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Review

Status and development trends of phosphogypsum utilization in China

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ABSTRACT

Phosphogypsum (PG) is a byproduct generated in large quantities by the phosphate industry, and it serves as a significant source of total phosphorus (TP) pollution along the Yangtze River. Environmentally sound management of PG has, therefore, become a critical challenge. This review outlines the generation processes and environmental risks associated with PG in China. It further examines the technical characteristics of various PG utilization methods and explores the relevant technical standards and policy frameworks. Enhanced utilization of PG in building materials, road construction, soil remediation, and other high-value products is essential. Additionally, the urgent need to promote ecological restoration of PG tailings ponds is emphasized. This study provides a valuable reference for developing effective technological systems for managing PG and preventing TP pollution in China.

1. Introduction

Phosphogypsum (PG) is a byproduct of the wet phosphoric acid process, with calcium sulfate as its primary component. Approximately 4.5−5.0 t of PG are generated per ton of phosphoric acid produced (Li & Gu, 2016). Globally, the cumulative stockpiles of PG have reached 6 billion t, with an annual increase of 200 million t (Ou et al., 2021). By the end of 2020, PG stockpiles in China had exceeded 830 million t. The most common method for PG disposal is stockpiling, leading to the formation of hundreds of PG tailings ponds. This extensive accumulation poses a significant environmental threat.

In recent years, 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 (Chen et al., 2023; Yang et al., 2021). The industrial sector has been identified as the primary source of TP pollution, specifically from the "three phosphorus" sectors: phosphate mines, the phosphorus chemical industry, and PG tailings ponds (Qin et al., 2018).

Strengthening the management of TP pollution is a key priority in China's "14th Five-Year Plan". In 2021, the State Council of China issued the "Further Promoting the Nationwide Battle to Prevent and Control Pollution," which highlighted the need for stricter regulation of the "three phosphorus" industries and the implementation of more targeted measures. Additionally, the National Development and Reform Commission (NDRC) issued two key documents focused on optimizing the utilization of bulk solid waste and promoting a circular economy. These documents set a goal of achieving a 60% comprehensive utilization rate for newly generated PG by 2025, emphasizing the need to expand PG utilization pathways and advance large-scale PG utilization technologies.

Several comprehensive utilization routes for PG have been developed, with its main applications in the production of cement retarders, building gypsum, and related products. In the chemical industry, PG is utilized in the production of sulfuric acid co-production cement, ammonium sulfate, and potassium sulfate. Additionally, it serves as a soil amendment in agriculture (Ou et al., 2021). However, the presence of impurities in PG necessitates pretreatment to make it harmless before use, which increases costs and limits the market competitiveness of PG products. Therefore, exploring new technologies for large-scale and high-value utilization of PG is critical.

This paper is structured into four sections. First, the chemical characteristics and environmental impacts of PG are reviewed.

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Table 1
Chemical composition of PG.

No.	Constituent (Wt. %)							Province in China	Ref.
	SO_3	CaO	SiO_2	P_2O_5	Al_2O_3	F^-	Fe_2O_3		
1	49.77	41.29	5.99	0.94	0.67	0.86	0.13	Guizhou	Zou et al. (2022)
2	42.40	32.93	4.26	1.03	0.25	0.50	0.47	Guizhou	Liang et al. (2022)
3	44.20	31.32	2.39	1.36	0.20	0.23	0.28	Guizhou	Yang (2022)
4	32.20	28.63	17.06	0.70	0.24	0.52	0.21	Yunnan	Li (2019)
5	36.42	28.19	12.03	0.92	0.74	0.32	0.14	Yunnan	Zhang et al. (2022)
6	49.03	39.47	3.68	1.78	2.59	0.06	1.95	Sichuan	Wang et al. (2019)
7	51.95	35.93	8.42	1.51	0.52	0.42	0.54	Hubei	Li et al. (2019)
8	40.19	28.98	6.89	0.45	0.20	1.01	0.48	Hubei	Lv et al. (2022)
9	55.95	34.46	5.82	0.79	0.66	0.87	0.51	Chongqing	Zhao et al. (2017)
10	56.92	33.64	6.30	0.70	0.64	0.91	0.33	Chongqing	Zhao et al. (2015)
Avr	45.90	33.48	7.28	1.02	0.67	0.57	0.50		

Second, the current status and developmental trends of comprehensive utilization of PG are discussed. The third section focuses on the relevant technical standards and policy frameworks guiding PG utilization. Finally, the paper examines various PG utilization and disposal routes, with specific emphasis on the implications for China.

2. Generation characteristics and environmental impacts of PG

2.1. Basic properties and pollutant concentration of PG

PG is a byproduct generated during phosphoric acid production through a wet process that utilizes phosphate rock as the primary raw material. This process includes the hemihydrate, dihydrate, and di-hemihydrate processes. Among these, the dihydrate process is the most widely adopted due to its mature technology, stable and reliable operation, and strong adaptability to different ore types.

The primary chemical components of PG are $CaSO_4 \cdot 2H_2O$ or $CaSO_4 \cdot 0.5H_2O$, with a pH range of 1–4. PG is considered a renewable resource, capable of replacing natural gypsum after proper purification. It typically appears as a fine solid powder, varying in color from grayish white to dark-gray. Temperature fluctuations can cause varying degrees of crystalline water precipitation, while the release of pore water from PG can alter its physical properties. The chemical composition of PG predominantly includes calcium oxide and silicon dioxide, which together account for approximately 80% of its total mass (see Table 1). In addition, PG contains small amounts of soluble phosphorus, soluble fluorine, iron oxide, organic materials, and other impurities.

