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Review

Systematic Assessment of Phosphogypsum Resource Utilization in China: Pathways, Hotspots, and Policy Implications for a Circular Economy

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Abstract

The stockpiling of phosphogypsum poses severe environmental risks, and its resource utilization remains a global challenge. In this study, we systematically review the status of phosphogypsum utilization, and identify research hotspots through bibliometric analysis of 656 publications from the Web of Science Core Collection (2015–2025) using VOSviewer and Citespace. Four primary utilization pathways—building materials, chemical industry, agriculture, and filling materials—are compared regarding technical characteristics, economic benefits, and environmental issues. The results show that China's phosphogypsum utilization rate reached 61.6% in 2024, with a mean annual increase of 10.2% over the past five years. The building materials pathway dominates, accounting for 64.0% of total, and was identified as a hotspot via bibliometric analysis, and this pathway—especially building gypsum and high-value-added products—demonstrates obvious advantages in terms of technical maturity, cost-effectiveness, and carbon mitigation, with lower environmental risks relative to the other pathways. Future development trends are primarily characterized by scale-up consumption of building materials and upgrading high-value-added production. To facilitate these development trends, relative policy recommendations should be effectively implemented, especially for mandatory "green procurement" policies. Our findings are expected to contribute to the sustainable management of industrial solid waste and accelerate the transition toward a circular economy.

Keywords: phosphogypsum; resource utilization; bibliometric analysis; building materials; policy recommendation

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Academic Editor: Antonio Caggiano

Received: 30 June 2026
Revised: 27 July 2026
Accepted: 4 August 2026
Published: 11 August 2026

1. Introduction

Phosphogypsum (PG) is a typical industrial by-product of the wet-process production of phosphoric acid, and approximately 4.5 to 5.0 tons of PG is generated for every ton of phosphoric acid manufactured [1,2]. As the world's largest producer of phosphate fertilizers, China alone generated 86 million metric tons (Mt) of PG in 2024 [3], with its cumulative stockpile reaching 870 Mt, accounting for roughly 15% of the global total PG inventory [4,5]. PG generally presents as a grayish-white or grayish-black powdery solid composed of crystalline particles, which are predominantly needle-like, plate-like, or columnar in morphology. The main chemical component of PG is calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), and its typical impurities mainly include phosphorus-containing substances, soluble fluorides, organic additives, heavy metals, and radioactive components [6,7]. As summarized in Table S1, these impurities not only impart acidity to PG but also pose leaching risks, and the excessive concentrations of heavy metals and radionuclides are particularly troublesome; once they infiltrate the soil or groundwater, they may pose a potential threat to the ecological environment, making them the primary bottleneck restricting PG's large-scale resource utilization as a resource [8]. The composition of PG varies significantly depending on the phosphate core source and production process, and a recent study in which researchers conducted extraction-toxicity-leaching tests on PG showed that the leachate concentrations of eight typically occurring heavy metals—Pb, Cr, Cd, As, Hg, Zn, Cu, and Ni—all exceeded the Class III limits of the Standard for groundwater quality (GB/T 14848-2017) [9]. Furthermore, Hg, Cd, Pb, Ni, and Cr even surpassed the Class IV–V thresholds [9–13]. Detailed results are presented in Table S2. The total phosphorus (TP) pollution has emerged as the predominant pollutant in the Yangtze River, accounting for 62.5~80.0% of the total excess section [14,15]. The industrial sector has been identified as the primary source of TP pollution, specifically with respect to the "three phosphorus" sectors (i.e., phosphate mines, the phosphorus chemical industry, and PG tailings ponds) [15]. The resource utilization of PG is undoubtedly an effective measure for preventing TP pollution and mitigating environmental risks, which represent a critical impetus for China to advance its green and low-carbon transition and foster the high-quality development of a circular economy in the industrial sector.

During the 14th Five-Year Plan period, a series of policy measures and regulations were enacted to promote the resource utilization of PG [16,17]. In 2024, the Chinese government sectors such as the National Development and Reform Commission (NDRC) promulgated the Action Plan for the Comprehensive Utilization of PG, which establishes a core goal of achieving a 65% resource utilization rate (RUR) by the end of 2026 [17]. Concurrently, this plan stipulates the construction of ten characteristic industrial bases for PG resource utilization (PRU), with the aim of gradually fostering a sustainable development paradigm featuring upstream–downstream coordination and cross-industry, cross-regional collaborative utilization. Despite the remarkable improvement in PRU efficiency achieved with the advancement of China's economy and technology, prominent bottlenecks still remain, such as enormous historical stockpiles, a low overall level of resource utilization, shortages of key core technologies, and high treatment costs. These constraints collectively hinder the effective mitigation of the large-scale PG accumulation dilemma. Existing reviews have mainly focused on specific utilization technologies, environmental impacts, or general development trends pertaining to PRU [15,18], while a comprehensive evaluation integrating research evolution, utilization pathway comparison, and policy implications remains limited. Although bibliometric methods have been increasingly applied to investigate research hotspots, their connection with practical utilization strategies and policy optimization has not been sufficiently explored. Therefore, this study proposes an integrated framework combining literature reviews, bibliometric analysis, multi-dimensional pathway assessment, and policy evaluation to foster a systematic understanding of PRU.

The efficient utilization of PG is of profound significance for advancing resource circularity, underpinning China's "dual carbon" objectives (carbon peaking and carbon neutrality), and fostering green and low-carbon development. Currently, PRU has evolved from solely modification and disposal toward multi-source solid waste synergistic utilization, through the collaborative incorporation of PG with industrial solid wastes such as Bayer red mud, carbide slag, and coal gangue [19,20], encompassing various resource utilization pathways (RUPs) including building materials, chemical engineering, agriculture, and filling materials [21], while the widespread application of PG products remains a critical challenge because the presence of impurities in PG. For example, the heavy -metal leaching (e.g., Cr and Cd) contaminates soil when there is inadequate sintering for building materials (ceramics) [22]. Against the backdrop of increasing environmental risks induced by PG stockpiling and a persistently low RUR, systematic and scientific evaluations on the status and the development trend of PG utilization pathways are critical. Nevertheless, relevant studies (especially for quantitative analyses such as bibliometric analyses) in this field remain insufficient. Therefore, this study is structured around three sections, detailed as follows: (1) elaborating the current status of PG resource utilization globally and in China by region; (2) identifying prevailing research hotspots among the various RUPs based on the a bibliometric analysis; and (3) comparing the hotspots and other RUPs according to the characteristics of technology, economic feasibility, and environmental environmentally. Finally, we put forward the policy implications regarding the improvement of the RUR.

2. Methods and Data Sources

2.1. A Literature Review and Bibliometric Methods

In the study, we primarily adopt a literature review approach, summarizing relevant journal articles, laws and regulations, and government reports to analyze the current status of PRU across China. To identify current research hotspots, a bibliometric method is also employed, with the Web of Science Core Collection (WOSCC) serving as the data source. The relevant literature was retrieved from the WOSCC database. Subsequently, data analysis was conducted using VOSviewer (v1.6.20) and Citespace (v6.4.R4) software.

2.2. Review on Bibliometric Methods

2.2.1. Data Source

The WOSCC database, the data source for this study, covers over 200 disciplines and indexes, more than 18,000 high-impact journals, and numerous conference proceedings and books. With a retrospective coverage of more than a century and over one billion cited references, it offers exceptional disciplinary breadth, high data quality, and complete citation records, and is widely regarded as a comprehensive and authoritative academic resource within the international scholarly community [23,24]. Officially recognized as the authoritative source for impact factors and the Journal Citation Report (JCR), the WOSCC offers reliable citation metrics. Exported in plain text format as "Full Record and Cited References," the database offers a consistent and stable data structure [25]. Furthermore, its seamless integration with tools such as VOSviewer and Citespace enables advanced bibliometric analyses, including co-citation analysis, bibliographic coupling, and thematic similarity analysis. This compatibility ensures not only a robust analytical process but also dependable research outcomes, making it the most suitable choice for this study's methodology.

2.2.2. Data Analysis

VOSviewer is a powerful tool for creating visual bibliometric networks, which performs keyword co-occurrence analysis by examining the frequencies of shared terms across the literature. This process generates a knowledge network map (where node size reflects word frequency, line thickness indicates co-occurrence intensity, and color denotes research theme clusters), thereby offering an intuitive representation of the discipline's inherent knowledge structure [26–28]. Here, we employed VOSviewer software to perform keyword co-occurrence analysis on the retrieved publications, which facilitate the identification of research hotspots of PG RUPs, the overarching framework, and interdisciplinary relationships within the field of PG resource utilization.

Citespace is a specialized tool for analyzing scientific literature and mapping knowledge domains, designed to extract key insights from large datasets and help identify developmental trajectories, research hotspots, and emerging trends in specific fields [29–31]. Therefore, we also employed Citespace software to construct a keyword timeline view of the retrieved literature. Using this visualization, the timeline view organizes data with the *X*-axis representing publication years and the *Y*-axis denoting research clusters. Citespace groups related keywords into colored clusters, with node sizes reflecting keyword frequency and colors indicating temporal attributes (cool tones for older keywords and warm tones for newer ones). The nodes (circles) in the diagram denote keywords, and their sizes reflect the occurrence frequency of the keyword during the corresponding period—the larger the circle, the more popular the keyword was in the previous studies [32,33]. The node colors indicate the temporal attribute of the keywords, following a gradual "cool-to-warm" color scheme (e.g., from purple to yellow): purple or blue generally signifies earlier appearances, while red or yellow indicates recent or the most active occurrences. If a node displays multiple colors simultaneously, it means that the keyword appeared across multiple years. The connecting lines represent co-occurrence relationships between different keywords.

