent role in PG resource utilization studies, as discussed in Section 3.3.1. The collaboration network exhibits a modular structure, with Qu Guangfei showing strong collaborative ties to Wu Fenghui, Jin Zihao, and He Xingyang. This pattern reflects the formation of a highly productive research cluster that has made substantial contributions to the advancement of PG resource utilization.

Keyword analysis

Keyword co-occurrence network analysis

Keyword co-occurrence network analysis effectively reveals the research topics and content within the field of PG utilization, reflecting its developmental trajectory and research hotspots. This approach helps researchers quickly grasp the dynamic evolution of knowledge structures in this field. The visualization and analysis, using PG utilization keywords as nodes, are presented in Fig. 5 and Table 3. The results show strong interconnections among keywords, with the most frequently occurring being "fly ash" (50 times), followed by "gypsum" (41), "cement" (32), "waste" (31), "hydration" (31), "PG" (27), "strength" (22), and "compressive strength" (21). Keywords with a co-occurrence network centrality values greater than 0.1 include "gypsum" (0.25), "fly ash" (0.24), "waste" (0.17), "cement" (0.15), "PG" (0.14), "carbon dioxide" (0.13), "rare earth elements" (0.11), "soil" (0.11), and "lime" (0.10). Among these, "gypsum", "fly ash", "waste", and "PG" exhibit both high frequency and high centrality (greater than 0.1), representing the core research themes and broadly indicating the main directions of current PG-related studies.

Table 3. Top 20 keywords in studies related to PG utilization.

No.	Keywords	Frequency	Centrality
1	fly ash	50	0.24
2	gypsum	41	0.25
3	cement	32	0.15
4	waste	31	0.17
5	hydration	31	0.08
6	PG	27	0.14
7	strength	22	0.04
8	compressive strength	21	0.04
9	acid	19	0.06
10	behavior	19	0.02
11	mechanical property	18	0.02
12	lime	16	0.1
13	calcium sulfate hemihydrate	16	0.02
14	performance	14	0.05
15	impurity	14	0.02
16	water	11	0.07
17	portland cement	11	0.02
18	cemented paste backfill	10	0.05
19	building materials	10	0.05
20	original PG	10	0.03

PG is an industrial by-product generated during phosphate fertilizer production. Due to its high and complex impurity content, it is difficult to use directly (Cao et al., 2022a). The keyword "gypsum" highlights a major research hotspot in PG utilization. For example, Capasso (2021) produced gypsum boards from PG for construction applications, demonstrating properties such as low weight, sound absorption, and thermal insulation. Similarly, Singh (2005) demonstrated that calcining PG at 1000°C removes phosphorus impurities, enabling the production of stable hard gypsum suitable for floor tiles. Depending on the wet-process phosphoric acid production method, PG by-products can be classified as anhydrous gypsum, hemihydrate gypsum, dihydrate gypsum, or hemihydrate-dihydrate gypsum (Cao et al., 2022b). Gypsum has wide industrial applicability, serving as a cement retarder, building plaster, α-type high-strength gypsum, gypsum-slag cement, type-II anhydrite gypsum, soil conditioner, and as a raw material for co-producing sulfuric acid and cement (Cao et al., 2022b). These findings are consistent with those of Chernysh (2021), indicating that research hotspots in PG resource utilization are primarily concentrated in the construction and agriculture sectors - particularly in the production of gypsum-based building materials and soil conditioners.

The production of sulfuric acid and co-produced cement from PG involves high-temperature decomposition of PG into CaO and SO_2. The resulting CaO is mixed with SiO_2, Al_2O_3, and Fe_2O_3 to produce cement, while SO_2 is catalytically oxidized to SO_3 for sulfuric acid production (Liu et al., 2020b). This process not only enables the resource utilization of PG but also reduces cement production costs (Liu et al., 2019; Liu et al., 2020a). Additionally, a two-step wet process applied to PG can enhance P_2O_5 recovery and simultaneously producing calcium sulfate hemihydrate (Wang et al., 2021). Calcium sulfate hemihydrate is a versatile inorganic material characterized by strong plasticity, in situ self-curing ability, and good biocompatibility, making it widely applicable in both medical and construction fields (Reigl et al., 2024).