The composition of PG is influenced by several factors, including the source and grade of the phosphate rock and the phosphoric acid production process. Phosphate rocks from different regions contain varying impurities, such as soluble phosphorus, eutectic phosphorus, fluorides, radioactive elements, and other pollutants, which play a significant role in determining the composition of PG. The phosphoric acid production process also affects PG composition, as gypsum crystallization can be achieved through one- or two-step methods. The two-step method, referred to as the recrystallization process, produces α-hemihydrate PG, which possesses superior cementitious properties compared to conventional dihydrate PG (Wang et al., 2021). This technological advancement offers new potential for the high-value utilization of PG.

Moreover, PG may contain toxic metals such as cadmium, arsenic, chromium, lead, and mercury, as well as radioactive elements like uranium and radium, depending on the region (Cao et al., 2001). The presence of these impurities can have detrimental environmental effects and may restrict the direct application of PG in various industries (see Table 2).

2.2. Environmental impacts of PG

PG is primarily stockpiled in tailings ponds, which are often constructed by damming valleys or repurposing abandoned mining sites. Closed PG tailings ponds are typically covered with soil and vegetation to mitigate their environmental impact. Fig. 1 illustrates both active and closed PG tailings ponds in Hubei Province, China.

Soluble phosphorus and fluorine present in PG stockpiled in tailings ponds can leach into the surrounding environment through rainwater, leading to contamination of local ecosystems. According to the “Second National Pollution Source Census,” TP emissions from the “three phosphorus” industries in the Yangtze River Basin amount to 1399 t, representing 29.3% of the TP emissions from industrial sources (Li et al., 2022; Shi et al., 2020). These emissions are concentrated mainly in the mid- and upstream regions of the Hubei, Sichuan, Guizhou, and Yunnan provinces, which account for 76.4% of the TP emissions from the “three phosphorus” industries across 12 provinces (Shen et al., 2022).

Table 2
Occurrence state and hazard of impurity components (Li et al., 2023).

Impurity	Content (wt.%)	Occurrence state	Impact
Silicon	>1%	Primarily as SiO_2, minor as Na_2SiF_6/K_2SiF_6	Induces wear in machinery and affects the purity of gypsum and high-end applications
Phosphorus	>1%	Insoluble phosphorus ($Ca_5(PO_4)_3F$, $Ca_3(PO_4)_2$, $FePO_4$, etc.), soluble phosphorus (H_3PO_4, H_2PO^{4-}, $HPO_4{}^{2-}$, $PO_4{}^{3-}$), eutectic phosphorus (H_3PO_4, H_2PO^{4-}, $HPO_4{}^{2-}$, $PO_4{}^{3-}$, etc.)	Soluble phosphorus reduces product strength; large amounts of phosphorus cause eutrophication
Fluorine	0.01%–1%	Mainly insoluble fluorine (CaF_2, Na_2SiF_6, K_2SiF_6, etc.), a small amount is soluble fluorine (F^-, NaF, KF, HF, H_2SiF_6)	Pollutes water and soil, leads to dental fluorosis or skeletal fluorosis, reduces the strength of gypsum, and poses a safety risk when used as a backfill material
Metals	0.01%–1%	Fe, Al, and other metals. Fe predominantly in the inclusion state, Al mainly as oxide	Fe affects the whiteness of phosphogypsum, Al affects the purity of calcium sulfate
Trace metals	<0.01%	Cd, Cu, Zn, Pb, etc.	Bioaccumulation function; pollutes water, soil, and plants
Radioactive elements	<0.01%	Ra^{226}, U^{238}, U^{234}, Pb^{210}, etc.	Pollutes soil and damages health

Fig. 1. Phosphogypsum tailings ponds in the Hubei Province.

PG tailings ponds are the largest contributors to TP emissions within the "three phosphorus" industries, accounting for 60.1% of the total emissions. The phosphorus chemical industry and phosphate mining contribute 36.7% and 3.2%, respectively (Li et al., 2021a; Liu et al., 2020; Wu et al., 2020a). As depicted in Fig. 2, PG tailings ponds are the primary source of phosphorus pollution in the Yangtze River Basin, with approximately 55% of enterprises being classified as environmentally problematic (Wu et al., 2020a).

Currently, around 100 PG tailings ponds have been identified in the Yangtze River Basin, with 40 located in Hubei Province and 30 in Sichuan Province (Liu et al., 2020; Wang et al., 2020). In Hubei Province, PG stockpiles have reached 296 million t, with 18 of these tailing ponds situated less than 5 km from the Yangtze and Han rivers. The primary safety and environmental risks associated with PG tailings ponds include the potential for dam collapses, which could cause significant environmental pollution (Guo et al., 2022). In addition, unregulated stockpiling, inadequate leachate management, and insufficient flood control systems increase the risk of phosphorus contamination in both surface and groundwater.

