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TOPICAL REVIEW

Research progress on resource utilization of phosphogypsum

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Abstract

Phosphogypsum is a by-product generated during wet phosphoric acid production. The massive accumulation of phosphogypsum has caused serious environmental issues, making the development of innovative and comprehensive utilization methods critically important. Both phosphogypsum and natural gypsum primarily consist of $CaSO_4 \cdot 2H_2O$ and treated phosphogypsum can be converted into valuable gypsum resources for various applications. This Review provides an overview of the impurities in phosphogypsum and elaborates on the common methods for its pretreatment, highlighting that the key challenge in the resource utilization of phosphogypsum lies in reducing and removing its impurity content. Phosphogypsum pretreatment serves as the foundation, and the diversification of pathways for its resource utilization will be an inevitable trend. As indicated in previous studies, phosphogypsum can be combined with various materials through a carefully designed mix-and-match strategy, resulting in significant improvements in engineering properties and expanding its range of applications. However, achieving high-value utilization of phosphogypsum remains a major challenge. The 'synergistic effect of solid waste' and 'treating waste with waste' will be the new trends in the high-value development of phosphogypsum. This Review focuses on the modification method of phosphogypsum and the direction of resource utilization to provide a reference for promoting the high-value development of phosphogypsum.

1. Introduction

Phosphogypsum refers to the solid by-products produced when treating phosphate ore with sulfuric acid in the production of phosphoric acid, which contains a variety of impurities such as phosphorus, fluorine, and organic matter [1]. The problem of excessive radioactivity and heavy metals present in phosphogypsum will be the main challenge for the resource utilization of phosphogypsum. The content of radioactive elements and heavy metals in phosphogypsum varies in different regions of the world (table 1), and the trace element content of phosphogypsum varies with the process used to treat the phosphate rock. Although phosphogypsum contains only small amounts of trace elements, its relatively high concentrations of radionuclides and heavy metals pose environmental and health risks, significantly restricting its resource utilization. From the phosphogypsum Ra-226 radioactive activity concentration in different countries (figure 1), the radioactivity of phosphogypsum in Spain [2] and Morocco [3] is significantly higher, while that in China [3] and Brazil [4] is significantly lower, which meets the requirements of national standards. The global disparity in PG radioactivity necessitates region-tailored management strategies, with high-radiation regions such as Morocco needing to prioritize Ra removal technologies, while low-radiation regions such as China needing to promote large-scale recycling in in construction, aligning with circular economy targets. Addressing the challenges associated with phosphogypsum resource utilization remains a major environmental and technological issue for phosphoric

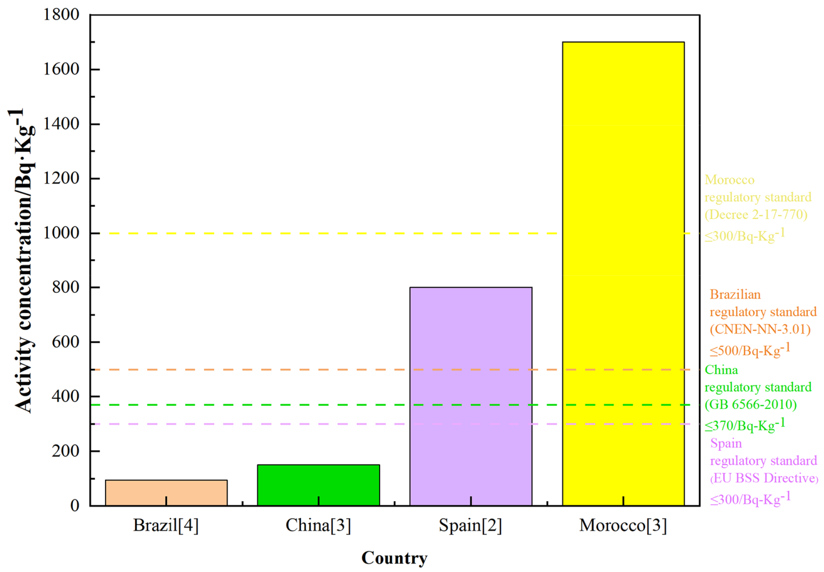


Figure 1. Activity concentration of Ra-226 in phosphogypsum in different countries.

Table 1. Trace element content in phosphogypsum in different regions.

Trace elements	Canada [8]	Tunisia [9]	Morocco [10]	Spain [11]
Cd	20	17.70 ± 1.77	6	2.14 ± 0.07
Pb	5	0.9 ± 0.09	6.2	0.03 ± 0.002
As	—	1 ± 0.1	—	2.6 ± 0.2
Cr	—	13 ± 1.30	20	18.3 ± 0.3
Zn	60	137 ± 13.7	8	11 ± 2
Cu	27.6	9.60 ± 1.37	21	5.2 ± 0.5
Ni	9	4.10 ± 0.41	<1	12 ± 2
U	9.4	1.6 ± 0.16	8.3	16.0 ± 0.2
Th	—	0.74 ± 0.7	4	2.42 ± 0.02

acid production facilities all over the world. The stockpile of phosphogypsum in China has reached 400 million tons and is still increasing at 50 million tons per year [5, 6]. In recent years, due to the limitations of stockpile sites and other constraints, China has reduced the stockpile of phosphogypsum under the implementation of relevant policies. Currently, China is experiencing a phase of rapid advancement under the ‘14th Five-Year Plan’, with the development of a circular economy serving as a key strategy for fostering green growth. With the development of the national economy and technology, the comprehensive utilization rate of China’s phosphogypsum has been significantly improved and entered a new stage. However, challenges such as a low comprehensive utilization rate, a lack of key technologies, and high treatment costs persist, preventing the effective resolution of the issue of large phosphogypsum stockpiles [7].

The rational application of phosphogypsum can not only realize the high-value application of phosphogypsum resources but also is an important link in solving China’s resource, energy, and environmental problems to achieve the ‘dual-carbon goal’ and sustainable development, which is in line with the current national green economy development policy [12]. Although there is more research on phosphogypsum, improving the level of phosphogypsum resource utilization is still an important challenge, therefore, the development of low-cost and high-value phosphogypsum still needs our continuous exploration [13]. Based on the relevant research on the resource utilization of phosphogypsum in recent years, this paper gives an overview of the status of the utilization of phosphogypsum, its main components, the impurities present, and the ways of resource utilization. It discusses the difficulties and problems faced in the process of resource utilization, looks forward to the future development trend of phosphogypsum, and provides references for the further scale and resource utilization of phosphogypsum under the premise of meeting the environmental requirements of phosphogypsum radioactivity and heavy metals.