PG also serves as an effective soil amendment in regions with poor or high-pH soil. It can reduce heavy metal activity and toxicity to plants while improving soil fertility and promoting plant growth (Merino-Gergichevich et al., 2010; Rehman et al., 2017). Therefore, future research should focus on developing site-specific strategies for PG resource utilization, particularly for improving impoverished soil areas. Moreover, deeper investigation into the mechanism of phosphorus transfer involving PG, soil microbes, and plants could provide valuable insights for expanding its sustainable applications.

Timeline visualization of keyword co-occurrence clustering analysis

The timeline visualization consists of 299 nodes and 13,397 connecting lines, and the cluster analysis shows the research hotspots on PG utilization across different time periods (Q =

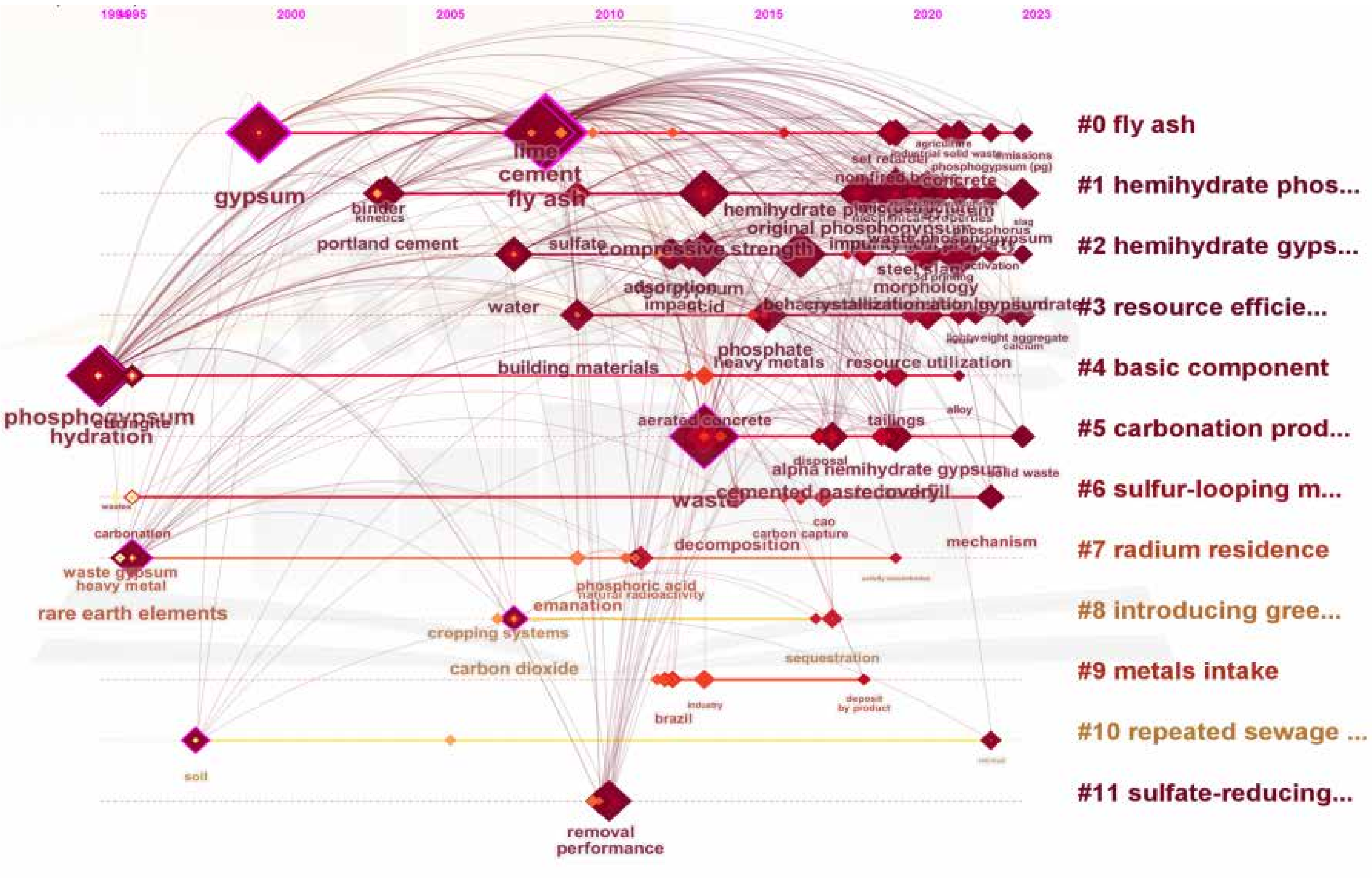

Fig.6. Timeline visualization of keyword co-occurrence cluster analysis in PG utilization studies.