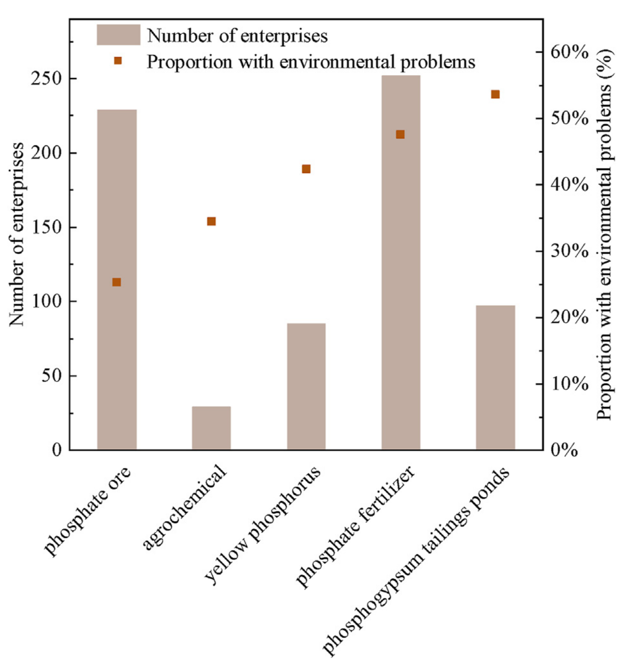

Fig. 2. Statistics on environmental concerns in "three phosphorus" enterprises.

In Guizhou Province, an assessment of PG tailings ponds revealed that insufficient leachate control had caused severe groundwater contamination, with elevated levels of phosphorus and fluorine contributing to the eutrophication of the Wu River, posing a serious threat to aquatic ecosystems (Duan et al., 2008). In Hubei Province, leakage from a tailings pond resulted in the contamination of a zone where TP concentrations in nearby surface water exceeded the Class III standard by 794 times, leading to fish deaths downstream and negatively impacting local communities (Null, 2021).

3. Status and development trends of comprehensive utilization of PG

3.1. *Current status of the comprehensive utilization of PG*

Table 3 presents the data on the generation, disposal, and utilization of PG in several countries in 2020. PG management practices vary significantly across countries. In major PG-generating countries, such as Morocco and the United States, PG is primarily stockpiled -or dumped into the sea, with its comprehensive utilization focused on agriculture and building materials. In contrast, Japan has achieved notable success in the comprehensive utilization of PG, particularly in the production of building materials. Other countries, including Finland and Spain, use only a small proportion of PG in agriculture and building materials, with the majority still being stockpiled (Hilton et al., 2020; Ou et al., 2021).

These differences in PG management are influenced by factors such as the availability of phosphate resources and the level of economic development in each region. For instance, Japan's scarcity of natural phosphate resources has driven the country to place greater emphasis on the comprehensive utilization of PG. Morocco,

Table 3
Generation and utilization of PG in the world (Cui et al., 2022; Hilton et al., 2020).

Country	Disposal and utilization	Generation (1000 metric tons)
China	50% for comprehensive utilization, mainly for building materials	75,000
Morocco	Dumping in the sea, minor applications in agriculture and road studies	37,000–42,000
United States	Mainly stockpiled, minor use in agriculture, cement, roadbed materials, backfill	32,000
Japan	100% for building materials	–
Brazil	85% for agriculture and 100% for building materials	10,000
India	~60% for cement; minor use in agriculture	8270
Philippines	50% for cement, minor use in agriculture and rare earth recycling	1000
Belgium	95% for building materials; 5% for agricultural production	5
Finland	Principally stockpiled; minor pilot projects in agriculture and road	–
Spain	Mainly stockpiled; minor research for fertilizer and soil amendment	–

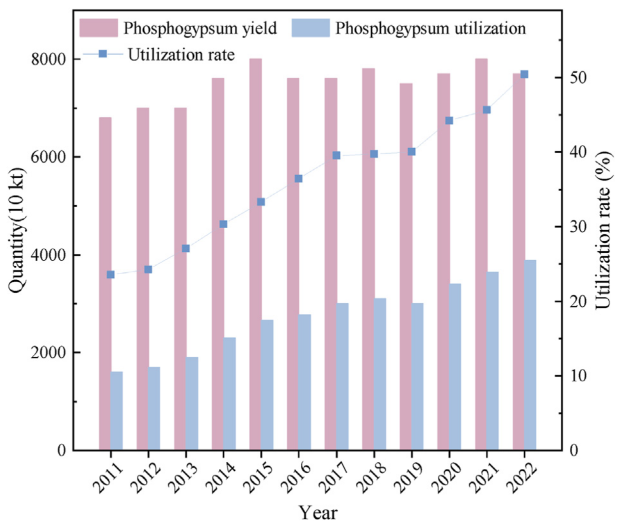

Fig. 3. Generation and utilization of PG in the past decade in China.

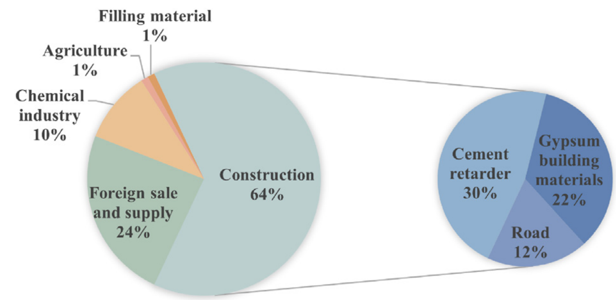

Fig. 4. Comprehensive utilization routes of PG in China.

benefiting from its proximity to the Atlantic Ocean, utilizes its geographical advantage to dump PG into the sea, further facilitated by more lenient environmental regulations. In contrast, the United States faces restrictions on PG use due to the presence of radioactive substances, such as R^{226}, leading to the stockpiling of most of its PG.