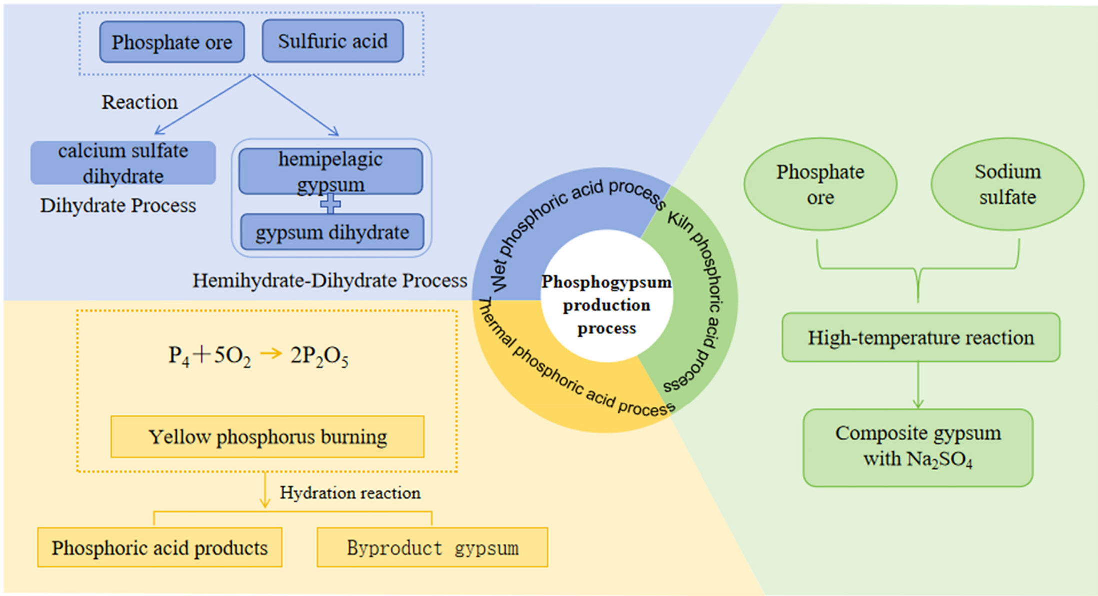


Figure 2. Phosphogypsum production process.

2. Current status of resource utilization of phosphogypsum

Phosphogypsum as a kind of solid waste is mainly handled in the way of stockpiling at present, this treatment method occupies a large amount of land resources, and phosphogypsum itself contains harmful impurities, which also pollute the environment, so it is very urgent to solve the problem of stockpiling of phosphogypsum at present [14, 15]. Based on this, many scholars have conducted research on the resource utilization of phosphogypsum, and at present the comprehensive utilization of phosphogypsum is mainly concentrated in the fields of construction, agriculture, and roads, the understanding of phosphogypsum is not systematic enough, and the efficiency of phosphogypsum's resource utilization is still to be improved [16].

2.1. Sources of phosphogypsum generation

Phosphoric acid production mainly involves three processes: the wet process, the kiln process and the thermal process (figure 2). Wet phosphoric acid production is currently the mainstream of phosphoric acid production. The wet phosphoric acid process includes the dihydrate process and hemidihydrate-dihydrate process. In the wet phosphoric acid process, phosphogypsum is produced as a result of the reaction between sulfuric acid and phosphate ore. After the extraction of phosphoric acid, the remaining calcium sulfate, containing a small amount of phosphorus, precipitates as calcium sulfate dihydrate, forming phosphogypsum. Every production of 1 t of phosphoric acid is accompanied by the production of 4-6t of phosphogypsum [14]. The hemihydrate-dihydrate method requires better reaction conditions compared to the dihydrate method in the wet phosphoric acid process, but there are fewer impurities in the phosphogypsum, which is dominated by hemihydrate gypsum, which can be crystalline controlled and calcined in order to make it use for ceramic molds. Despite the high impurity content of phosphogypsum, its low production cost has made it dominate the market, and it can be washed for phosphogypsum, lime neutralization method to reduce the influence of magazines, and is widely used for cement retarder. The thermal phosphoric acid process in phosphoric acid production does not directly generate phosphogypsum, as it uses yellow phosphorus as the raw material and bypasses the sulfuric acid decomposition of phosphate ore. Instead, it involves the high-temperature calcination of phosphate ore to produce phosphoric acid, during which phosphogypsum is also formed. This phosphogypsum primarily exists in the form of anhydrous gypsum type II and contains minimal impurities, rendering it suitable for direct application in medical-grade gypsum products. In contrast, the kiln phosphoric acid process generates phosphogypsum that contains Na_2SO_4, which can cause alkali flooding. After undergoing water leaching, sodium removal, and calcination, this phosphogypsum can be employed as a fireproof coating.

2.2. Status of comprehensive utilization of phosphogypsum

Comprehensive utilization of phosphogypsum is a worldwide problem, according to relevant information, the global stockpile of phosphogypsum has exceeded 6 billion [5], but its development and utilization are low, and the comprehensive utilization rate is only about 25% globally [17]. The global distribution of phosphogypsum is

Table 2. Comprehensive utilization of phosphogypsum in main producing countries.

District	Main application areas
China [18]	Stockpile-based, focusing on low-value products
United States [19]	Predominantly stockpiles, with a small amount used for agriculture
Russia [20]	Agricultural applications have been commercialized
Morocco [21]	Most are stored or discharged into the ocean
Tunisia [22]	Stockpiled in piles, partly used in cement manufacture

mainly concentrated in phosphate mining and agricultural production areas. The production and consumption of phosphogypsum are mainly concentrated in countries such as China, the United States, Russia, Morocco, and Tunisia. Among them, Morocco is one of the world's largest phosphate mining regions and an important source of global phosphogypsum supply. Because of the different national conditions of each country, the focus of phosphogypsum treatment also differs across countries (table 2). In most cases, such as in most countries, such as the United States, stockpiling remains the primary method for managing phosphogypsum.