0.5385> 0.3, S = 0.8099> 0.7, Fig. 6). During the early stage of research (1993-1998), hot spots were concentrated in Cluster #4 (basic componet) and Cluster #7 (radium residence). Around 2000 and 2008, Cluster #0 (fly ash) emerged as the dominant research focus. Since 2010 onwards, the research emphasis has gradually shifted toward Cluster #1 (hemihydrate PG), Cluster #2 (hemihydrate gypsum), Cluster #3 (resource efficiency), Cluster #5 (carbonization products), and Cluster #10 (sulfate-reduction). In recent years, hemihydrate PG and hemihydrate gypsum have become major research hotspots. Hemihydrate PG is one of the by-products generated during phosphoric acid production and is widely used as a filling material due to its abundant availability and low cost (Jiang et al., 2022). Jiang (2018) reported that treating hemihydrate PG with 1.5% quicklime for 2 hours significantly increased its flexural and compressive strength, fully neeting the requirements for backfill binders.

Hemihydrate gypsum is another major research focus, widely applied as a building material for manufacturing gypsum boards, gypsum lines, gypsum flower decorations, fixing brackets, artworks and sculptures. It can also be used to repair or fill interior walls, ceilings and partitions of buildings. Jia (2021) investigated the effect of H_3PO_4 on the hydration properties of gypsum during hemihydrate gypsum preparation from PG. The study revealed that H_3PO_4 accelerates the dissolution of hemihydrate gypsum and the precipitation of dihydrate gypsum. To ensure optimal hemihydrate gypsum formation, the concentration of H_3PO_4 should be maintained below 0.1%.

Co-citation analysis

CiteSpace provides a literature co-citation analysis function, which can reveal research hotspots and trends in a given field over different time periods. Co-citation occurs when two documents appear in a third document; these two documents are then referred to as co-cited documents (Li et al., 2022a). In this study, we performed co-citation analysis of both authors and publications to investigate the knowledge structure and research trends in PG utilization.

Author co-citation analysis

The top 10 authors in terms of co-citation frequency, centrality and burst intensity of for articles on PG utilization are summarized in Table 4. Tayibi Hanan was the most frequently co-cited author, with 82 co-citations, followed by Singh Manjit (74), Rashad Alaa M (64), Değirmenci Nurhayat (50), He Yuqi (47), Zhou Jun (44), Ma Baoguo (43), Yang Lin (39), Chen Qiusong (37), and Liu Shuhua (29). In terms of centrality, the top authors are Singh Manjit (0.29), Tayibi Hanan (0.16), Altun İ Akın (0.12), Rashad Alaa M. (0.08), Değirmenci Nurhayat (0.07), He Yuqi (0.07), Kumar Sunil (0.06), Zhou Jun (0.04), Ma Baoguo (0.04) and Liu Shuhua (0.03). Regarding the magnitude of the eruption intensity values, the leading authors are Pérez-López Rafael (7.8), Kumar Sunil (6.59), Tayibi Hanan (5.34), Chen Qiusong (5.28), Değirmenci Nurhayat (4.79) and Shen Yan (4.15), Taher M.A (4.11), Ma Baoguo (4.04), He Yuqi (3.88) and Garg Mridul (3.65). Notably, Tayibi Hanan, Rashad Alaa M, and Ma Baoguo exhibit high co-citation frequency, centrality, and intensity of outbursts,

Table 4. Top 10 authors in co-citation frequency, centrality and burst strength.