3. Current Status of PRU

3.1. Current Status Globally

The resource utilization of PG remains a global challenge. Currently, the worldwide PG stockpile amounts to approximately 6.0 billion tons (Bt), increasing at an annual rate of 100.0–280.0 Mt [34]; however, the RUR of PG is only around 25% [15]. Significant disparities exist between developed countries and developing countries in PRU, as shown in Table 1. Developed countries initiated relevant research and application relatively early: for instance, Japan and Germany have achieved PG recycling rates of 100% and 95%, respectively [35]. In contrast, most of the countries (excluding China) predominantly rely on stockpiling with a few adopting ocean discharge as a disposal practice; for example, the phosphate industry in Morocco discharges approximately 20 million tons of PG into the Atlantic Ocean annually [36]. The RUR of PG in developing countries is generally below 10%, and the small amounts of PG are mainly applied to agriculture and pilot road projects, such as in Morocco and Brazil [21].

Table 1. Status of resource utilization of PG in typical developed and developing countries.

<table>
<tr><th colspan="2">Globe</th><th rowspan="2">RUR</th><th colspan="2">RUPs and the Description</th><th rowspan="2">Data Source</th></tr>
<tr><th>Country Type</th><th>Name</th><th>RUPs</th><th>Share/Application</th></tr>
<tr><td rowspan="8">Developed countries</td><td rowspan="2">Belgium</td><td rowspan="2">100%</td><td>Building materials</td><td>95%</td><td rowspan="2">[15]</td></tr>
<tr><td>Agriculture</td><td>5%</td></tr>
<tr><td rowspan="3">Japan</td><td rowspan="3">100%</td><td rowspan="2">Building materials</td><td>60%/building gypsum</td><td rowspan="3">[15]</td></tr>
<tr><td>30%/a cement retarder</td></tr>
<tr><td>Chemical industry</td><td>10%/food and medical industries</td></tr>
<tr><td>Germany</td><td>95%</td><td>Building materials</td><td>95%/a cement retarder</td><td>[35]</td></tr>
<tr><td rowspan="2">Finland</td><td rowspan="2"><10%</td><td>Agriculture</td><td><5%</td><td rowspan="2">[21]</td></tr>
<tr><td>Filling material</td><td><5%/road construction</td></tr>
</table>

Table 1. *Cont.*

Globe		RUR	RUPs and the Description		Data Source
Country Type	**Name**		**RUPs**	**Share/Application**	
	Spain	1%	Agriculture	<1%/fertilizers	[37]
				<1%/soil amendments	
	United States	2%	Agriculture	—	[37]
			Filling material	<1%/cement-based backfill	
				<1%/road base materials	
				<1%/backfilling	
Developing countries	Morocco	<10%	Agriculture	—	[38]
			Filling material	pilot road projects	
	Philippines	50%	Building materials	50%/cement production	[38]
			Agriculture	<1%	
	Kazakhstan	<10%	Agriculture	soil conditioner	[38]
	China	61.6%	Building materials	64%	[3,15]
			Chemical industry	10%	
			Agriculture	1%	
			Filling material	1%	
			Supplied and sold externally	24%	

Note: RUR and RUPs stand for PG resource utilization and the pathway, respectively.

3.2. PG Utilization Pathways in China

As the world's largest producer of phosphate fertilizers, China's PG production exceeded 80 Mt as early as 2021, yet its RUR remained relatively low at only 45.6% [39]. Figure 1 provides the annual PG output volumes over the past decade, corresponding utilization amounts, and the application and the distribution region. Driven by the implementation of China's policies related to the resource utilization of PG, the PG RUR exhibited a continuous upward trend during one decade and a half (Figure 1a), with a mean increasing rate of 10.2% annually in the last five years, reaching 61.6% by the end of 2024 (Supplementary Table S3) [3]—for which the building materials, chemical industry, agriculture, filling material, and international supply and sales accounted for 64%, 10%, 1%, 1%, 24% (as shown in Figure 1b) [15], respectively.

PG is primarily distributed in regions abundant in phosphate resources, as shown in Figure 1c, mainly concentrating in five typical provinces—the Hubei, Yunnan, Guizhou, Sichuan, and Anhui provinces—accounting for a total of 90% of the country's PG output [40], with the contribution of the former three provinces exceeded 70% of the total (Figure 1c). In particular, as the largest phosphate chemical industry base, Hubei's PG output was nearly one-third of the national level [18]. Possibly owing to disparities in socioeconomic factors and local policy orientations, the RUR and the RUPs for PG vary by region (Figure 1d), with the RUR of 69% [41], 66% [42] and 93% [43] for Hubei, Yunnan and Guizhou, respectively. Additionally, as the largest PG generator at the province level (with 40% of the total, Figure 1c), Hubei Province's PG also varies by region, which mainly concentrated in Yichang, Jingmen, and Xiangyang city. Benefiting from the "production determined by utilization" policy and the convenient transportation along the Yangtze River Golden Waterway in Hubei, PG is primarily used as a cement retarder and in gypsum-based building materials, accounting for 39.6% and 38.7%, respectively [44]. The Yunnan and Guizhou provinces, located in China's southwestern plateau region of China, face high transportation costs and limited local market capacity in some areas, restricting the large-scale development of building materials applications. These regions primarily focus on mine backfilling and ecological restoration. Specifically, in 2024, mine backfilling accounted for 68.7% of the total utilization in Yunnan Province [45], whereas in Guizhou Province, this proportion reached 52.3% in 2023 [43].

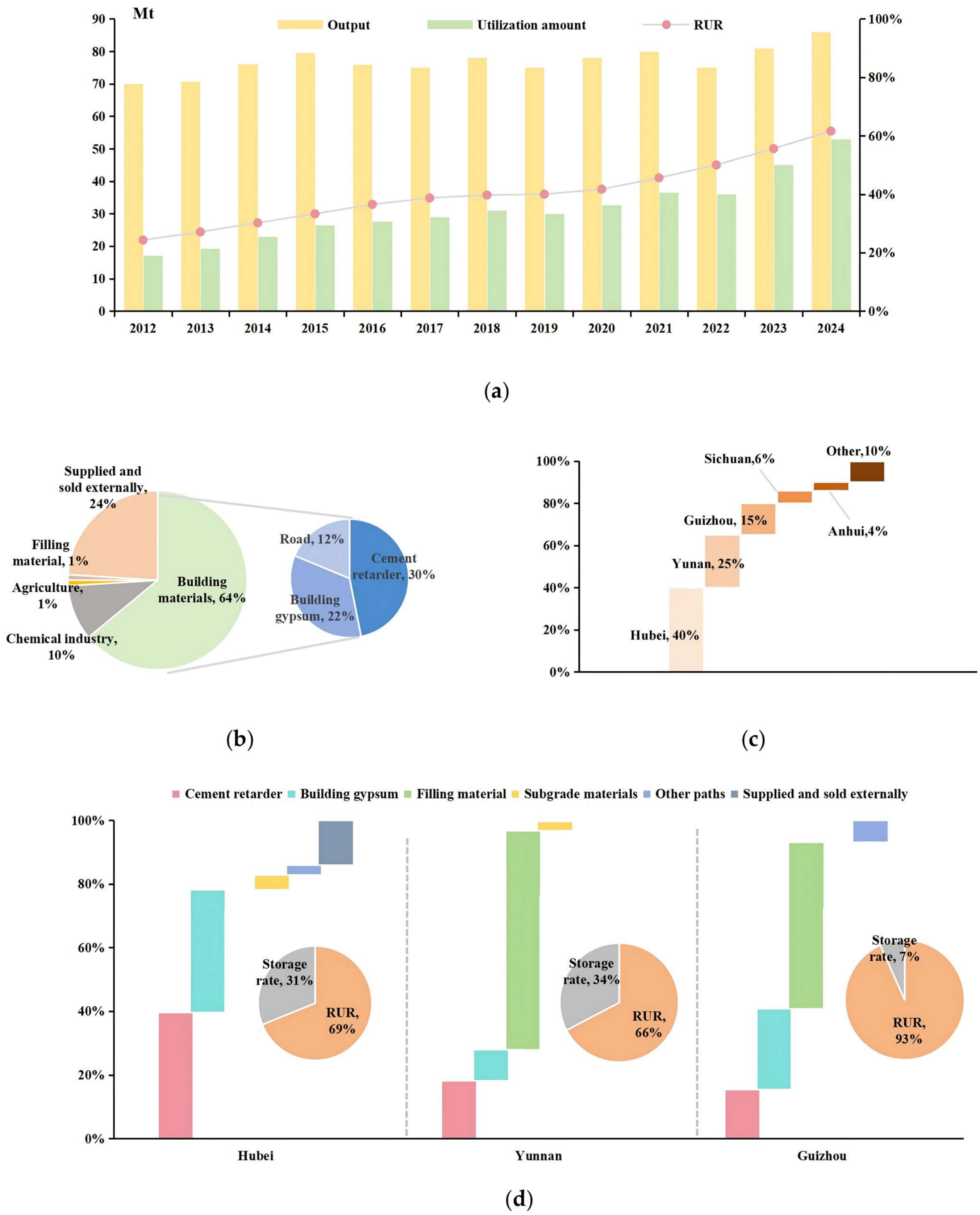

Figure 1. The current status of PRU from 2012 to 2024: (**a**) national-level production, utilization amount, and RUR of PG; (**b**) national-level RUPs for PG and the relative application; (**c**) distribution of PG production across the country; (**d**) main three provinces' (e.g., Hubei and Guizhou, 2023; Yunnan, 2024) RUPs for PG and the specific application.

4. Research Hotspots of Regarding PG RUPs

4.1. Literature Retrieval and Classification Statistics

In this study, the literature retrieval was performed using the WOSCC. The retrieval topics were set as "PG utilization", "PG resource utilization", and "comprehensive utilization of PG", with a ten-year time span from 1 January 2015 to 31 December 2025. A total of 656 valid publications were retrieved, and the full-record data for all retrieved documents were exported to construct the basic dataset for subsequent analysis in this study.