Globally, PG disposal practices are gradually transitioning from traditional stockpiling methods to more sustainable and comprehensive utilization. Despite some progress, challenges remain in areas such as technology, economics, and policy, which hinder broader utilization of PG.

In recent years, China has seen a significant increase in PG generation due to the rise in phosphate fertilizer production. Under the guidance of national industrial and environmental policies, the comprehensive utilization of PG in China has steadily improved. Fig. 3 illustrates the generation and utilization rates of PG in China over the past decade, with PG generation reaching approximately 75 million t and a comprehensive utilization rate of 50% in 2022 (Revolutionary Committee of the Chinese Kuomintang, 2023).

To enhance PG utilization efficiency, enterprises and research institutions have actively explored high-value utilization routes in areas such as building materials, the chemical industry, and agriculture. Fig. 4 shows the distribution of comprehensive utilization in China in 2022, including its use in building materials, the chemical industry, agriculture, and filling materials. With continuous technological advancements and supportive policy frameworks, the future of PG utilization is expected to expand, leading to broader applications and improved sustainability.

3.2. *Comprehensive utilization technology and comparative analysis*

The development of comprehensive utilization technologies of PG has progressed through three stages: 1985–2012, 2013–2017, and from 2018 to the present (Wei & Deng, 2022).

During the first stage (1985–2012), research primarily focused on the comprehensive utilization of PG in building materials, the effective removal of metals, and the evaluation of radioactive elements. Under specific technical conditions, PG can replace natural gypsum in the production of building materials, which promotes energy conservation, environmental protection, and sustainable growth in the construction and phosphate chemical industries (Silva et al., 2022; Wei & Deng, 2022). Among them, anhydrous gypsum type II, obtained through calcination at temperatures exceeding 700 °C, has garnered considerable attention due to its enhanced water resistance and stability, making it suitable for producing high-value-added products.

From 2013 to 2017, research expanded to include the use of PG for soil improvement, fertilization, carbon capture, and the recovery of rare earth elements (REEs). REEs are considered critical and nonrenewable resources with significant strategic importance for China's economic development and national security. PG contains concentrations of REEs exceeding 0.01 wt%, providing substantial extraction potential. Studies by Melki and Gueddari (2018) and Rychkov et al. (2018) demonstrated the successful purification of a rare earth solution with 97%–99% purity through acid leaching with sulfuric acid. This process was enhanced by grinding, ultrasonic treatment, and resin addition, optimizing the extraction of REEs.

Since 2018, research has increasingly focused on the use of PG as an agricultural fertilizer. PG's rich phosphorus and sulfate content makes it an attractive supplement for enhancing crop production. Additionally, it has been used to regulate soil pH, improve soil fertility, and mitigate soil salinization.

3.2.1. Construction

PG has found extensive use in construction materials, particularly as a cement retarder, cement mineralizer, slag cement component, wall material, and decorative building material. In addition, PG is utilized to produce gypsum powder and other innovative building materials (Ma et al., 2021; Wu et al., 2020b; Wu et al., 2020c; Zhang et al., 2019). Impurity removal processes such as dissolution, crystallization, or dehydration enable PG to be effectively used in construction materials (Wu et al., 2022).

3.2.1.1. Cement retarder. In China, approximately 30% of PG is used to produce cement retarders. PG serves as a substitute for natural gypsum, but its lower pH and higher concentrations of impurities such as F^-, P_2O_5, and organic materials can influence the cement's setting time and strength. The presence of these impurities requires the use of modifiers to mitigate their negative effects on cement performance. However, the variability of PG's impurities, depending on its age and origin, can affect cement stability. Compared to desulfurization gypsum and other types of gypsum, the need for modifiers increases production costs and diminishes the competitiveness of PG-based products in the cement industry.

3.2.1.2. Gypsum building materials. The use of PG in the production of gypsum building materials is well established. Current production methodologies include both "one-step" and "two-step" processes, typically represented by rotary kilns and boiling furnaces. PG is commonly processed into gypsum blocks and boards. Different dehydration processes can make PG into various crystalline forms. Modified PG can effectively replace natural gypsum in the production of a wide range of gypsum building materials.

Yunnan Yuntianhua Co., Ltd., China, has developed fluidized calcination technology for PG, addressing the inefficiencies of conventional methods, such as low productivity and inconsistent product stability. This innovative technology comprises a three-step process involving drying and preheating, calcination, and cooling and aging. The calcination process removes impurities like fluorine, phosphorus, alkalis, and organic matter, resulting in a shorter setting time for treated PG. As a result, the final products demonstrate stable quality, contributing to increased sales (Zhang et al., 2023).

3.2.2. Chemical industry

PG has traditionally been used in the chemical industry for the production of sulfuric acid, ammonium sulfate (a co-product of nitrogen and potassium compound fertilizers), and potassium sulfate (commonly used as potash fertilizer) (Bai, 2020; Ma, 2019b).