No.	Cited authors (frequency)	Cited authors (centrality)	Cited authors (burst strength)
1	Tayibi Hanan (82)	Singh Manjit (0.29)	Pérez-López Rafael (7.8)
2	Singh Manjit (74)	Tayibi Hanan (0.16)	Kumar Sunil (6.59)
3	Rashad Alaa M (64)	Altun İ Akın (0.12)	Tayibi Hanan (5.34)
4	Değirmenci Nurhayat (50)	Rashad Alaa M. (0.08)	Chen Qiusong (5.28)
5	He Yuqi (47)	Değirmenci Nurhayat (0.07)	Değirmenci Nurhayat (4.79)
6	Zhou Jun (44)	He Yuqi (0.07)	Shen Yan (4.15)
7	Ma Baoguo (43)	Kumar Sunil (0.06)	Taher M.A (4.11)
8	Yang Lin (39)	Zhou Jun (0.04)	Ma Baoguo (4.04)
9	Chen Qiusong (37)	Ma Baoguo (0.04)	He Yuqi (3.88)
10	Liu Shuhua (29)	Liu Shuhua (0.03)	Garg Mridul (3.65)

suggesting that their research is widely recognized and is likely to continue influencing the field of PG utilization in the future.

The authors' corresponding topics in Table 4 are: Tayibi Hanan (Tayibi et al., 2009), Singh Manjit (Singh et al., 1994), Rashad Alaa M (Rashad 2017), Değirmenci Nurhayat (Degirmenci et al., 2007), He Yuqi (He et al., 2023), Zhou Jun (Zhou et al., 2019), Ma Baoguo (corresponding author) (Jin et al., 2023), Yang Lin (corresponding author) (Chen et al., 2023a), Chen Qiusong (Chen et al., 2023b), Liu Shuhua (Liu et al., 2020a), Altun İ Akın (Akın Altun et al., 2004), Kumar Sunil (Kumar 2002), Pérez-López Rafael (Pérez-López et al., 2016), Taher M.A (Taher 2007), Garg Mridul (Garg et al., 2009).

Literature co-citation analysis

The frequency with which a document is co-cited reflects its influence in the field, with higher co-citation counts indicating greater impact. In this study, a co-citation analysis of literature related to PG utilization identified the top 10 co-cited articles,

Table 5. The top 10 most highly co-cited articles.

No.	Article title	Year	Reference	Citation Frequency	Total Citations
1	PG as a construction material	2017	(Rashad 2017)	42	447
2	Synthesis of α-hemihydrate gypsum from cleaner PG	2018	(Ma et al., 2018)	29	120
3	Recycling PG and construction demolition waste for cemented paste backfill and its environmental impact	2018	(Chen et al., 2018)	27	322
4	PG Recycling: A Review of Environmental Issues, Current Trends, and Prospects	2021	(Chernysh et al., 2021)	22	222
5	Mechanism of calcination modification of PG and its effect on the hydration properties of PG-based supersulfated cement	2020	(Liu et al., 2020b)	19	157
6	Low cost and high efficiency utilization of hemihydrate PG: Used as binder to prepare filling material	2018	(Jiang et al., 2018)	17	106
7	Immobilization of PG for cemented paste backfill and its environmental effect	2017	(Li et al., 2017)	16	179
8	Calcination parameters on PG waste recycling	2020	(Geraldo et al., 2020)	16	84
9	Efficient removal of phosphate impurities in waste PG for the production of cement	2021	(Cai et al., 2021)	15	67
10	Valorization of PG as a road material: Stabilizing effect of fly ash and lime additives on strength and durability	2021	(Meskini et al., 2021)	15	96