The 656 retrieved publications were classified and statistically analyzed by year; after screening the abstracts, relevant content, and conclusions of the literature, publications without sufficient information related to PRU were excluded. The remaining publications were further classified, and the detailed classification results are provided in Table S4. As shown in Figure 2a, over the past decade, the number of publications on PG resource utilization in the WOSCC has displayed an overall upward trend, which can be divided into two stages: a slow growth period from 2015 to 2018—during which the publication count increased steadily—and a rapid growth period from 2019 to 2025, during which the number of publications multiplied as scholarly attention continued to intensify. In terms of application fields, existing studies are mainly concentrated on building materials, the chemical industry, agriculture, and filling materials. Among these, the growth in publications on building materials has been the most pronounced. In 2025, a total of 196 relevant papers were published, of which 90 focused on building materials, accounting for nearly half (approximately 46%). These included 48 papers on building gypsum, 20 on cement retarders, 8 on road base materials, and 14 on high-value-added products, as illustrated in Figure 2b. These results indicate, over the past decade, that domestic and international research on PRU has consistently revolved around the building materials field as the core hotspots, and that building gypsum and cement retarders, which are relatively highly technologically advanced, constitute the primary research directions within this field.

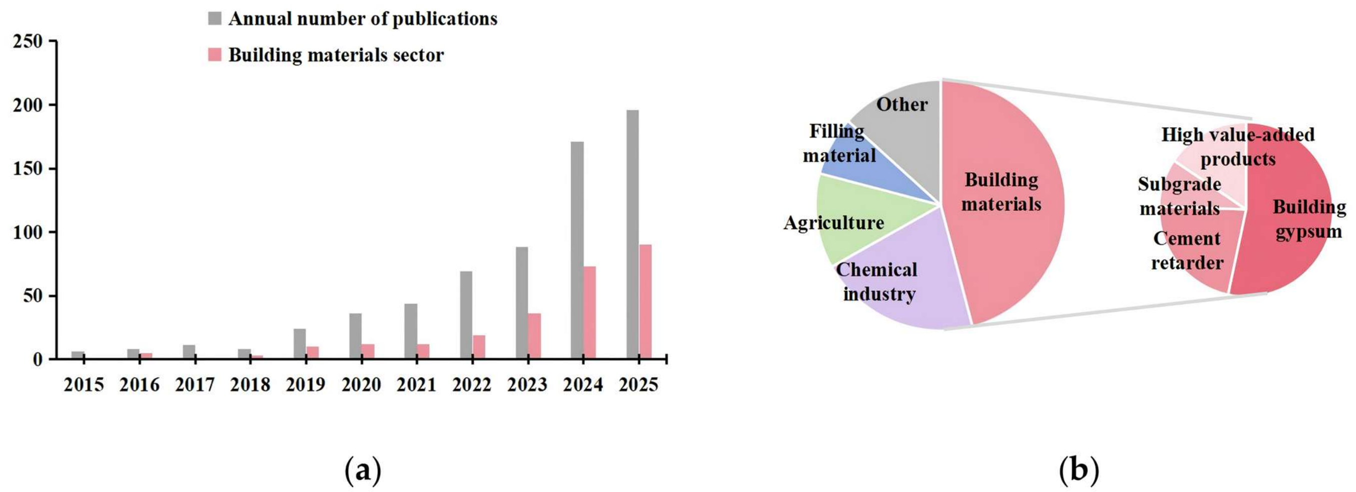

Figure 2. Analysis of the literature on the resource utilization of PG during 2015~2025: (**a**) annual number of publications on the PRU and building materials sector over time, and (**b**) proportional distribution of PRU literature by pathway and the application of building materials in 2025.

4.2. Keyword Co-Occurrence Analysis

The literature was exported in "Tab delimited file" format, and imported into VOSviewer to generate visualization maps based on Web of Science data for keyword co-occurrence analysis. All keywords were selected, and the threshold for keyword occurrence frequency was set to no less than three times. The procedure employed is shown in

Figure S1. The threshold of keyword occurrence frequency was set to no less than 3, and a total of 405 valid keywords were screened out (Table S5). After irrelevant keywords were removed, 78 keywords highly related to PG resource utilization were obtained (Table S6) and further classified into four categories according to research fields, including 34 keywords for building materials, 20 for chemical engineering, 18 for agriculture, and 6 for filling materials. A keyword co-occurrence network map was constructed based on these 78 core keywords.

Figure 3 illustrates the keyword co-occurrence network map of PRU. In the map, each node represents an individual keyword, and the node size indicates the frequency with which the corresponding keyword occurs. The connections between nodes reflect the co-occurrence relationships among keywords, and the thickness of the connections represents the correlation strength between paired keywords. Clusters with different colors correspond to different research application fields [46]. Specifically, the red, purple, green, and blue clusters represent the fields of building materials, chemical engineering, agriculture, and filling materials, respectively. High-frequency keywords can effectively reflect the research hotspots and development trends of a given field. The network map shows that keywords in the building materials field account for more than half of all large nodes with relatively larger node sizes. This demonstrates that the building materials field has been the core research hotspot of PRU in the past decade. Given the vast historical stockpiles and the persistently low RUR, the building materials sector—by virtue of its ultra-large consumption capacity and inherent advantages in terms of large-scale solid waste disposal—has emerged as the most direct pathway for rapidly consuming PG and alleviating stockpile pressure in the short term. This has further accelerated the development of PRU in the field of building materials. This study not only confirms the effectiveness and generalizability of this utilization pathway but also indicates that the building materials route will remain a key direction for eliminating stockpile-related pollution and achieving solid-waste-resource utilization in the future.

4.3. Timeline View of Keywords

The retrieved literature was exported in the "Plain text fil" format and subsequently imported into CiteSpace, with the WOSCC selected as the data source. The analysis period was set from 2015 to 2025, and "Keywords" was selected as the node type for visualization analysis. The keyword timeline view was generated by optimizing the labels, links, and annotation settings. The details of the procedure are provided in Figure S2.

As shown in Figure 4, the emergence time, developmental trends, popularity changes, and interrelationships of each cluster in PG resource utilization research can be clearly presented. What is special, is that the keyword timeline map generated using CiteSpace illustrates the evolution of research topics related to PG from 2015 to 2025. The resulting network consists of 356 nodes and 708 links, with a network density of 0.0112. Clustering performance was evaluated using the Modularity Q and weighted mean silhouette S values. The Modularity Q value was 0.7568, substantially exceeding the commonly accepted threshold of 0.3, while the weighted mean silhouette value reached 0.8868, approaching 1. These results indicate that the identified clusters exhibit well-defined boundaries and strong internal thematic consistency, demonstrating the reliability of the clustering results.

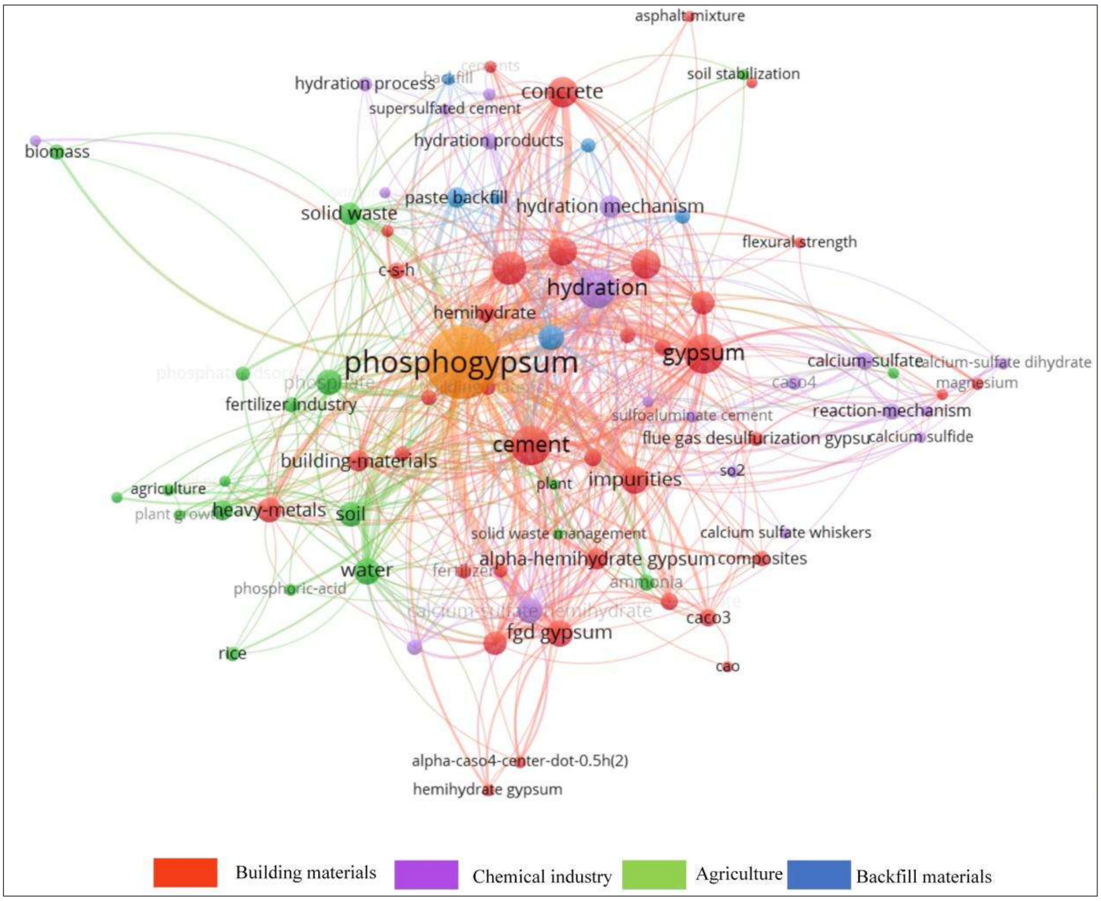

Figure 3. VOSviewer keyword co-occurrence analysis network map: nodes represent keywords, with size indicating frequency; links denote co-occurrence, with thickness reflecting association strength; clusters of different colors correspond to distinct research areas.