Murali *et al* [23] summarized the application of phosphogypsum in building materials and studied the properties and microstructure of phosphogypsum in applications, which showed that phosphogypsum is used less in several value-added processes and that there is a huge potential for resource utilization of phosphogypsum. Lutskiy *et al* [24] analyzed the existing methods and approaches to the resource utilization of phosphogypsum in the Russian regions, based on which they showed the possibility of extracting rare earth elements from phosphogypsum, which can be promoted by using integrated processing technologies to maximize the extraction of valuable components. Canovas *et al* [25] reviewed the different potential uses of phosphogypsum, provided some insights into new value-added pathways, and described the advantages and disadvantages of each pathway. Due to the low utilization of phosphogypsum, new value-added pathways should be evaluated when pursuing new value-added pathways to ensure that each pathway is successful. From the overall situation of phosphogypsum application in foreign countries, phosphogypsum has developed maturely in the field of construction, developed rapidly in the field of agriculture, gradually explored in the field of roads, and gradually developed to high value.

The Phosphorus fertilizer industry is currently rapidly developing, and China is the largest producer of phosphogypsum [18], the production of phosphogypsum is huge, most of the phosphogypsum in China is mainly stockpiled, and the application in the field of building materials is the main way to deal with phosphogypsum. The comprehensive utilization level of phosphogypsum in China in 2023 compared with 2015 has been significantly improved, with the comprehensive utilization rate growing from 33.3% in 2015 to 55.6% in 2023, and the utilization volume growing from 26.5 million tons in 2015 to 45 million tons in 2023 (figure 3), but the gap between the utilization volume and the production and discharge volume is still very large, and there is an urgent need for China to phosphogypsum Efficient utilization ways and methods to solve the problem of large amounts of phosphogypsum stockpiles.

Cui *et al* [17] analyzed the generation and utilization of phosphogypsum in China, although the method of resource utilization of phosphogypsum in China has been relatively mature, and some provinces in China have low resource utilization, and the understanding of phosphogypsum needs to be further strengthened. Cui *et al* [28] summarized the current comprehensive utilization of the phosphogypsum industry development mode, based on the problems faced, put forward a new model of 'comprehensive utilization of phosphogypsum development platform', which accelerated the further development of phosphogypsum. Qin *et al* [29] analyzed the chemical composition of phosphogypsum, pretreatment methods, and application aspects of phosphogypsum, the study showed that calcination is a good pretreatment, it is proposed that prefabricated phosphogypsum-based road base plate and recycled aggregate with phosphogypsum used for base will be the new development direction for phosphogypsum-based materials.

The impurity content of phosphogypsum varies from region to region; for example, the vast majority of phosphorites in Florida, USA, contain natural radioactive elements such as U, Th, Ra, etc, and the strong radioactivity limits the application of phosphogypsum. Phosphogypsum in Morocco is also radioactive, but the radioactivity can be significantly reduced with appropriate treatment [30]. The vast majority of China's phosphate rock contains low levels of radioactive elements and relatively high Mg, Al, and Si content. Pretreatment can help reduce the content of Mg, Si, and Al and promote the complete reaction of phosphate rock as much as possible [31]. At present, the direction of phosphogypsum utilization in China is mainly focused on cement retarders, gypsum building material, ecological restoration, etc (figure 4), and the low-value utilization of phosphogypsum still accounts for the main body; to promote the development of phosphogypsum resource utilization, China is gradually transitioning to a new type of utilization of phosphogypsum.

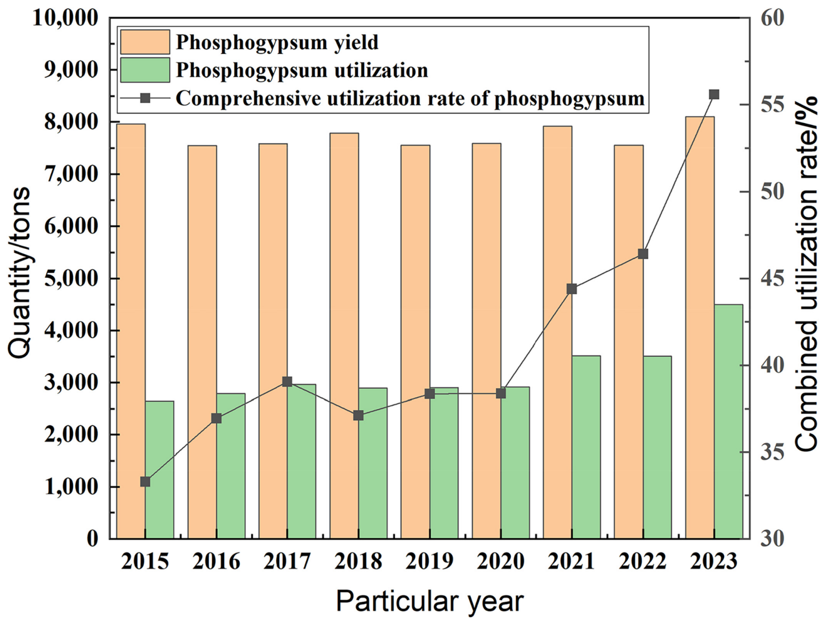


Figure 3. Comprehensive changes of phosphogypsum in China from 2015 to 2023 [17, 26, 27].

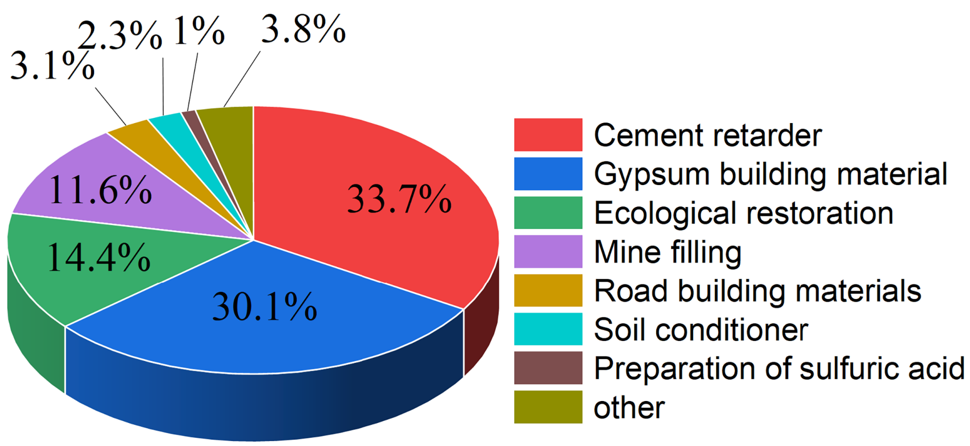


Figure 4. Distribution of phosphogypsum utilization channels in China in 2023. Reproduced from [27]. CC BY 4.0. CNKI Literature Database.