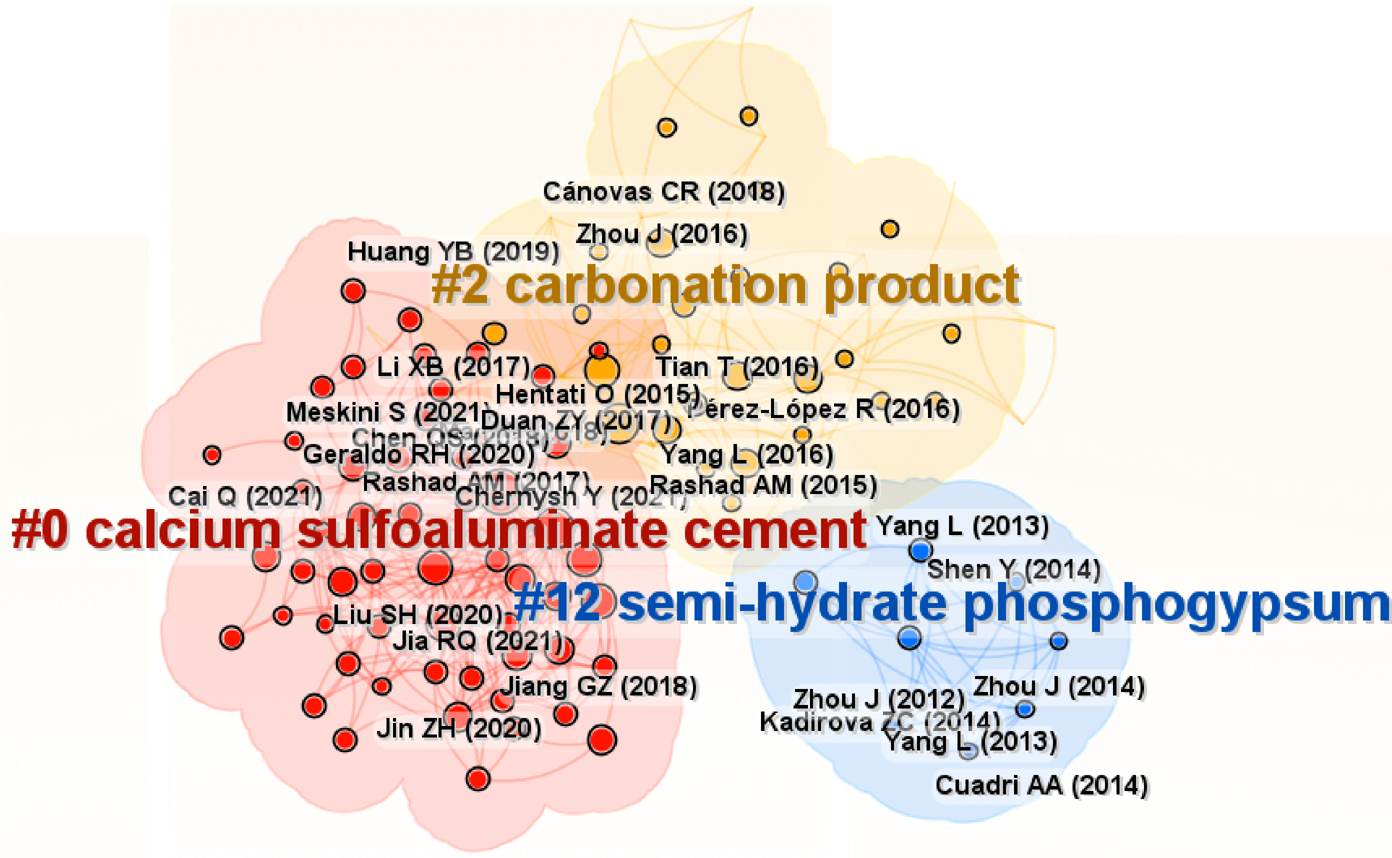

Fig. 7. Document co-citation network.

as presented in Table 5. These articles highlight current PG applications, including building materials, α-hemihydrate gypsum synthesis, cement production, and filling materials. These research areas are likely to remain popular topics and serve as a theoretical basis for the large-scale PG utilization.

The results of this study differ significantly from those reported by Wei (2022), who reviewed PG resource utilization studies published before 2020. Only one of the top 10 co-cited documents in this study (Rashad 2017) overlaps with Wei's list. In Wei (2022), the 2 most cited articles focused on the environmental impacts and management of PG, followed by research on its applications in construction and agriculture. In contrast, nine of the top 10 co-cited articles in this study focus on PG applications in construction, with only one addressing environmental issues. These differences can be attributed to two main factors: 1) the search timeframe of 1985-2020 is now outdated, whereas recent studies indicate that PG utilization research has intensified in the past decade (Section 3.1), and 2) research hotspots have shifted from environmental impact to resource utilization (Tayibi et al., 2009; Lou et al., 2024).