3.2.2.1. Production of sulfuric acid co-production cement. At high temperatures, PG undergoes reductive decomposition in the presence of coke, yielding sulfuric acid as the main product. The solid byproduct, calcium oxide (CaO), is subsequently used in cement production. Research has focused on improving the fluidized decomposition of PG, especially in areas such as particle agglomeration and the introduction of additives to enable low-temperature calcination and decomposition. Despite being a relatively mature technology, challenges remain, including high preparation costs, significant energy consumption, and considerable gaseous emissions. These issues have hindered the widespread adoption of this technology, and further development is needed.

Producing sulfuric acid from PG is regarded as an efficient and environmentally friendly method due to the high utilization rate of PG. However, the high energy consumption and associated costs have prompted ongoing research in this field. Wang et al. (2018) developed key technologies for the low-temperature decomposition of PG to produce high concentrations of SO_2 and established a 10,000-t demonstration facility, achieving high conversion rates of PG. The Shandong Lubei Group developed several new technologies, including low-temperature waste heat recovery and a novel phosphoric acid extraction process, which significantly enhanced the efficiency of PG resource utilization(Gao, 2019).

3.2.2.2. Ammonium sulfate. PG, calcium carbonate, and ammonia undergo complex decomposition reactions to produce ammonium sulfate and calcium carbonate. This reaction is heterogeneous and influenced by numerous variables, which affect the efficiency of the process.

3.2.2.3. Potassium sulfate. Potassium sulfate can be produced from PG through two main processes: the one-step and two-step methods. The one-step process synthesizes potassium sulfate using PG, potassium chloride, ethanol, and ammonia as reactants. The two-step process uses PG, ammonium bicarbonate, potassium chloride, and ammonia to fabricate potassium sulfate via a two-stage composite decomposition reaction. Although extensive research has been conducted on these processes, a fully established and commercially viable manufacturing method for potassium sulfate from PG has not yet been developed.

Globally, scholars and enterprises are exploring innovative processes for PG utilization in the chemical industry. Notable developments include the decomposition of PG in a two-stage fluidized bed for acid production. This approach enables the co-production of sulfuric acid and high-quality CaO. Additionally, the bifurcation of PG into reduction and oxidation phases in two-stage low-temperature technology has significantly improved the purity of CaO and the concentration of SO_2. The decomposition products of PG, such as calcium sulfide (CaS), can be used for carbon capture and the production of high-quality calcium carbonate ($CaCO_3$) and hydrogen sulfide (H_2S). Moreover, the chemical looping gasification of lignite to syngas, using PG, utilizes the carbon monoxide generated during the reduction and decomposition processes to prepare syngas. These technologies offer further applications for PG in the chemical industry.

3.2.3. Agriculture

PG is primarily utilized in agriculture as a soil conditioner, sulfur and calcium fertilizer, and as a slow-acting nitrogen fertilizer (Ma, 2019a; Ou et al., 2021; Pan et al., 2019). PG contains essential nutrients for crop growth, including sulfur, phosphorus, calcium, and silicon. However, its inherent acidity and corrosive properties prevent its direct application to soil. Once PG undergoes harmless treatment, it becomes viable for use in soils and crops where these elements are deficient. PG can improve the physical and chemical properties of soil, enhance the conditions for soil microorganisms, and increase crop yields. It is particularly beneficial for acidic, saline, and alkaline soils, as well as soils contaminated with heavy metals. Nevertheless, the utilization of PG in agriculture remains limited due to the presence of deleterious substances and potential environmental hazards, compounded by regulatory restrictions imposed by agricultural and environmental authorities.

3.2.4. Filling materials

PG is also employed as a filling material, primarily in the backfill of mined-out voids (Li et al., 2021b; Zhang et al., 2019). The process involves mixing PG or processed aggregates with an appropriate

Table 4
Comparison of major utilization routes for PG.

Field	Utilization route	Benefit	Limitation	Economic consideration
Construction	Cement retarder	Established technology; large-scale applicability.	Impurities affect cement strength; necessitates the use of modifiers.	Simple equipment, low investment; low market competitiveness.
	Gypsum building material	Substantial phosphogypsum utilization; sophisticated technology; advanced equipment.	Low quality and stability; intense market rivalry; restricted scale; diminished product marketability.	High technological value added; hindered by transportation expenses and market penetration.
Chemical industry	Sulfuric acid co-production cement	Mature technology theory; resource recovery of calcium and sulfur; efficient phosphogypsum recycling.	High energy consumption, long process; suboptimal early cement strength; insufficient SO_2 levels.	Extensive equipment, high investment, challenging to achieve operational profitability.
Agriculture	Soil amendment	Straightforward application; mitigates soil acidity and salinity.	Environmental safety concerns; subject to regulatory restrictions.	Low operational expenses; escalated transportation costs.
Filling material	Mining backfill	Simple operation; mature technology; large treatment quantity.	Phosphogypsum's acidic components compromise the fill material's initial strength.	Low costs.

amount of cementitious material and water to create a filling slurry. This slurry is then transported via pipelines and deposited into voids, where it solidifies, forming a filler with sufficient strength and structural coherence. However, the acidic impurities in PG, such as phosphorus and fluorine, reduce the initial strength of the filler body, limiting its broader application. Despite this, using PG as a filling material offers the dual benefit of reducing PG stockpile volumes and alleviating environmental pressure. This method is straightforward to implement, economically viable, and holds significant potential for widespread application. The technology is well established and has been widely adopted in the Yunnan and Guizhou provinces (Deng et al., 2024).