A total of 16 research clusters (Cluster #0 to Cluster #15) were identified along the timeline from 2015 to 2025. Among them, Cluster #0 (mechanical properties) was the largest cluster, accounting for 96% of the literature analyzed, highlighting the dominant role of PG-based building materials research in this field. The size of each node represents the frequency of keyword occurrence and its betweenness centrality, while node colors indicate the peak activity period of corresponding keywords. The connections between keywords across different clusters and time periods represent co-occurrence relationships, and the long-span links reflect the continuity and interdisciplinary integration of research themes. Overall, the clustering results reveal that PG-related research can be primarily categorized into four research areas: building materials, chemical industry, agriculture, and filling materials. The building materials category includes Clusters #0 (mechanical properties), #1 (compressive strength), #2 (calcium carbonate), #5 (fly ash), #7 (alpha-hemihydrate gypsum), #12 (industrial solid waste), and #14 (Bayer red mud). The chemical industry category comprises Clusters #6 (reaction mechanisms), #8 (carbonation product), and #11 (crystal morphology), while the agriculture category includes Clusters #9 (adsorption) and #10 (heavy metals). The filling materials category corresponds to Cluster #3 (drilling cuttings). In addition, several clusters, including #4 (behavior), #13 (waste valorization), and #15 (resource utilization), represent broader research topics without being restricted to a specific application direction. Among these research areas, building materials represent the most prominent research direction, exhibiting the highest concentration of keywords and the strongest temporal continuity. In particular, Clusters #0, #1, and #2 are closely associated with the performance evaluation for construction materials. Furthermore, high-frequency keywords with large node sizes, such as “cement”, “hemihydrate phosphogypsum”, and “compressive strength”, further demonstrate that the application of PG in cement production and building materials has remained a major research focus throughout the period investigated.

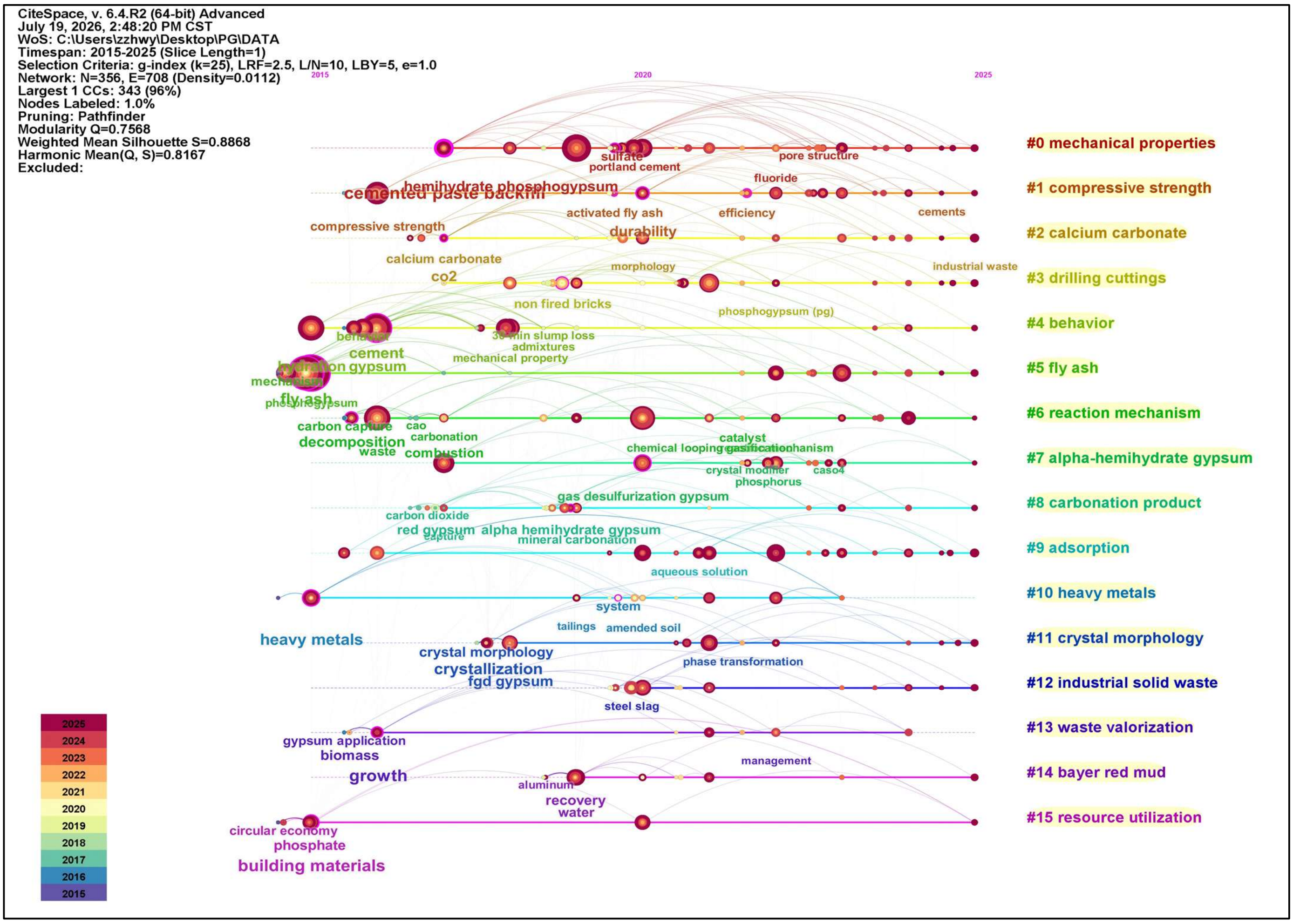

Figure 4. Timeline view of keywords over the 2015~2025 period: In this 2015–2025 PG timeline, node denotes size/color for frequency/year, links denote co-occurrence, and clusters mean #0–#15 for themes. The horizontal axis reveals evolutionary trends.

From 2015 to 2025, research on PG-based building materials underwent a progressive transition. During the early stage (2015–2018), studies primarily focused on fundamental physicochemical properties and application feasibility. Keywords such as “phosphogypsum”, “cement”, and “concrete” were frequently observed, indicating that researchers mainly investigated the feasibility of replacing natural gypsum with PG in cement production and evaluated its effects on basic material properties, including strength and durability. During the intermediate stage (2019–2022), research gradually shifted toward performance enhancement and synergistic utilization. Keywords such as “fly ash”, “calcium carbonate”, and “industrial waste” became increasingly prominent. In contrast with earlier studies focusing on individual material systems, in this period, researchers explored the combined utilization of PG with other industrial solid wastes (e.g., fly ash) to improve the mechanical properties and microstructural characteristics of building materials through compositional optimization. More recently (2023–2025), PRU research has increasingly focused on high-value and advanced applications. The strengthened associations among keywords such as “alpha-hemihydrate gypsum”, “circular economy”, and “building materials" indicate a gradual shift from conventional bulk utilization toward the development of high-value-added products.

5. Analysis of the PRU

5.1. Framework of the RUPs for PG

On the basis of the aforementioned literature review and bibliometric analysis, we can glean that the current resource utilization of PG mainly covers four technical pathways: building materials (Pathway 1), agriculture (Pathway 2), chemical industry (Pathway 3) and backfill materials (Pathway 4) [15]. Figure 5 provides the technical framework of PG RUPs, e.g., the PG source, harmless treatment (pretreatment), PG RUPs, and the specific application. Pretreatment technologies can be employed to process the raw PG, thereby improving its physicochemical properties, reducing impurity content, and making it more suitable for subsequent resource utilization [47]. Pretreatments were mainly divided into three categories according to the technical characteristics and the application scenarios: physical, chemical, and thermal treatment [18,48]. Detailed information is provided in Table S7.