The most frequently co-cited article is Rashad (2017), which reported that PG can be used as a building material. Incorporating PG into construction matrices reduces processing requirements, density and mechanical strength, while increasing shrinkage, expansion and water absorption. PG can also prolong the setting time of concrete when replacing part of the cement, with an increase of 728.57% observed at a 25% substitution rate (Ma et al., 2018). PG is also widely used for the synthesis of α-hemihydrate gypsum, Ma (2018) used the HCl-H_2SO_4 method to synthesize α-hemihydrate gypsum to obtain material with superior qualities. This method has attracted significant attention from scholars, resulting in 29 co-citations for the article. α-hemihydrate gypsum is a high-value cementitious material used extensively in dentistry, orthopedics and construction. Its traditional preparation requires high temperature and pressure, which is energy-saving potential, making alternative methods highly desirable (Yang et al., 2012). PG is also used as a filling material, offering cost savings while mitigating issues such as surface subsidence, seismic hazards, and groundwater discharge. For example, Chen (2018) utilized PG combined with construction waste to prepare cemented paste filling materials that met Class III environmental standards for leachate quality in China (DZ/T 0290-2015) and enhanced mine safety. Jiang (2018) modified hemihydrate PG with 1.0-1.5% quicklime to produce a filling binder, achieving a compressive strength of 16.0 MPa, which exceeds that of C20 concrete (13.4 MPa) after 3 days, at a cost of \$0.41-0.96 per m^3. Overall, literature co-citation analysis effectively reflects the current hotspots in PG utilization research and enables researchers to quickly identify high-quality, influential studies in the field of PG utilization.

Co-citation cluster analysis

In this study, author and literature co-citation cluster analysis was conducted using CiteSpace, as shown in Fig. 7, to summarize the current research hotspots and potential future trends in PG utilization. The network graph consists of 288 nodes (with node colors indicating the direction of PG clustering) and 901 links ($Q = 0.8309 > 0.3$, $S = 0.901 > 0.7$). Cluster analysis of the cited literature initially generated 12 clusters, of which 9 were deemed irrelevant and excluded. Co-citation analysis of authors and literature revealed that authors with the highest citation frequencies do not always correspond to the most frequently cited literature. Notably, Rashad Alaa M, a highly cited author, corresponds to highly cited literature that focuses on calcium sulphoaluminate cement and carbonation products in PG utilization. In total, three literature clusters related to PG utilization were identified: calcium sulfoaluminate cement (2020), carbonation products (2016), and hemihydrate PG (2013). The clusters are specifically analyzed as follows:

(1) Calcium sulfoaluminate cement
Calcium sulfoaluminate cement (CSA) cement is a common quick-setting cement characterized by high temperature resistance, corrosion resistance, freeze-thaw durability, and high strength. It is widely used in emergency repairs, prefabricated components, GRC products, low-temperature construction, and seawater-exposed structures. For example, Guan (2017) reported that CSA concrete can rapidly repair pavements while maintaining good compressive strength and repair performance. CSA cement is cost-effective and can be produced from a wide range of raw materials, including solid wastes such as PG, fly ash, slag and municipal sludge (Xu et al., 2018). Using PG to prepare CSA cement not only reduces environmental pollution but also lowers production costs, offering both environmental and economic benefits. The main component of PG, gypsum, can be decomposed at high temperatures to form CSA cement, whose strength meets the Chinese National Standard (Label 525, GB/T 20472-2006) (Wu et al., 2020b). However, the high-temperature decomposition method used for PG requires substantial energy input, which poses challenges for sustainable development (Dong et al., 2023; Wu et al., 2020a; Shen et al., 2014). Consequently, as environmental protection and sustainability become increasingly important, research on CSA cement has begun to focus on environmental performance and sustainability. Future efforts should aim to develop more environmentally friendly production processes and alternative raw materials, promoting the sustainable development of the construction industry.

(2) Carbonation product
The main components of PG are gypsum and phosphate, which can be converted into products such as calcium carbonate and ammonium sulfate through carbonization. Calcium carbonate has wide industrial, agricultural and daily applications, including food additive, calcium supplement, soil conditioner, and filler. PG-derived calcium carbonate primarily utilizes the gypsum content, which absorbs CO_2 to form high-purity calcium carbonate under controlled conditions. For example, Idboufrade (2021) used a two-step ammonia carbonization process to synthesize ammonium sulfate and calcium carbonate from PG, finding that a temperature of 25°C, rotational speed of 500 rpm, and CO_2 flow of 20 mL/min yielded high-purity ammonium sulfate and calcium carbonate. Similarly, Xie (2016) demonstrated using membrane electrolysis technology that PG exhibits high carbonation reactivity, yielding calcium carbonate with purity exceeding 90% at room temperature, standard atmospheric pressure, and pH 11. In recent years, PG-derived carbonization products have aligned with the goals of carbon emission reduction and carbon neutrality. These approaches not only enable resourceful utilization of PG but also contribute to CO_2 mitigation. Such studies provide a theoretical foundation for energy-saving and carbon-reduction strategies in the PG industry (Xu et al., 2024; Peng et al., 2023; Li et al., 2025).