Table 4 provides a comparative analysis of the technologies associated with the major utilization routes for PG, highlighting their respective benefits and limitations. PG's use in cement retardation presents a low-cost option but faces challenges related to impurities and market competition. Gypsum building materials, while technologically advanced, are burdened by high investment and transportation costs. The chemical co-production of sulfuric acid and cement offers resource recovery potential but requires significant investment and energy. Agricultural use as a soil amendment is straightforward, but carries environmental risks. Each utilization route requires careful consideration of economic feasibility and environmental sustainability, factoring in both technological and market conditions for broad-scale application.

Different sources of PG can affect its composition and properties, which in turn influence the stability and quality of products derived from its comprehensive utilization. Currently, the primary focus of PG utilization technologies is on building materials, such as cement retarders and gypsum products. However, most PG-based products are inferior to those made from natural gypsum. Increased research and development are needed to enhance the volume and value of PG's comprehensive utilization. As a bulk solid waste, PG cannot be fully addressed by any single technology. Therefore, a synergistic approach, combining multiple treatment modes, is essential to establishing an optimal development paradigm for the PG industry.

3.3. *Development trends*

Technological advancements in PG resource utilization have progressed significantly, driven by stockpiling pressures and stringent environmental protection policies. A range of innovative technologies, including fluidized calcination, decomposition of PG in two-stage fluidized beds for acid production, and its use in mine backfill, have been developed and implemented across industries. As a result, an interdisciplinary and comprehensive utilization paradigm has emerged within the industrial framework.

However, PG utilization is still constrained by high concentrations of impurities such as phosphorus, fluorine, and other acidic compounds. The content of these impurities varies according to the origin and storage duration of the PG, which can impact production stability. Laboratory-scale technologies for PG purification—such as washing, flotation, neutralization, and calcination—have demonstrated success, but their scalability for large-scale industrial applications remains a challenge, requiring further research and development.

Several enterprises have actively pursued large-scale strategies to reduce PG stockpiles. For example, Guizhou Wengfu Zijin Company has implemented a 400,000-t PG washing project that meets industry standards. Similarly, Wuhuan Engineering Corporation developed a modified harmless treatment technology, which has been applied in Yunnan Xiangfeng's 2 Mt/yr PG washing and purification facility and Hubei Xiangyun's 5 Mt/yr comprehensive utilization project.

From an economic perspective, PG is mainly utilized as a substitute for natural gypsum. Despite its low-cost, the decontamination process is expensive due to the necessary treatments to render it harmless. This economic burden makes it difficult for enterprises to generate profits, thereby hindering the large-scale industrialization of PG. The quality of PG-based products is generally inferior to those made from desulfurized or natural gypsum, further weakening its market competitiveness. In addition, public acceptance of PG products is low. In the short term, the PG industry will likely require government subsidies and promotional efforts to support its development. In the long term, the sustainability of PG utilization will depend on continued research and development, particularly the promotion of high-value products.

The key to advancing comprehensive utilization technology for PG lies in developing low-cost, efficient, and simple methods for decontamination. Strengthening the integration of research and industry is essential to scale comprehensive utilization technologies for large amounts of PG. While significant research progress has been made in high-value technologies such as carbon capture and the recovery and extraction of REEs, these technologies have yet to reach industrial-scale production.

4. Policy system related to the comprehensive utilization of PG

PG as a bulk industrial solid waste, has garnered substantial attention from government agencies and regulatory bodies in recent years. To guide the comprehensive utilization of industrial solid waste like PG, a series of policies and regulations have been introduced. Table 5 outlines key policies and regulations relevant to PG. One of the notable initiatives comes from the General Office of the State Council, which launched a pilot program focused on the construction of “waste-free cities” with an emphasis on PG management. The goal of this program is to explore the implementation

Table 5
Policies and regulations.

Level	Department[a]	Release time	Title	Highlight
National	Office of the leading Group for the development of the Yangtze river	2019 January	Guidance on Strengthening pollution Prevention and control of tailings storage Facilities in the Yangtze river	Phosphogypsum tailings ponds will be incorporated into the primary regulatory scope for tailings ponds.
	MEE	2019 January	Action plan for the Yangtze river protection and restoration Battle	Coordinate Hubei, Sichuan, Guizhou, and other provinces and municipalities to conduct a special investigation and remedial action for the “three phosphorus” issue.
	MEE	2019 April	Yangtze river “three phosphorus” special investigation and remedial action implementation program	Remediation of phosphogypsum tailings ponds focuses on regular monitoring of groundwater.
	MEF	2019 October	Announcement on VAT policy on comprehensive utilization of resources	Taxpayers selling self-produced comprehensive phosphogypsum products are eligible for immediate VAT refunds.
	NDRC	2021 March	Guidance on the comprehensive utilization of bulk solid waste in the Fourteenth Five-Year plan	The utilization rate of phosphogypsum reaches 60% in 2025.
	NDRC	2021 May	The 14th Five-Year plan for the development of circular Economy	Expanding ecological restoration, green mining, green building materials, and transportation projects of phosphogypsum
	State council	2021 October	Peak carbon Action program by 2030	Explore the application of phosphogypsum in soil improvement and roadbed construction.
	State council	2021 November	Opinions on continuing to Fight the Battle Against pollution	Implement remediation measures for the “three phosphorus” industry.
Local	Guizhou Provincial People's Government	2018 April	Accelerating the comprehensive utilization of Phosphogypsum resources	Beginning in 2019, the phosphogypsum stock will be reduced by at least 10% per year.
	Standing Committee of Hubei Provincial People's Congress	2022 June	Regulations on Prevention and control of Phosphogypsum pollution in Hubei province	Encourage and support enterprises that produce phosphogypsum as well as other relevant operators to comprehensively utilize phosphogypsum.
	Yunnan Provincial department of Ecology & Environment	2023 October	Yangtze river Basin (Yunnan section) TP pollution control program	By the end of 2025, systematically reduce the stockpile of phosphogypsum.