2.3. Phosphogypsum stockpiling problems

China generates a massive amount of phosphogypsum, and its extensive stockpiling has resulted in significant environmental pollution issues [32]. As public awareness of environmental protection continues to grow, the resource utilization of industrial solids such as phosphogypsum has received increasing attention. Due to the underdeveloped phosphorite decomposition process, the by-product phosphogypsum contains various impurities. These impurities along with the immature treatment method, limit the comprehensive utilization of phosphogypsum and lead to its large-scale accumulation. The impurities contained in phosphogypsum can seep into groundwater, surfaces, soil, and air, causing environmental pollution. These impurities can further enter the human body through environmental pathways, posing serious threats to human health [33]. The massive production of phosphogypsum in China has exceeded the capacity of existing storage sites, making it difficult to manage the growing stockpiles (figure 5). Therefore, under the 'three phosphorus' remediation, the '14th Five-Year Plan' comprehensive utilization of bulk solid waste, and other implemented policies, phosphogypsum production has been indirectly reduced. This has been achieved by restricting the construction of new phosphogypsum stockpiles and requiring enterprises to scale back phosphoric acid and phosphate fertilizer production based on the level of phosphogypsum's comprehensive utilization [17]. The introduction of the policy of 'determining production by slag' is to fundamentally solve the issue of comprehensive utilization of phosphogypsum and achieve 'balance of production and consumption,' thus improving the competitiveness of

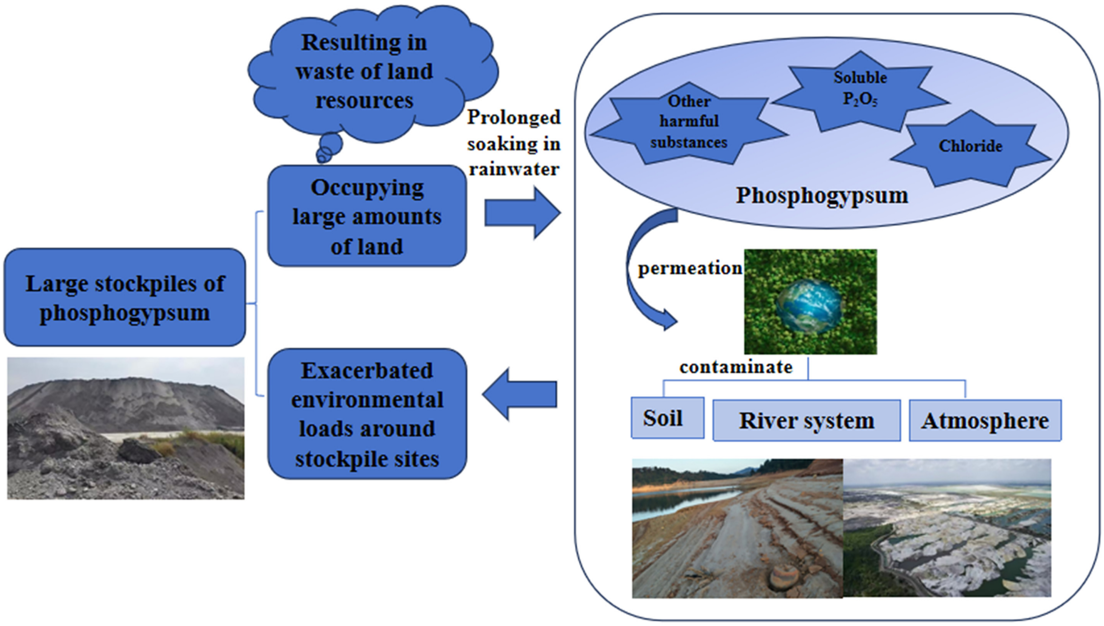


Figure 5. Hazards of large phosphogypsum stockpiles.

the phosphorus chemical industry. However, the comprehensive utilization level of phosphogypsum in China is not high, and its resource utilization is insufficient to offset the growing phosphogypsum output, even as the production of phosphoric acid and phosphate fertilizer continues to meet market demand. This forced some enterprises to reduce or even stop production, limiting the development of the phosphorus industry.

The storage of phosphogypsum poses environmental pollution risks and hinders its comprehensive utilization, both due to the presence of impurities. Therefore, the key to solve the issue of phosphogypsum storage is whether the impurities in phosphogypsum are effectively removed. This requires the development of a reliable pretreatment method to modify phosphogypsum. Once properly treated, phosphogypsum can be used as a raw material to achieve green transformation and improve its comprehensive utilization rate aligning with the goals of the current 'double carbon' strategy. As a central component of the 'three phosphorus' problem, phosphogypsum requires significant attention in terms of treatment and utilization. Diversifying its applications is the inevitable path toward maximizing its resource potential.

3. Main components and impurities of phosphogypsum

Phosphogypsum is mostly presented in powder form, with the appearance of gray-black or gray-white [34], and the crystal shape is mostly presented in plate form, different production processes can lead to different proportions of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) and calcium sulfate hemihydrate ($CaSO_4 \cdot 0.5H_2O$) contained in phosphogypsum, but $CaSO_4 \cdot 2H_2O$ is the main constituent [35]. Phosphogypsum is a better renewable resource [36–38].