(3) Semi-hydrate PG
Phosphogypsum (PG) hemihydrate is a form of PG with wide-ranging applications in building materials, agriculture and environmental protection. Jiang (2022) reported that semi-hydrated PG can be used as a gelling filling material; its gelling activity decreases with aging time, but ir remains suitable as a filling gel when the pile height is 1.5m and the aging time is 137h. Wang (2020) utilized hemihydrate PG as raw material for foam insulation production. By adding 20 % slag and 2-3% fibers, high-performance composite insulation materials with strong compression and bending resistance were prepared. In agriculture, hemihydrate PG contains phosphorus, calcium, hydrogen, sulfur, sodium and other elements, making it an effective soil conditioner. It can regulate soil pH, improve soil permeability and water retention, enhance fertility, and promote crop growth (Bossolani et al., 2021). Hemihydrate PG has also been applied in environmental protection due to its capacity to absorb heavy metal ions. It is increasingly used in wastewater treatment and environmental pollution remediation efforts (Altas et al., 2017; Wu et al., 2024a; Lu et al., 2024). Overall, research and application of hemihydrate PG in construction, agriculture, and environmental protection continue to expand, contributing significantly to the development of these fields.

Prospects and challenges

Based on comprehensive analysis, PG possesses significant utilization value. However, due to its associated environmental pollution and land occupation issues, the efficient utilization and treatment of PG have become global concerns (Wu 2024; Wang et al., 2024a). The future directions for PG utilization can be considered from the following aspects:

(1) Cement & Retarder
PG is rich in calcium sulfate, an important component in cement preparation. It can be mixed with cement clinker to produce calcium sulfate cement, which effectively improves the setting time and durability of cement. Bossolani (2021) reported that replacing natural gypsum with PG at a 20% blending ratio for low-carbon calcium sulfate cement achieved optimal performance, simultaneously enabling PG utilization and reducing carbon emissions. In addition, PG can be used to prepare cement retarders. The SO_4^{2-} in PG reacts with cement hydration products to form monosulfur-type hydrated calcium thioaluminate, to synthesize polysulfur-type hydrated calcium thioaluminate. This process reduces the contact area between cement clinker and water, thereby slowing the hydration reaction.

In context of carbon emission reduction and carbon neutrality, using PG as a blended mineral to produce low-carbon cement and retarders offers significant advantages. In particular, the preparation of low-carbon calcium sulfate cement from PG aligns well with contemporary sustainability goals. Currently, research on PG-based cement and retarder production remains largely theoretical, with limited large-scale application (Wu et al., 2024b; Hu et al., 2024). Therefore, future efforts to scale up the use of PG as a blending raw material have broad prospects, offering both economic and environmental benefits while promoting the effective utilization of PG solid.

(2) Construction & Filling materials
PG has certain limitations as a construction and filling material because of its low strength, poor water stability, limited corrosion, and high-temperature resistance, and variability in source quality. Consequently, research modifying or processing PG for construction and filling applications has become a current hotspot. To achieve low-carbon, green, and low-cost modification methods, many studies have explored compound modification of PG as a blended raw material for waste resource utilization. Mixing PG with other mineral solid wastes can alter he microstructure and mechanical properties of the resulting materials. Furthermore, adjusting the PG content and particle size allows for optimization of material properties, particularly in filling applications. Although progress has been made in PG-based mixed modifications, large-scale applications in construction and filling remain limited (Li et al., 2024a; Liu et al., 2024a; Zhou et al., 2024a). Future research should focus on combining PG with materials such as gangue, red mud, and steel slag to develop composite multifunctional materials, thereby promoting comprehensive resource utilization.