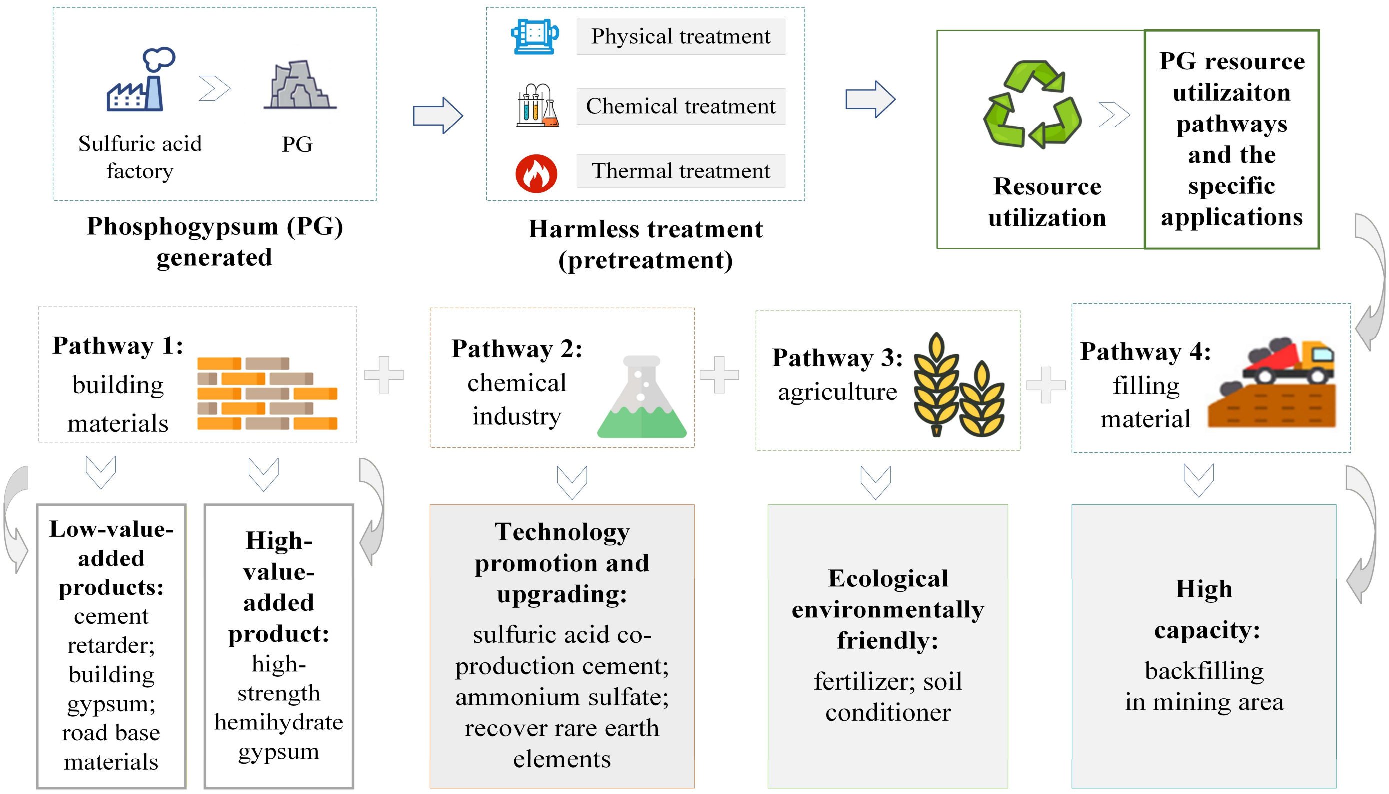

Figure 5. Technical framework of the RUPs for PG and the applications: The upper panel presents the major sources of phosphogypsum generation, the middle panel summarizes four resource utilization pathways, and the lower panel details the specific applications within each pathway.

In terms of the RUPs for PG, the building materials route has become the most extensively investigated and rapidly industrialized research hotspot because of its large-scale PG consumption capacity and relatively mature technical system. To leverage the valuable elements such as calcium and silicon presented in PG, various construction materials are produced through pozzolanic reactions triggered in an alkaline environment by incorporating cement or coupling it with other solid wastes [49], such as building gypsum, cement retarders, subgrade materials and other high-value-added products [50]. In the chemical industry, PG is primarily utilized for producing sulfuric acid—which is co-produced with cement—and ammonium sulfate (a fertilizer raw material), as well as for recovering rare earth elements [51,52]. In the agricultural sector, PG is primarily used for the production of fertilizers and soil amendments [53].

Accordingly, this study systematically analyzes the four pathways from three dimensions: technical characteristics, economic feasibility, and environmental benefits. We aim to comprehensively evaluate the techno-economic performance and green low-carbon potential of each utilization pathway, and further provide a scientific reference for the formulation of efficient and sustainable PG resource utilization strategies.

5.2. Research Hotspots Regarding the RUPs of PG

Building gypsum. The conversion of PG into β-hemihydrate gypsum for architectural plaster has matured into one of China's most well-established and fully industrialized routes for PG valorization, accounting for 22% of the nation's total PG recycling volume [15]. Derived PG plaster products, including gypsum powder, plasterboards, and gypsum blocks, serve as mainstream bulk construction materials. This pathway constitutes a core strategy for stockpiled PG abatement and underpins the waste minimization, detoxification and resource recovery regarding industrial solid wastes. Industrial-scale thermal dehydration of dihydrate PG into hemihydrate phases is predominantly realized via pan calciners and rotary kilns, enabling full conversion of waste PG into usable construction feedstock [54]. Han et al. optimized the raw material formulation for PG through SPSSv19.0-aided data fitting and a holistic material balance method. The resultant β-hemihydrate gypsum satisfied all mechanical and physicochemical benchmarks defined by national standards for construction plasters, with a manufacturing cost of CNY 164.76 per ton—markedly lower than the market price of natural gypsum (CNY 350–600/t)—and thus delivers substantial profit margins [55]. Meanwhile, Hu et al. reported that the PG blocks and other PG-based building materials, when used as substitutes for conventional concrete building materials, can achieve significant environmental benefits, with a maximum of 26% [56]. The production of building gypsum from PG has entered a phase of large-scale industrial application, with several leading domestic enterprises successively commissioning large-scale production lines, with an annual output ranging from 1 to 30 million m^2/year [57,58].

Cement retarder. The calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) content in PG exceeds 85% [59], substantially exceeding the dihydrate gypsum content of natural gypsum, which rendering PG a high-performance alternative cement retarder. Currently, approximately 30% of domestically generated PG is deployed for this purpose [15]. Li et al. devised a composite stabilization protocol incorporating 6 wt.% carbide slag and 4 wt.% circulating fluidized bed fly ash. After a controlled aging curing stage, the stabilized PG exhibited drastically reduced soluble phosphorus and fluoride fractions; leaching tests confirmed all heavy metal concentrations complied with the thresholds outlined in GB 5085.3 [10], reflecting well-contained environmental hazards [60]. Economic assessments conducted by Yuan et al. verified that complete substitution of natural gypsum with modified PG reduces production expenditure by CNY 19.80 per ton of finished cement. For a plant with an annual output of 100,000 tons of retarded cement, this cost reduction translates to an annual direct economic surplus exceeding CNY 2 million, demonstrating synergistic gains in production cost control, operational efficiency and pollution mitigation [61]. Our recent study based on the LCA method revealed that the cement retarder route yielded the most significant environmental benefits relative to the other three pathways (including PG stockpiling, sulfuric acid coproduction cement, and ecological restoration), with a net emission reduction of up to 2.1 t CO_2eq per ton of PG [62]. Currently, the production of PG-based cement retarder has achieved industrial implementation domestically, owing to the high technical maturity, with multiple enterprises having successively commissioned and implemented their production lines, with a range of 0.2 to 1.0 Mt/year [58].

Subgrade materials. Performance-compliant pavement subbase mixtures can be fabricated by blending PG with supplementary cementitious materials including fly ash, lime and ordinary Portland cement, where mechanical hardening arises from continuous hydration reactions. Laboratory mix designs reported by Dutta [63] and Zmemla [64] both attained a 28 day compressive strength of 2.2 MPa, meeting fundamental mechanical requirements for road base layers. Supplementary environmental leaching assays conducted by Yang et al. [65] demonstrated that composite mixtures incorporating 15 wt.% pretreated PG were free of cadmium, arsenic, and nickel, while concentrations of chromium, manganese, zinc, and copper remained below both industrial wastewater discharge criteria and Class III groundwater quality limits, indicating negligible risks of soil and groundwater contamination along highway corridors. Despite these promising laboratory outcomes, large-scale field implementation of this technology remains constrained by intricate pretreatment workflows, unresolved long-term heavy metal leaching uncertainties, an incomplete standardized specification framework, and low market acceptance among construction stakeholders. Further systematic validation of its whole-life economic performance and long-term environmental safety is required before its full comprehensive benefits can be unlocked.

High-value-added products. High-value PG derivatives, chiefly α-hemihydrate gypsum and calcium sulfate whiskers, integrate superior mechanical performance with inherent environmental benignity. Their compressive strength ranges from 20 to 50 MPa, vastly outperforming conventional β-hemihydrate plaster, endowing them with wide application potential in precision casting, premium construction components, art craftwork and aerospace manufacturing [66,67]. Liu et al. adopted a combined flotation and atmospheric salt recrystallization route to synthesize α-hemihydrate gypsum meeting the α30 grade specification, with impurity indices conforming to Grade I PG classification standards [68]. Furthermore, this technology demonstrated considerable carbon mitigation potential. According to Zeng et al., the monetized environmental benefits associated with PG utilization were estimated at approximately USD 8.0 per tonne of PG utilized [62]. However, the sustainable industrial uptake of such high-value PG materials is hindered by exorbitant production costs and narrow profit margins, alongside persistent gaps in fundamental research and scalable application technologies [69]. To reconcile economic growth with environmental stewardship, novel low-cost, clean manufacturing workflows must be developed to overcome prevailing profitability bottlenecks, thereby facilitating large-scale industrial deployment of high-value PG recycling and elevating overall circular economy benefits.

5.3. Other Pathways

5.3.1. Chemical Industry

Sulfuric acid co-production cement. Producing sulfuric acid co-production cement from PG involves mixing PG with auxiliary materials such as coke and clay, followed by a reduction decomposition reaction at high temperatures ranging from 1200 to 1400 °C. The core reaction process is as follows:

$$CaSO_4 + 2C \xrightarrow{\Delta} CaS + 2CO_2 \uparrow \quad (1)$$

$$4CaS + 5O_2 \xrightarrow{\Delta} 2CaO + 4SO_2 \uparrow \quad (2)$$

$$2SO_2 + O_2 \rightarrow 2SO_3 \rightarrow H_2SO_4 \quad (3)$$

The solid product, CaO, is utilized for cement clinker production, while the gaseous product, SO_2, is converted into sulfuric acid, which can serve as a feedstock for fertilizer manufacture [70,71]. This technique not only conserves natural mineral resources but also enables the large-scale consumption of PG, effectively alleviating stockpile pressures. Moreover, compared with conventional cement production routes, it directly reduces CO_2 emissions by approximately 0.15 t per tonne of cement clinker, demonstrating significant low-carbon benefits [72]. However, the process is subject to multiple constraints: the high reaction temperature entails substantial energy consumption and persistently high production costs, and the release of gaseous species such as CO_2 and SO_2 during the reaction poses a risk of secondary pollution if tail-gas purification is inadequate. Furthermore, the capital investment is considerable—a production line with an annual processing capacity of 1 million tonnes of PG requires a total investment of approximately CNY 500 million. The economic viability of the project is also highly sensitive to fluctuations in the market price of sulfuric acid; economic estimates indicate that when the price of sulfuric acid falls below CNY 200/t, an enterprise would incur losses [73]. Owing to these techno-economic bottlenecks, the process has not yet found large-scale industrial application to date.