In addition to $CaSO_4 \cdot 2H_2O$ as the main component, phosphogypsum also includes phosphorus, fluorine, organic matter, heavy metals, and radioactive impurities. The primary toxic and harmful components of phosphogypsum are mainly phosphorus and fluorine [39], which result from the incomplete decomposition of phosphate ores by sulfuric acid. A portion of the fluorine remains in the phosphogypsum, contributing to its impurity content. Most of the impurity phosphorus in phosphogypsum exists in the three forms of eutectic phosphorus, soluble phosphorus, and insoluble phosphorus [40–42], of which soluble phosphorus is the most significant form of existence that affects the properties of phosphogypsum. Soluble phosphorus is mainly composed of phosphoric acid, which exists in solution in the form of ions, which can react with calcium ions, and the calcium salt generated by the reaction is a kind of insoluble substance covering the surface of the phosphogypsum to prevent further hydration of the phosphogypsum [43]. Eutectic phosphorus exists in the form of eutectic crystals, which precipitate from the crystal lattice during hydration, and the reaction produces phosphate, a refractory substance that covers the surface of the crystals hindering further hydration of phosphogypsum. Refractory phosphorus exists in the form of $Ca_3(PO_4)_2$, which is difficult to dissolve in water and is characterized by its stable nature and concentrated distribution [44]. Fluorine impurities in phosphogypsum exist in the form of soluble fluorine and insoluble fluorine, insoluble fluorine is more stable and does not participate in the reaction [45], whereas the presence of soluble fluorine in phosphogypsum will weaken the intermolecular forces of phosphogypsum and accelerate the coagulation of phosphogypsum. In addition to the organic matter inherent in phosphogypsum, organic impurities include organic additives added during the production process, which are usually attached to the surface of phosphogypsum in the form of flocculants, which are insoluble substances [46]. In addition to this, trace amounts of radioactive and heavy metal elements are also present in phosphogypsum, and the content of heavy metals and radioactive elements in Chinese phosphorites is lower compared to those in other countries, resulting in lower levels of heavy metal-type and radioactive impurities in phosphogypsum . But their presence can also pose a threat to the environment and human health [40].

Phosphogypsum from different sources contains varying amounts ofmajor chemical components (figure 6). According to several studies, the average mass fractions of P_2O_5 and F in phosphogypsum are approximately 1.31% and 1.27%. Despite the complex composition of impurities in phosphogypsum, P_2O_5 and fluoride are the main impurity components. Impurities such as fluoride, phosphorus pentoxide, and free phosphoric acid are the main contributors to environmental pollution during the stockpiling of phosphogypsum. Phosphogypsum contains different types of impurities, and the corresponding forms of existence and hazards of different types of impurities are different [47] (table 3). Phosphogypsum contains a small amount of incompletely decomposed phosphorite and soluble nitrate class, which can corrode the production equipment and hinder the development of its resource utilization [26]. Therefore, phosphogypsum must be pretreated to reduce the impact of impurities before utilization. After pretreatment, it can be used as a raw material for resource applications, serving as the foundation and and key of phosphogypsum resource utilization.

4. Pretreatment of phosphogypsum

Phosphogypsum is an industrial waste with complex composition and diverse impurities, which can be used to produce hemihydrate gypsum to reduce the use of natural gypsum. The complex and diverse impurities in phosphogypsum and the not easily detectable state of its existence will not only cause harm to the environment but also hinder the process of phosphogypsum resource utilization, resulting in a low comprehensive utilization rate of phosphogypsum. Therefore, it is necessary to adopt efficient pretreatment methods for phosphogypsum to reduce the effects caused by impurities. Currently, there are many research reports on the mechanism of the effect of phosphogypsum impurities on gypsum [59], which mainly include physical, chemical, and thermal treatment processes to remove impurities [60, 61] (table 4).

4.1. Physical methods

4.1.1. Water washing method

The mature technology of the water washing method is currently the most commonly used method of phosphogypsum resource utilization, phosphogypsum in the organic matter is insoluble and its density is smaller than water, The water washing method is based on the organic matter is insoluble in water and floats on the surface of the water and water-soluble impurities dissolved in water characteristics to remove most of the impurities in phosphogypsum. The water washing method can be determined by measuring the PH value to determine whether the expected effect [62], when not reached, the water temperature can be controlled, and the number of times of washing to achieve better removal effect [46].

Although the water washing approach is straightforward and lessens the effect of soluble contaminants during resource consumption, it consumes a significant amount of water. Liu *et al* [63] found that most of the impurities were removed from phosphogypsum after washing by comparing the content of soluble phosphorus and fluorine impurities in phosphogypsum before and after washing. Fang *et al* [64] developed a new water-washing purification process by using vacuum pumps and filters in the water-washing process, which changed the traditional water-washing method of large water consumption shortcomings and removed most of the impurities other than eutectic phosphorus and silica so that the content of harmful impurities in the phosphogypsum is much lower than the standard requirements. Hou *et al* [65] synthesized calcium sulfate whiskers by washing and calcining respectively, and compared the calcium sulfate whiskers prepared by washing treatment with those prepared without washing treatment, and their research shows that the surface of phosphogypsum is smooth after washing, and most of the soluble impurities are removed, and the whiskers synthesized by using it as raw material have higher purity.

4.1.2. Ball-milling method

The ball-milling method requires the phosphogypsum to be ball-milled, the ball-milling time and intensity are the factors influencing the shape of phosphogypsum particles and gradation changes, and these elements can be adjusted to produce varied results. After the pretreatment of the ball milling process, the particles of