[a] NDRC, National Development and Reform Commission of China; MEE, Ministry of Ecology and Environment of China; MEF, Ministry of Finance of China.

of the “generation based on use” policy, aiming to balance solid waste generation and consumption. In parallel, the Ministry of Industry and Information Technology, in conjunction with the NDRC and eight other departments, has issued the “Implementation Plan on Accelerating the Comprehensive Utilization of Industrial Resources.” This plan aims to accelerate PG applications, particularly in the co-production of sulfuric acid and cement, as well as in alkaline fertilizers, high-strength gypsum powder, and related products. Furthermore, it encourages the exploration of PG for use in filling underground voids and road construction materials. The plan also supports the development of large-scale PG projects in key provinces such as Hubei, Sichuan, Guizhou, and Yunnan, while promoting the construction of demonstration projects to showcase the efficient utilization of PG. In addition, where feasible, the plan supports the adoption of a “production based on slag” model to facilitate the integrated use of PG.

Governments and industry authorities have implemented several standards to encourage and regulate the rational utilization of PG and its products. These standards serve both normative and guiding roles, promoting the efficient use of PG while ensuring the stability of product quality. However, the lack of comprehensive national PG standards poses a challenge. Existing standards, such as “Specification for the Treatment and Disposal of Phosphogypsum” (GB/T 32124-2015) and “Industrial Byproduct Gypsum Used in Cement” (GB/T 21371-2019), provide some guidance, but they are insufficient for broader applications, especially in the building materials sector. In addition, many local standards have low thresholds and lack robust indicator settings, contributing to inconsistent regulation. Furthermore, the standardization of PG tailings pond management is deficient, particularly regarding harmless treatment, storage standards, and effective management practices. The absence of a “one tailings pond, one policy” guideline for the environmental management of PG tailings ponds has led to a lack of standardized operational and management procedures for these enterprises. Overall, the comprehensive utilization of the PG standard system must be improved.

5. Implications for the comprehensive utilization of PG

5.1. Comprehensive utilization of PG

The process for treating PG is illustrated in Fig. 5. To address the challenges associated with PG utilization, it is critical to focus on both reducing stockpiles and effectively utilizing newly generated PG. To improve the recycling rate of phosphorus resources and enhance PG quality, source reduction technologies, such as the α-hemihydrate gypsum process and the hemi−dihydrate process, should be developed for newly generated PG. The comprehensive utilization of PG can contribute to reducing stockpiles and eliminating newly produced PG. Two primary strategies can be employed to mitigate the challenges of PG stockpiling. First, improving the management of PG tailings ponds is essential to prevent environmental issues. Second, utilizing comprehensive methods, including ecological restoration and backfilling, can address the generation of new PG and reduce existing stockpiles. To manage both historical stockpiles and newly generated PG, a comprehensive technological approach, encompassing source reduction, utilization, and the restoration of PG tailings ponds, should be developed.

Technological advancement is essential for improving the PG utilization process. This involves focusing on two key areas: high-value addition and high-volume applications. Enhancements in current treatment and utilization methods should aim to improve product performance, reduce costs, and lower energy consumption. The ultimate goal is to promote the industrialization of harmless treatment technologies while developing high-value-added or high-volume products, such as building materials, road construction materials, and soil remediation solutions. For low-value-added products, like cement retarders, which are constrained by transportation costs, gradual reduction or elimination is recommended.

To achieve effective PG utilization, it is vital to foster synergies across various industries and establish a circular economic model. Collaboration with the construction industry would enable the use