Ammonium sulfate. The process of producing ammonium sulfate from PG is based on the principle of a double decomposition (metathesis) reaction, using PG and ammonium carbonate as raw materials. The core reaction is as follows:

$$CaSO_4 + (NH_4)2CO_3 \rightarrow CaCO_3 \downarrow + (NH_4)SO_4 \quad (4)$$

Yang et al. [74] employed PG for CO_2 mineralization to co-produce ammonium sulfate. Their study demonstrated that each tonne of PG can mineralize 0.25 t of CO_2, while simultaneously generating 0.78 t of ammonium sulfate and 0.58 t of calcium carbonate, thereby achieving both CO_2 emission reduction and the resourceful recycling of industrial solid waste [75]. However, the economic viability of this process remains suboptimal. Statistical data indicate that producing 1 t of ammonium sulfate requires approximately 250 kg of liquid ammonia. Based on a liquid ammonia price of 2500 CNY/t, the raw material cost alone amounts to 625 CNY/t, whereas the market price of the main product (ammonium sulfate) is approximately 480 CNY/t, so the feedstock cost already exceeds the product revenue. When additional expenses such as utilities, labor, and equipment depreciation are factored in, the operation would incur a net loss. Furthermore, the process imposes stringent pretreatment requirements on PG: a single pretreatment method is generally insufficient, and a combined approach involving water washing and acid leaching is typically adopted; this process can achieve an impurity removal rate exceeding 90% [75]. Nevertheless, improper control of the water-washing step may lead to secondary pollution issues.

Recycling of rare-earth elements. Rare-earth elements (REEs) are globally critical strategic resources, and their significant enrichment in PG, with a maximum content exceeding 2000 mg/kg [76], renders PG a highly promising secondary resource for REEs. Currently, the technology for extracting REEs from PG remains immature, and the methods employed have various drawbacks. Overall, they can be divided into two main categories: acid leaching and bioleaching [77]. Acid leaching encompasses two systems: inorganic strong acids and organic weak acids. Inorganic acid leaching offers advantages such as high leaching efficiency and a straightforward process, but the high acidity of the leachate poses a risk of secondary pollution. Organic acid leaching can improve selectivity to some extent; however, it involves higher reagent costs, and residual organic solvents increase the difficulty of subsequent utilization of the leaching residue and may cause environmental problems [78]. Bioleaching features simple equipment, low energy consumption, and reduced pollutant generation, yet its slow leaching rate severely restricts its industrial application [79]. Moreover, the economic benefits of this process remain unsatisfactory; scenario analysis by Adam Smerigan et al. [80] pointed out that economic feasibility is achievable only when the processing capacity exceeds 100,000 kg/h and the REEs content in PG is higher than 0.5 wt%, whereas numerous low-grade sources (0.02–0.1 wt% REEs) remain unprofitable under current conditions due to excessive acid consumption and neutralization costs. Overall, the extraction of REEs from PG involves multiple steps, lengthy processes, and high costs, resulting in poor economic viability. The industrialization of enriching and extracting REEs from associated rare-earth phosphate ores still faces considerable challenges. Therefore, developing novel leaching agents that are efficient, economical, and environmentally compatible—along with exploring pathways for the comprehensive high-value utilization of all PG components—represents a key direction for future research.

5.3.2. Agriculture

Fertilizer. PG is rich in essential macronutrients for plant growth, such as calcium and sulfur, as well as micronutrients including iron, magnesium, and zinc. It can effectively supplement soil nutrients and promote crop growth and development [81]. Previous studies have demonstrated that PG application exerts positive effects on improving crop yield and quality. In a field experiment, Li et al. [40] found that applying an additional 2100 $kg{\cdot}hm^{-2}$ of PG on top of conventional fertilization increased wheat yield by up to 37.7%, while also reducing CO_2 emissions [82]. Despite the advantages of PG in agricultural resource utilization, such as abundant supply and low costs, its large-scale adoption remains limited. The primary limiting factor is the potential risk posed by the heavy metals and radioactive elements present in PG, which may threaten soil quality, crop safety, and human health. A study by Wang et al. on the application of PG as an agriculture fertilizer revealed that PG poses a leaching risk for multiple heavy metals and fluorine [13]. As shown in Table S2, they tested four typical PG samples from the agricultural soil and detected the seven types of typical heavy metals—namely, Pb, Cr, Cd, As, Hg, Zn, and Cu—and the leaching concentrations exceeded the Class III limits of the standard for groundwater quality (GB/T 14848-2017); furthermore, the concentrations of Hg, Cd, Pb, Ni and Cr even exceeded the Class IV-V standards. Therefore, to promote the safe utilization of PG in agriculture, it is crucial to rigorously control its impurity risks and to adopt scientifically sound application strategies.

Soil conditioner. PG exerts multiple positive effects on agricultural soil amelioration. On the one hand, its acidic nature can effectively neutralize alkaline soils and regulate soil pH, while simultaneously reducing soil salinity [83–85]. On the other hand, PG supplies secondary nutrients, such as calcium and sulfur, along with trace amounts of phosphorus, thereby improving soil fertility [86]. In a field study, Wang et al. [87] reported that the combined application of organic fertilizer and PG in saline–alkali soil planted with kidney bean increased the bean yield by 91.9%. Elloumi et al. demonstrated that a low application rate (2.5%) of PG, without inhibiting crop growth, significantly elevated chlorophyll and carotenoid contents in sunflower leaves and supplemented available calcium and phosphorus, thus contributing to reduced fertilizer inputs and lower production costs [88]. However, the agricultural use of PG also poses potential risks, as heavy metals and radionuclides present in the material may be gradually released, threatening environmental quality and food safety. Yuan determined the total heavy metal concentrations in leachate from a PG-based plant-growing substrate and found that the levels of Fe, Mn, Cu, Zn, and Pb exceeded the risk screening values for contaminated agricultural soils [89]. Comprehensive analysis indicates that although modified PG can enhance environmental benefits and significantly reduce production costs in agricultural applications, the modification and purification processes are technically complex and may lead to heavy metal enrichment, posing a hazard to human health. These drawbacks severely constrain its large-scale utilization in agriculture.

5.3.3. Filling Material

The goafs in China's mining areas are enormous in scale, with a total volume exceeding 25 billion cubic meters. The preparation of backfill materials from harmlessly treated PG can not only effectively alleviate the pressure of PG stockpile disposal, but also substantially reduce the high cost of traditional cement-based backfill materials, thereby simultaneously addressing two major global challenges [90]. PG backfill material is primarily composed of PG, supplemented with cementitious materials and admixtures (e.g., quicklime and steel slag). After being mixed with water to form a homogeneous slurry, it is pumped into underground goafs, where it consolidates and hardens to support the roof and control surface subsidence, thus ensuring safe and efficient mining extraction [91]. Backfilling disposal represents an important approach for the large-scale utilization of PG and is of positive significance for the green transformation of the phosphorus chemical industry and the sustainable development of mining operations [92]. However, the presence of hazardous elements (such as heavy metals and fluorides) in PG constitutes a key bottleneck restricting its widespread application in backfilling. Panke Zhang et al. clearly pointed out that when PG is used for mine backfilling, its environmental risks primarily arise from the leaching behavior of pollutants (TP, F-, Cr (VI), As, Mn, and Se), and there remains a risk of long-term release if environmental conditions (e.g., acidification of mine water) change [93]. In summary, although PG backfilling technology offers significant dual environmental and economic advantages, its promotion must be grounded in the solidification/stabilization treatment of hazardous elements, optimization of backfill mix proportions and processes, and the establishment of a full life-cycle environmental monitoring system, so that large-scale application can be achieved while ensuring ecological safety.

5.4. Development Trend of PRU

In the present study, combined with the literature review and bibliometric methods, building materials utilization is identified as the dominant research hotspot in this field (see Table S8 and Figures 3–5 for details). Figure 6 concludes the comparative result between the hotspot and other pathways according to the four aspects mentioned above. By contrast, building materials involve high technical maturity (well-established industrial chain), high economic benefit and environmental benefit (carbon mitigation), as well as low environmental risk—especially for the building gypsum and cement retarder—making it the most reliable route for stockpile abatement. Accordingly, the building materials pathway will remain the core direction of domestic PRU development in the long term.

The future upgrading of PG building materials utilization will focus on two strategic directions. First, to optimize and upgrade product structures, transforming the industrial product system from low-value bulk products (e.g., β-hemihydrate gypsum and cement retarder) to high-value refined products (e.g., α-hemihydrate gypsum and calcium sulfate whiskers) to improve the overall industrial added value. Second, to improve product performance and environmental safety through advanced impurity removal technologies. Developing low-cost purification processes and energy-efficient calcination techniques is essential to break through the current profitability bottlenecks while ensuring stable product quality, thereby facilitating the high-quality and sustainable development of the PG building materials industry.