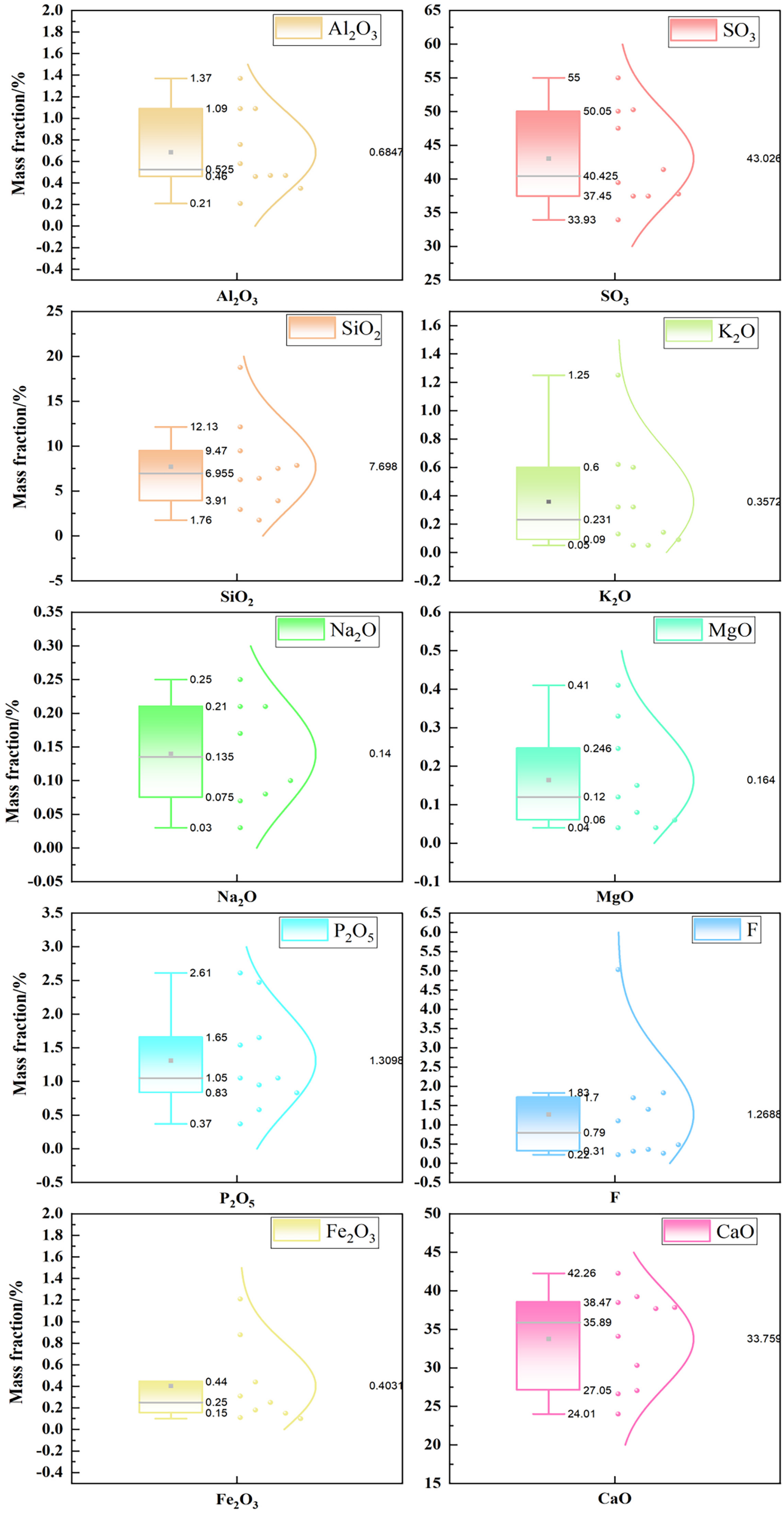


Figure 6. Main chemical composition of phosphogypsum [39, 48–56].

Table 3. The existence form and harm of impurity in phosphogypsum [57, 58].

Types of impurities in phosphogypsum	Forms of existence	Jeopardize
Phosphorus impurities	Phosphoric acid, Eutectic phosphorus, H_2PO^{4-}, HPO_4^{2-}, H_3PO_4	The presence of phosphorus impurities hinders the hydration of phosphogypsum and reduces the strength of the product
Fluorine impurities	F^-, CaF_2, SiF_6^{2-}, $NaAlF_6$, $CaSiF_6$	Due to the coagulation-promoting effect of soluble fluorine, when its mass fraction is greater than 0.3%, it will cause the crystal coarsening of the hydration product, and reduce the strength of the building products.
Organic impurities	Solid organic matter, Additives	Phosphogypsum used in building materials has a significant increase in water demand, which leads to a loose structure and reduced strength
Radioactive elements	Ra_{226}, Pb_{210}, Po_{210}	Contaminates of soil affect plant growth and cause serious harm to humans and the environment.
Other impurities	Complexes formed by metallic elements such as potassium and sodium with phosphates and sulfates	Sodium, and potassium alkali metals cause phosphogypsum surface flour, and frost, so dry gypsum product surface crystallization.

Table 4. The advantages and disadvantages of common impurity removal methods of phosphogypsum [60, 61].

Methodologies	Impurity removal methods	Advantages	Drawbacks
Physical method	Water washing method	Removes large amounts of soluble impurities without chemical reagents	The decontamination process is complicated, high cost, and small treatment capacity. The decontamination of sewage contains phosphorus, fluorine, etc, causing secondary pollution.
	Ball-milling method		
	Flotation method		
Chemical method	Lime Neutralization	Simple process, low cost, significant removal effect on most magazines, less secondary pollution	Different treatment agents need to be selected according to different types of phosphogypsum impurities, and there is a lack of analogous treatment technologies in different regions.
	Citric acid treatment		
Heat treatment method	High-temperature calcination method	Less environmental pollution, more complete removal of impurities. Excellent physical and chemical properties.	High energy consumption of the process and low treatment capacity. Corrosive to calcining equipment.
	Low-temperature calcination method		

phosphogypsum show diversified morphology, and the distribution of particles is changed to free distribution, which increases the fluidity of the cementitious material. Ball milling does not eliminate the harmful effects of organic impurities [66], therefore, the ball milling method needs to be combined with other pretreatment processes to decontaminate phosphogypsum.

Xu *et al* [67] discovered that particle size and morphology of phosphogypsum had different effects at different times of ball milling, and the strength of phosphogypsum hardened body is excellent in ball milling for 15–20 min, and the distribution of the particle size of phosphogypsum is categorized as 17–29 um. Chen *et al* [68] ground phosphogypsum in a ball mill for 50 min and added acetic acid to the process and it was found that impurities in the treated phosphogypsum decreased and the purity of phosphogypsum increased. Li *et al* [69] explored the particle size distribution of phosphogypsum under different milling times and the properties of its prepared building gypsum. The raw phosphogypsum can reduce the water consumption of standard consistency of building gypsum and improve its mechanical properties after the milling treatment, and the building gypsum can be prepared to meet the requirements by adjusting the milling time.

4.1.3. Flotation method

Flotation is the process of removing organic matter that floats to the surface after being washed with water by using a flotation device. Part of the principle of the flotation method is similar to that of the water washing method, but the flotation method compared to the water washing method is less water consumption, and water can be recycled, which is conducive to reducing costs. The flotation method has a good effect on the treatment of organic matter, which is conducive to the recovery of organic matter, and phosphorus and fluorine impurities do not apply to the flotation method for removing impurities, therefore, when the content of organic matter in the phosphogypsum is high, it can be used to remove impurities by flotation method [70].