(3) Soil improvement & Ecological remediation
The use of PG for soil improvement or ecological restoration is an important trend for its efficient utilization. With the ongoing intensification of desertification and salinization, the area of arable land is decreasing, making soil restoration in ecologically fragile or polluted regions increasingly critical. PG contains a variety of beneficial elements, including phosphorus, calcium, hydrogen, sulfur and sodium, which can promote plant growth. It can also serve as a soil conditioner, capable of regulating alkaline soil pH, improving soil fertility, and enhancing soil permeability and water retention. Additionally, PG can adsorb heavy metals, mitigating soil pollution. Future research may focus on screening phosphorus-releasing bacteria from PG soils, which could then be combined with PG as a soil amendment to further improve soil fertility and crop yields (Li et al., 2024b; Liu et al., 2024c; Liu et al., 2024b).

(4) Production of phosphate fertilizer
Phosphogypsum (PG) is a by-product of phosphoric acid production and often contains residual phosphate due to limitations in current production technologies. Phosphate, being the primary raw material for phosphate fertilizers, has seldom been recovered from PG for fertilizer production (Jin et al., 2024; Elbagory et al., 2024; Li et al., 2018b). Therefore, further research on PG-based phosphate recovery is necessary, as it holds significant potential for improving PG utilization and developing sustainable fertilizer production strategies.

Conclusion

In recent years, the utilization of PG has become a key factor influencing the high-quality development of phosphorus chemical enterprises. Addressing the challenge of large-scale PG utilization has therefore emerged as a critically important research area worldwide. A comprehensive and quantitative analysis of the literature is essential to fully understand the progress and current state of PG utilization research. In this review, 263 publications on PG utilization from 1993 to 2023 were statistically analyzed using bibliometric methods. CiteSpace software was employed to visualize and quantitatively assess countries, institutions, authors, keywords, references, and cited authors. The number of articles on PG utilization has grown rapidly since 2008, with the last five years alone accounting for 72.24% of total publications, reflecting increasing research interest in this area. Further analysis of geographic and institutional contributions indicates that the largest number of publications originate from China, India, Australia, the United Kingdom, and the United States, with Wuhan University of Technology and Kunming University of Science and Technology leading in institutional output. Key researchers in the field include Qu Guangfei, Jin Zihao, Wu Fenghui, and He Xingyang, who exhibit close collaborative networks. China's leading role at the national, institutional, and individual levels underscores its significant influence in advancing PG utilization. Keyword analysis highlights "fly ash", "gypsum", and "cement" as the most frequently occurring terms, reflecting the primary research directions for PG application. Highly cited literature aligns with these keywords, focusing on building materials (e.g., gypsum and cement) and backfilling materials. Co-citation cluster analysis identified three effective thematic clusters: calcium sulfoaluminate cement, carbonation products, and semi-hydrate phosphogypsum, which represent current research hotspots and development trends. Based on these findings, several promising directions for future research are proposed: (1) cement and retardants; (2) construction and filling materials; (3) soil improvement and ecological restoration; and (4) phosphorus fertilizer production.

The findings of this review can systematically assist scholars in understanding the current research status and developmental trends in PG utilization, thereby helping to identify future research priorities. They may also serve as a valuable reference for government agencies in formulating PG utilization policies and planning large-scale application programs. Although important insights were obtained through visual and quantitative analysis of PG-related literature from 1993 to 2023 using CiteSpace and the Web of Science Core Collection database, this study has certain limitations. The literature data were sourced exclusively from the Web of Science Core Collection, which includes only English-language publications, potentially overlooking relevant studies in other databases and languages.

Author contributions

Yuntao Zhang: Writing - original draft, supervision, formal analysis, Writing - review and editing. Yichao Lin: formal analysis, validation, visualization. Hai Jin: investigation and visualization. Yong Zhang: formal analysis, validation, and visualization, Lei Deng: supervision and validation. Wei Feng: investigation and visualization. Meiyan Si：visualization, writing - review and editing. Chunhua Wang: funding acquisition and project administration. Qingsong Li: funding acquisition, project administration, writing - review and editing. Hou Tao: funding acquisition and project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

The research did not involve human or animal participants, and there was no release of harmful substances to the environment because of the study. The authors followed the rules for good scientific practice, as described in the author guidelines.

Consent to participate

Not applicable, as there were no human participants in the study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online.

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