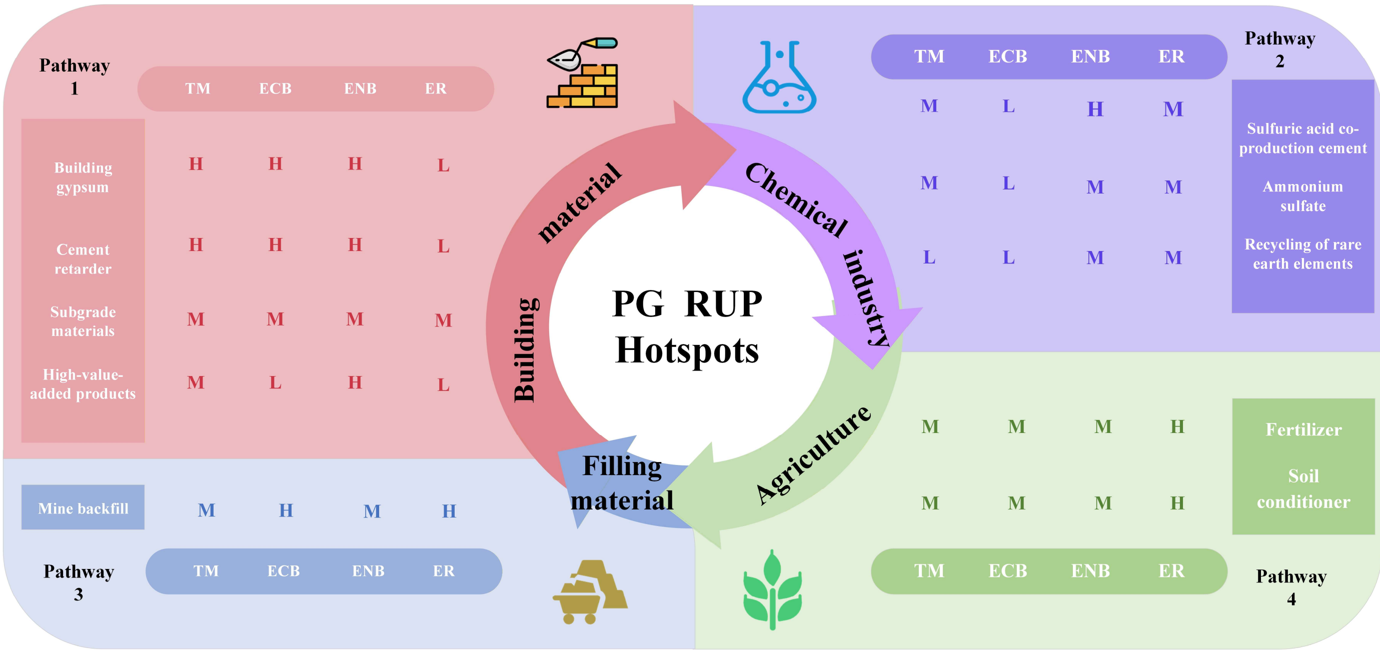

Figure 6. Comparison of PG RUPs based on technical maturity, economic benefit and environmental issue. Note: H, M, and L denote high, medium, and low, respectively; TM, ECB, ENB and ER denote technical maturity (High/medium/low, large-scale utilization/pilot/lab-scale application), economic benefit, environmental benefit (generally carbon mitigation), and environmental risk, respectively; the quantification of latter three indexes was based on the comparative result between the building materials and other RUPs. The information presented in this figure was collected from previous studies [13,56–63,69,70,73,74,76,78,81,90,91,94], and the corresponding data are also provided in Table S8.

In summary, the future development trends are specifically characterized by (1) building materials as the core pillar for large-scale consumption, continuously promoting the upgrade from low-value to high-value-added products; (2) synergistic utilization with other solid wastes (e.g., fly ash, steel slag, carbide slag) to enhance overall benefits and product performance; (3) the chemical industry and high-value extraction serving as strategic supplements to support long-term resource security; and (4) agriculture and backfill serving as supplementary pathways for specific scenarios. Overall, domestic PRU has gradually formed a development pattern of "building-materials-driven, diversified synergistic development."

5.5. Policy Implication

5.5.1. Existing Policy Systems and Standards

As one of the predominant bulk industrial solid wastes, the treatment and disposal of PG have attracted considerable attention from governmental authorities at both the national and local levels. This urgency is particularly pronounced in the Yangtze River Economic Belt, which serves as the primary PG-producing region in China, where intensified efforts to address PG management are imperative for the successful advancement of national ecological civilization construction and the sustainable development of the Yangtze River Economic Belt initiative. In recent years, a series of policies and regulations have been successively promulgated by relevant authorities at both national and sub-national levels, providing clear strategic guidance for the resource utilization of PG. These policy instruments are systematically summarized in Table 2.

Table 2. Policies and regulations related to the PG RUPs in the past five years.

Scale	Issuing Authority	Issuing Time	Policies/Regulations	Description	Data Source
National	NDRC	March 2021	Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste during the 14th Five-Year Plan Period	Efficient and green utilization of by-product gypsum, with a goal of 50% of utilization rate by 2025	[94]
	SC	October 2021	Action Plan for Carbon Dioxide Peaking by 2030	High-value utilization: soil improvement, underground backfilling, roadbed construction	[95]
	MEE	December 2021	Work Plan for the Construction of "Zero-Waste Cities" during the 14th Five-Year Plan Period	Establishing about 100 "zero-waste cities" by 2025 and highlighting PG utilization in green building materials, road construction, etc.	[96]
	MIIT	January 2024	Implementation Plan for Efficient and High-Value Utilization of PG Resources	Achieving 100% of harmless disposal of newly generated PG and historical stockpile reduction	[97]
	NDRC	April 2024	Action Plan for Comprehensive Utilization of PG	Obtaining 65% of Comprehensive utilization of PG by 2026 and building 10 specialized industrial bases in typical provinces	[17]
	MEE	March 2025	Technical Specification for Pollution Control of PG and Harmless Storage	Specify pollution control requirements for the utilization and storage of PG	[98]
Local	HPPGGO	October 2023	Implementation Plan for the Transformation and Upgrading of Guizhou's Chemical Industry (2023–2025)	To cultivate the fine phosphorus chemical industry and drive industrial transformation and upgrading	[99]
	GPPGGO	May 2024	Guizhou Provincial Opinions on Comprehensively Strengthening the Comprehensive Utilization of PG and Promoting Green Development of the Phosphorus Chemical Industry	To prevent new stock or reduce existing stock; promote green, efficient, high-value, and large-scale utilization of PG	[100]
	DEITSP	December 2024	Implementation Plan for Comprehensive Utilization of PG in Sichuan Province	Improving the utilization level of PG and harmless disposal rate, and building 2–3 specialized industrial bases.	[101]

Note: The abbreviations in this table are all names of government agencies. For details, see Abbreviations.

5.5.2. Policies Recommendations

A critical review of the policies (Table 2) enacted over the past five years reveals that the ambitious utilization targets for PG were established step by step, e.g., 50% RUR by 2025 [94], compared to 65% by 2026 [17], and accompanied by the achievement of a 100% of harmless disposal rate for newly generated PG [97]. These policies also help in constructing a foundational framework for pollution control. However, several inherent deficiencies persist that severely impede the high-value and large-scale application of PG, particularly within the building materials sector. Correspondingly, we gave the policy recommendations according to the policy deficiencies, and this was concluded as follows:

Recommend a quantitative evaluation system: Current policies reflect a "quantity-over-quality" orientation, and lack specific tiered incentive mechanisms to distinguish between low-value bulk applications (e.g., conventional basic cement retarders) and high-value and high-performance products (e.g., α-hemihydrate gypsum and calcium sulfate whiskers). To stimulate technological innovation within the building materials sector and propel the industry's transition from "bulk consumption" to "tiered high-value utilization", we therefore recommend a quantitative evaluation system. Instead of employing a single "utilization rate" metric, a three-tiered utilization index should be adopted, differentiating among (Tier 1) bulk fillers/retarders, (Tier 2) standard building gypsum, and (Tier 3) high-value-added products (α-hemihydrate gypsum and whiskers). A progressive subsidy and tax rebate mechanism should be linked to these tiers, explicitly rewarding enterprises that produce Tier 3 materials.

Establishing sound standard system: Current policies exhibit a pronounced absence of stringent, application-specific pollutant limit values for heavy metals and fluorides tailored to end-use scenarios (e.g., indoor applications, subgrade applications), which fails to provide end-users (e.g., construction firms, real estate developers) with absolute assurances regarding the long-term safety and reliability of PG-based panels, blocks, and subgrade materials. This regulatory ambiguity fuels market skepticism and severely restricts the large-scale substitution of natural gypsum and cement clinker. Thereby, we suggest a unified, performance-based national standard system for PG building materials, which should incorporate clear and mandatory classifications for environmental safety (e.g., Class I for indoor applications, Class II for outdoor/subgrade applications), accompanied by stringent leaching toxicity thresholds, effectively facilitating the large-scale substitution of natural gypsum and cement clinker.

Implementing mandatory "green procurement" policies: Owing to the shortage of robust demand-side policies, such as mandatory "green procurement" standards for public infrastructure projects, a closed industrial loop linking solid waste generation and end-user consumption cannot be established. Moreover, effective cross-sector coordination mechanisms remain weak. To build a stable and guaranteed market for high-quality PG-based building materials, we therefore recommend implementing mandatory "green procurement", supported by cross-sector coordination mechanisms, among the PG chemical industry, building materials manufacturing industry, and downstream construction sector.

How can format the implementable policies mentioned above be formatted? This may require phased collaborative efforts from multiple stakeholders. Taking "green procurement" policies as an example, shown in Figure 7. First of all, clarifying the responsible entities (including leading department, coordinating members, working group, etc.), further set short-, medium- and long-term targets. Finally, implementing this policy in phases according to the respective target. This includes (1) building a cross-departmental data-sharing platform that connects PG production, product sales, and engineering bidding; (2) implementing binding "green procurement policies" across all publicly funded construction projects (e.g., subsidized affordable housing, municipal infrastructure, and highway projects), mandating a minimum usage percentage (e.g., 50%, a target for PG resource utilization mentioned above) of PG-based building materials (such as gypsum boards, partition blocks, and pavement base materials); and (3) incorporating the performance of PG-related green procurement into the credit evaluation system for construction enterprises and phosphorus chemical enterprises.