Deng *et al* [71] found that the CM agent was effective in removing organic matter and silicate impurities by studying SEM and EDS of phosphogypsum before and after reverse flotation treatment with the CM agent. Zou *et al* [72] found that by using a 'screening pretreatment - flotation process' to treat phosphogypsum, the purification effect of phosphogypsum has been significantly improved, and promotes the resource utilization of phosphogypsum. Shen *et al* [73] used the technology of a roughing reverse flotation and the positive flotation of a roughing and five finishing, and the purity, yield, and whiteness of phosphogypsum could be up to 99.12%, 63.12%, and 81%, respectively, and the treatment of phosphogypsum purification and the whitening effect was obvious.

4.2. Chemical methods

4.2.1. Lime neutralization

Phosphogypsum is acidic, and its pH is low, which affects phosphogypsum products to a certain extent, it can be neutralized by adding lime and other alkaline substances, which in turn eliminates the effects of phosphorus, fluorine, and other acidic substances. The operation process of the lime neutralization method is simple and cost-effective, but when the alkaline material is mixed too much or too little, it will adversely affect the resource utilization of phosphogypsum, and this method is not obvious for the removal of organic matter, which has certain limitations.

Xie *et al* [74] found that phosphogypsum modified by limestone meets the production standard of ordinary silicate cement, but the amount of alkali added should be controlled to prevent the modified phosphogypsum from having too high or too low a pH. Li *et al* [75] treated phosphogypsum using the lime neutralization method, by studying the lime dosage, aging time, and infrared spectra of phosphogypsum before and after the treatment, it can be concluded that the lime neutralization method removes soluble phosphorus with good effect, soluble fluorine is not obvious, and it is not capable of removing eutectic phosphorus impurities. Wei *et al* [76] studied the effect of different lime dosages on the durability, frost resistance, impermeability, and sulfate corrosion resistance of phosphogypsum cement mortar, the study showed that the addition of the appropriate amount of quicklime can improve the durability, inhibit the frost resistance, with a mass fraction of 2% of the modified phosphogypsum cement mortar impermeability and resistance to sulfate corrosion of the best.

4.2.2. Citric acid treatment

Phosphorus and fluorine impurities in phosphogypsum can also react with the citric acid solution, and the products can be removed by water washing, thus reducing the impact of impurities. Phosphogypsum is treated by adding citric acid solution, and its microstructure is changed, resulting in improved properties [77]. Citric acid solution itself is acidic, to strictly control its concentration, pay attention to the effect of different ratios of the solution on the phosphogypsum.

Huang *et al* [78] soaked phosphogypsum with the citric acid solution at a concentration of 4% and found that the compressive strength of the treated phosphogypsum as a filler increased, and SEM showed that the microstructure of the treated phosphogypsum was improved and densification was better. Mashifana [79] studied the effect of four reagents, citric acid, oxalic acid, sodium carbonate, and sodium bicarbonate, on harmful impurities and radioactive components of phosphogypsum, respectively, and showed that citric acid reduces the presence of heavy metals and radioactive elements in phosphogypsum and that the best results were obtained when the leaching agent was 0.5 M citric acid. Singh [80] made the first attempt to treat phosphogypsum with aqueous citric acid solution to determine an improved method of phosphogypsum treatment by comparing the chemical, physical, and differential thermal analyses of treated and untreated phosphogypsum with citric acid solution.

4.3. Heat treatment methods

4.3.1. High-temperature calcination method

Phosphogypsum after high-temperature calcination, its soluble phosphorus and fluorine high-temperature activity is reduced into an inert material, reducing the soluble phosphorus, and fluorine on the phosphogypsum resource utilization caused by the impact of this way do not have to enter the other substances caused by the secondary pollution of a small, but this method of temperature has a very high requirement.

Zhong *et al* [81] found that the temperature was in the range of 300 ~ 500 °C by applying high temperature to phosphogypsum, the highest efficiency of removing impurities, and the continuous increase in temperature caused the whiteness of phosphogypsum to increase first and then decrease, and the treatment cost increased, but the impact of impurities and phosphogypsum pH is not significant, and the control of the calcination temperature should be considered comprehensively. Qin *et al* [29] showed that calcination is the most effective way compared to chemical and physical methods, phosphogypsum can be transformed at higher calcination temperatures, and based on comprehensive consideration of the economy and effectiveness, advanced calcination methods such as lowering the calcination temperature and adding additives can be used to improve the properties of phosphogypsum. Cao *et al* [82] systematically studied the effect of calcination temperature on the properties of phosphogypsum, which showed that the chemical mineral composition of untreated phosphogypsum and washed-treated phosphogypsum were similar under the same calcination temperature and that the increase of calcination temperature would reduce the content of fluorine impurities, but there was no change in the content of P_2O_5, and that calcined phosphogypsum had a dense microstructure and clear crystals at high temperature, and that calcination has a potential application in the recycling and utilization of phosphogypsum. There are potential application prospects in the recycling and utilization of phosphogypsum.

4.3.2. Low-temperature calcination method

Low-temperature calcination method also belongs to one kind of heat treatment method, compared with the traditional high-temperature calcination method, the low-temperature calcination method of phosphogypsum treatment can better retain the nature and shape of the particles, the calcination process is simple, but low-temperature calcination also has the corresponding shortcomings of this method on the size of the particles have a certain degree of requirements, and easy to appear in the process of calcination of the phenomenon of fracture. Liu *et al* [83] mixed three hydrochloric acids with phosphogypsum for low-temperature calcination, and it was found that ammonium chloride added to phosphogypsum was effective in reducing the soluble phosphorus and fluorine content in a low-temperature calcination environment. Geraldo *et al* [84] studied the effects of different calcination temperatures and times of phosphogypsum on the preparation of β-hemihydrous gypsum and the energy consumption in the calcination process, indicating that phosphogypsum calcined at 150 °C consumes the least energy and can obtain products with better performance. Li *et al* [85] investigated the dehydration of phosphogypsum at different temperatures and the changes of crystals, structure, and impurities of phosphogypsum, the results showed that the dehydration of phosphogypsum into β-semi-hydrate gypsum depended on the calcination temperature and time, and most of the phosphogypsum could be converted into β-semi-hydrate gypsum by calcining at 120 °C for 60 min, but there was no significant effect on the morphology and elemental distribution of the phosphogypsum at the temperature of 120 °C, and it was not able to remove phosphorus and fluorine impurities.