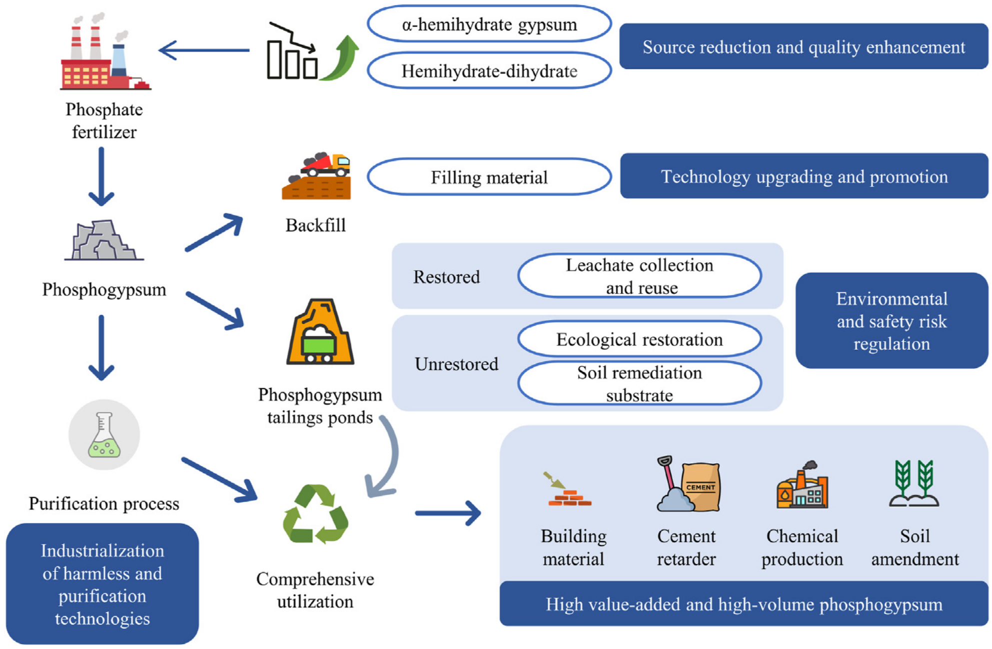

Fig. 5. Utilization and disposal routes of PG.

of PG in building materials, contributing to closed-loop resource utilization. Additionally, partnerships with the agricultural and environmental sectors can facilitate the use of PG in farmland improvement and soil restoration, promoting resource recycling. This approach supports a multi-industry development pattern that leverages the entire technological process and chain for PG.

For temporary stockpiles and closed PG tailings ponds, effective control, monitoring, and treatment are necessary. Standardized measures to prevent dust and leakage of leachate must be implemented during stockpiling. To address leachate issues from closed PG tailings ponds and mitigate environmental pollution, comprehensive ecological restoration technologies should be developed. These technologies should focus on in-situ pollution control and phytoremediation of PG. Additionally, a soil restoration substrate can be developed using PG as the primary raw material, facilitating the comprehensive use of PG in ecological landfill restoration.

The integration of comprehensive utilization and backfilling efforts should be emphasized. Temporary stockpiling and closed PG tailings ponds must be managed with effective source reduction, process control, and downstream utilization technologies. Establishing a comprehensive PG utilization system that encompasses the entire technological process is critical for addressing PG treatment challenges, mitigating environmental impacts, and ultimately achieving efficient resource utilization.

5.2. Implications and suggestions

5.2.1. Strengthening supervision of PG enterprises

PG tailings ponds are often located near the main streams or tributaries of the Yangtze River. Many of these ponds were constructed before the implementation of the “Safety Technical Regulations for Phosphogypsum Tailings Ponds” (AQ 2059-2016), leading to insufficient leachate control measures. This can result in elevated TP concentrations in downstream water bodies. Therefore, regular supervision and inspection of PG tailings ponds, leachate collection ponds, and flood interceptor ditches are essential. Establishing strict environmental management standards for PG tailings ponds is necessary to guide their construction, development, and ongoing operations.

5.2.2. Improvement in the standards for the quality of PG products

The use of PG in building materials, such as cement retarders, gypsum products, and road-base materials, represents a key method for large-scale consumption. However, low market recognition and limited sales constrain their use. Compared to traditional building materials, PG-based products often lack a competitive advantage. To address this, it is critical to establish a comprehensive product quality standard system for the utilization of PG, particularly in building materials. In addition, upgrading market access and introducing preferential policies can promote the healthy development of enterprises focused on the comprehensive utilization of PG.

5.2.3. Enhancement of the entire life-cycle control of PG

Achieving source reduction for PG requires the establishment of a classification and grading quality assessment index system for byproducts from different processes at the initial stages. In addition, optimizing and promoting advanced phosphoric acid production processes are essential. In the middle stages, research and development should focus on high-value-added technologies and improving pretreatment processes. At the back end, expanding PG elimination pathways is crucial. This can be supported by utilizing the well-developed water system of the Yangtze River Basin, particularly its water transport routes, to facilitate the transfer of PG resources from upstream and midstream areas to downstream regions, thereby addressing regional demand imbalances.

5.2.4. Strengthening the introduction and implementation of supporting policies and regulations

While governments at all levels have introduced policies and regulations related to the treatment, disposal, and resource utilization of PG, most policies are focused on macro-level control, addressing PG elimination and resource utilization but lacking specific implementation guidance. To guide the development of the PG utilization industry, the government should provide clear macro-direction and a comprehensive understanding of the current status of PG utilization. From an economic perspective, the government should introduce financial and tax policies, such as subsidies and special funds, to encourage the development of PG resource technology and offer financial support to enterprises engaged in its comprehensive utilization. Local governments should also tailor policies to their specific circumstances, considering local PG characteristics and industry developments to establish an effective utilization system. In addition, encouraging the use of PG products for municipal construction projects could help improve public acceptance and drive broader market adoption.

CRediT authorship contribution statement

Xiong Shi: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Ao Zeng:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Huabo Duan:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Hui Zhang:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation. **Jiakuan Yang:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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.

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