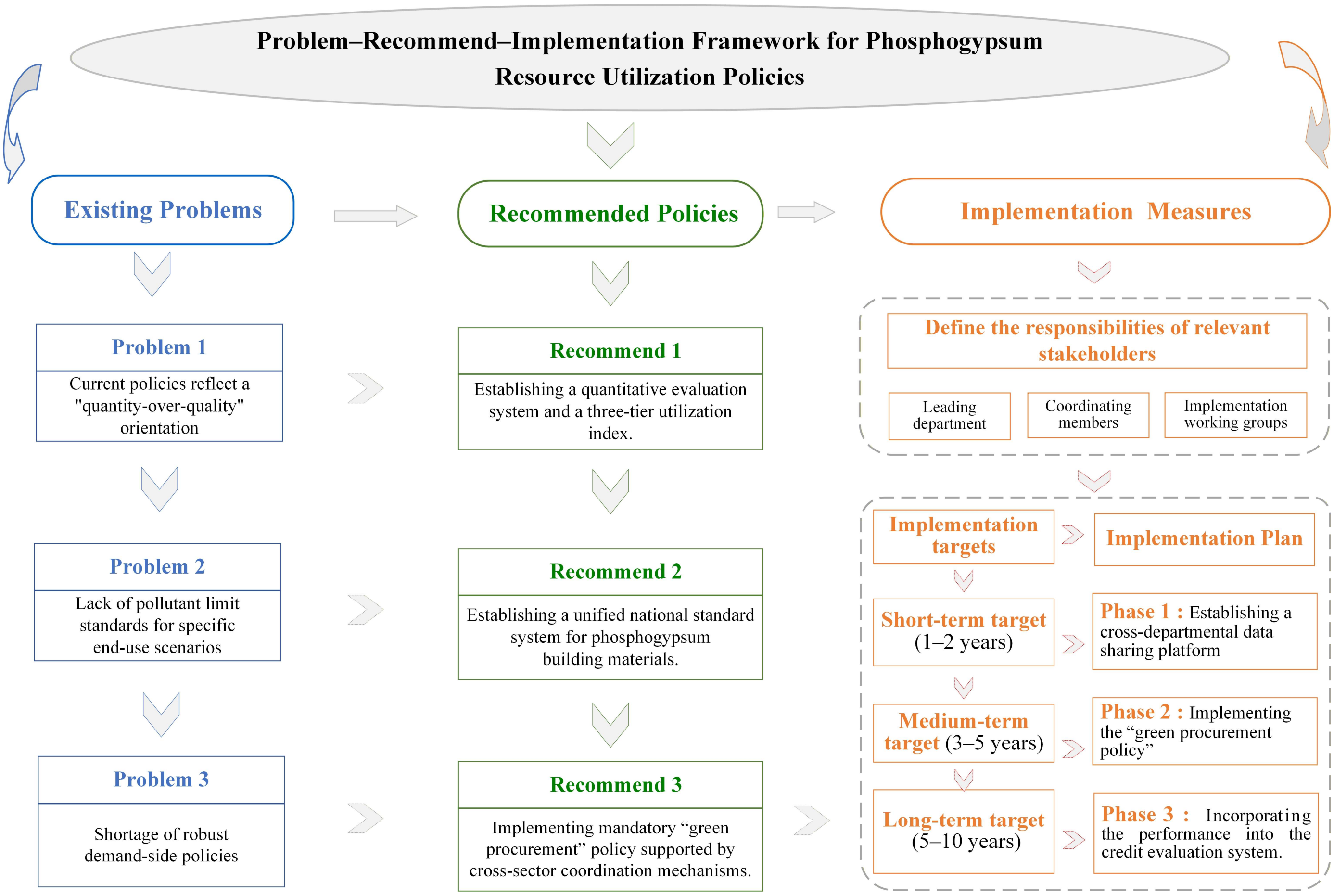

Figure 7. Problem–recommend–implementation framework for phosphogypsum resource utilization policies: This figure only presents the implementation measures of Recommend 3.

5.6. Limitation and Further Study

The study systematically assesses the PRU for PG based on a combination of a literature review and bibliometric method; however, there are several limitations and constraints.

First, we employed bibliometric analysis based solely on the WOSCC database to analyze the research hotspots, and the literature search period was restricted to the past decade. Although the WOSCC is widely recognized as a comprehensive and authoritative academic database with extensive disciplinary coverage and high-quality bibliographic information, reliance on a single database with a only ten years’ reference data may limit the number and diversity of retrieved publications, potentially affecting the robustness and generalizability of the results. In order to achieve a more comprehensive understanding of the evolutionary trajectory of PRU and further improve the temporal representativeness of the research findings, future research could incorporate additional authoritative databases, such as Scopus and Google Scholar, to expand the literature dataset and the retrieval period and conduct segmented analyses using five-year intervals (e.g., 2010–2015, 2015–2020, and 2020–present).

Second, the present study highlights the high environmental and economic benefit of building materials; however, these two indicators were not well-quantified, especially for the high-value-added products. This possibly underestimates its carbon reduction potential since high-value-added PG can substitute for natural gypsum and cement, which are carbon-intensive building materials. To promote the large-scale application of high-value PG under the dual- carbon goals, systematic and quantitative carbon reduction research and economic benefits on its utilization should be conducted from a life-cycle perspective, similar to our previous studies on the carbon mitigation of low-value PG [64].

Finally, we gave the implementation measures targeted at the deficiencies of the policies. However, implementing these policies also has potential implementation barriers, such as regional disparities—neither Policy 1 nor Policy 3 can be implemented under a unified national framework. In order to align with future development trends—actively promoting the large-scale consumption of building materials and the upgrade from low-value to high-value-added products—in a future study, we should further promote the regional implementation policies according to interviews with multiple stakeholders.

6. Conclusions

This study systematically evaluates the PRU status for PG, research hotspots, and development trends, and further proposes targeted policy recommendations. The main findings are summarized as follows.

Globally, the PG RUR remains low, with marked disparities between developed and developing countries; the latter generally achieve rates below 10% (excluding China), highlighting a common challenge for PG disposal. In China, driven by recent policy interventions, the national RUR has steadily increased, reaching 61.6% by 2024. PRU primarily concentrates on four pathways: building materials, chemical industry, agriculture, and filling materials, with building materials accounting for the largest share. Regional variations in utilization rates and pathway choices are evident across five major phosphate-producing provinces, attributable to differences in socioeconomic conditions and local policy orientations.

A bibliometric analysis of WOSCC publications over the past decade reveals a significant upward trend in PRU research, particularly accelerating in the last five years. Building materials consistently emerge as the core research hotspot, with building gypsum and cement retarder as primary focal points due to their high technological maturity; the keyword co-occurrence network corroborates this dominance. Meanwhile, the research focus in terms of the hotspot has undergone a clear evolutionary trajectory: it progressed from an initial exploration of the material fundamental properties, gradually shifted toward performance optimization and composite utilization, and has further ascended to the currently prominent directions of high-value and refined utilization.

A comparative assessment of the four pathways from technical, economic, and environmental perspectives indicates that the building materials route, characterized by large consumption capacity and well-established industrial chains, remains the current and future dominant direction, transitioning from low-value bulk products to high-value-added derivatives. The deficiencies of the existing policies severely impede the development trend of PG. We therefore gave the relative policy recommendations, such as a quantitative evaluation system and sound standard system, effectively facilitating the large-scale substitution of natural gypsum and cement clinker, further recommending formatting the implementable mandatory “green procurement” policies so as to build a stable and guaranteed market for high-quality PG-based building materials.

Future policy optimization should prioritize hierarchical evaluation mechanisms, standardized safety regulations, and demand-side incentives to promote high-value applications and large-scale adoption of PG-based products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18168209/s1. Section S1: Calculation of annual average growth rate; Figure S1: VOSviewer operation flowchart; Figure S2: CiteSpace operation flowchart; Table S1: Major contaminants in phosphogypsum and their associated hazards; Table S2: Comparison of leaching toxicity of pollutant elements in PG under Chinese environmental quality standards; Table S3: PG's resource utilization and the increasing rate during 2012–2024; Table S4: Annual publications and utilization pathway distribution of phosphogypsum resource utilization literature in WoSCC, 2015–2025; Table S5: Keyword co-occurrence analysis: frequency statistics of keywords; Table S6: Frequency statistics of resource utilization-related keywords derived from co-occurrence analysis; Table S7: Advantages and disadvantages of main pretreatment methods for phosphogypsum; Table S8: Comparison of PG resource utilization pathways based on technical maturity, economic feasibility, and environmental risk. References [102–105] are cited in the supplementary materials.

Author Contributions: Z.Z. (Zhihao Zhang): Writing—original draft, data Validation and Software; L.F.: Supervision and Reviewing; H.Z.: Conceptualization, Methodology, Writing—Reviewing and Editing; Y.L.: data Validation and Software; Z.Z. (Zhicheng Zhao): Drawing figures; S.L.: Drawing figures. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by Hubei Key Laboratory of Multi-media Pollution Cooperative Control in Yangtze Basin (No. MMPCC2508).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors would like to thank all researchers whose studies contributed to this review.

Conflicts of Interest: Co-author Lijia Fan is an employee of China Construction Fourth Engineering Bureau Corp, Guangzhou, China. The enterprise only provided basic field construction data for this research and had no involvement in study design, data collection, data analysis, manuscript writing, or the decision to publish. The remaining authors (Zhihao Zhang, Yunfu Li, Zhicheng Zhao, Shuangdou Li, Hui Zhang) declare no commercial, financial or non-financial competing interests that could be perceived to bias this work.

Abbreviations

Abbreviation	Full title or explanation
PG	Phosphogypsum
Mt	Million metric tons
TP	Total phosphorus
NDRC	National Development and Reform Commission
RUR	Resource utilization rate
PRU	PG resource utilization
RUPs	Resource utilization pathways
WOSCC	Web of Science Core Collection
Gt	Billion metric tonnes
REEs	Rare earth elements
TM	Technical maturity
ECB	Economic benefit
ENB	Environmental benefit
ER	Environmental risk

SC	State Council
MEE	Ministry of Ecology and Environment
MIIT	Ministry of Industry and Information Technology
HPPGGO	Hubei Provincial People's Government General Office
GPPGGO	Guizhou Provincial People's Government General Office
DEITSP	Department Economy and Information Technology of Sichuan Provincial
MHURD	Ministry of Housing and Urban-Rural Development

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