4.4. Modification mechanism analysis

Phosphogypsum is a common industrial waste with inherent limitations, including coarse particles, poor water absorption, and low strength. As a result, it requires modification to enhance its properties and broaden its potential applications. Phosphogypsum can be modified uisng physical, chemical, and comprehensive techniques, such as crystalline modification, $Ca(OH)_2$ neutralization modification, high-temperature modification. These methods alter its structural properties of reduce or eliminate the impact of harmful impurities, enhance its utilization value, and expand its application range, ultimately enabling resourceful utilization.

Phosphogypsum dissolved in water will produce SO_4^{2-} ions, and other materials produced by the material will produce a hydration reaction to generate the shape of the needle-like gel. Attached to the surface of the material will affect the flow of ions and water in the solution, which leads to a reduction in the rate of pre-reaction. SO_4^{2-} ions participate in the hydration reaction to form calcium-vanadite crystals. The network structure of calcium-vanadite crystals will increase the expansion rate of the material. Physical modification refers to improving the properties of phosphogypsum by physical means, such as grinding, screening, grinding, etc These methods can improve the particle size and distribution of phosphogypsum and improve its applicability. Chemical modification refers to the alteration of the internal structure and surface properties of phosphogypsum by means of chemical reactions, which substantially increases its value for agricultural and

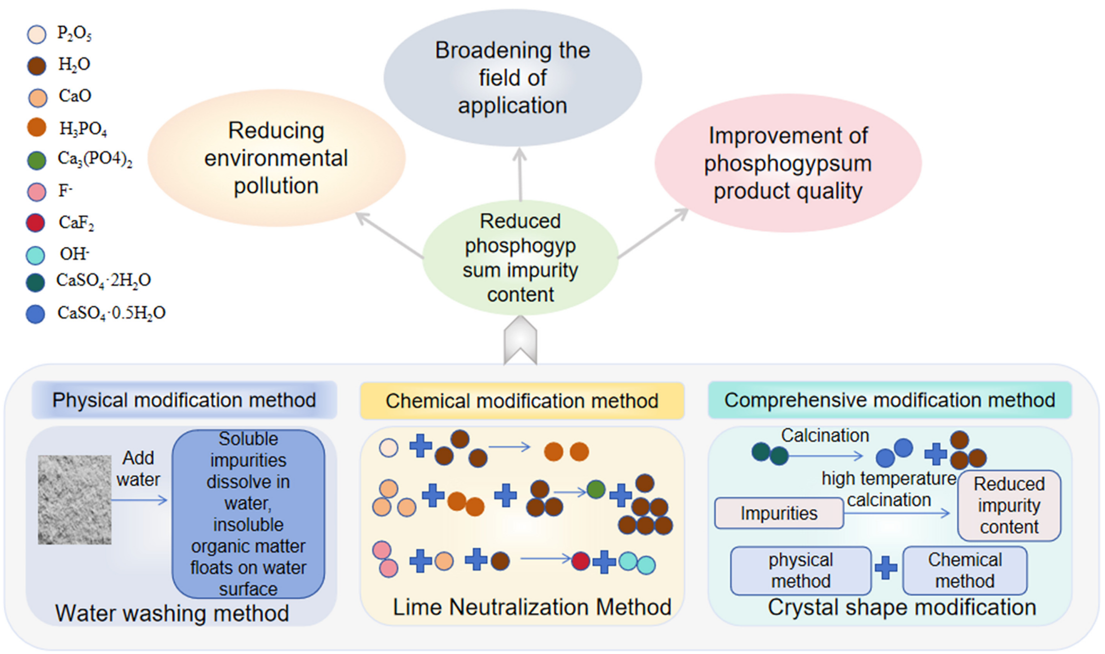


Figure 7. Common modification methods of phosphogypsum.

industrial applications. Commonly used chemical modification methods include lime neutralization modification, calcium sulfate modification, etc, which can improve the water absorption properties and strength of phosphogypsum. Comprehensive modification refers to the combination of physical and chemical methods to improve phosphogypsum comprehensively. This can give full play to the advantages of various modification means and improve the comprehensive performance of phosphogypsum (figure 7). Phosphogypsum modification is a fundamental and crucial aspect of its resource utilization. Depending on the composition of phosphogypsum and the intended end-use, appropriate modification methods are selected to treat it, reduce impurity content, and enhance its performance [86].

5. Resource utilization pathway of phosphogypsum

Most of China's phosphate mines contain low levels of radioactive elements, so phosphogypsum has low radioactivity, which creates favorable conditions for phosphogypsum resource utilization [87–89]. At present, China's comprehensive utilization of phosphogypsum technical routes is mainly based on the traditional low-value-added soil conditioning agents, cement retarders and other primary utilization pathways, and the lack of large-scale, large-doped, high-value-added technical application means. At present, how to solve the problem of phosphogypsum resource utilization and further promote the development of phosphogypsum resource utilization is a hot spot of current concern. The traditional utilization pathway cannot meet the requirements of efficient utilization of phosphogypsum at present, and the new utilization pathway is developing rapidly.

5.1. Ways of utilizing phosphogypsum

5.1.1. Preparation of cement retarder from phosphogypsum

Cement retarder is one of the raw materials for the production of silicate cement. The overexploitation of natural gypsum has led to a sharp decline in the reserves of natural gypsum, which can no longer meet the demand of the cement industry. Phosphogypsum and natural gypsum have the same main components and can be used in cement instead of natural gypsum to slow down the hydration time of cement and reduce the production cost of cement (figure 8), which not only reduces the overexploitation of natural gypsum but also consumes a large amount of phosphogypsum, which has good technical and economic benefits [90, 91]. According to statistics, China's cement production will be about 2,023 million tons in 2023, and phosphogypsum is expected to consume about 110 million tons of phosphogypsum instead of natural gypsum as cement retarder. As a result, utilizing phosphogypsum as a cement retarder is considered one of the most promising methods for its large-scale consumption [92]. Phosphogypsum preparation of cement retardation production process is a complex and important process, the new process of balling and phosphogypsum impurity modification technology

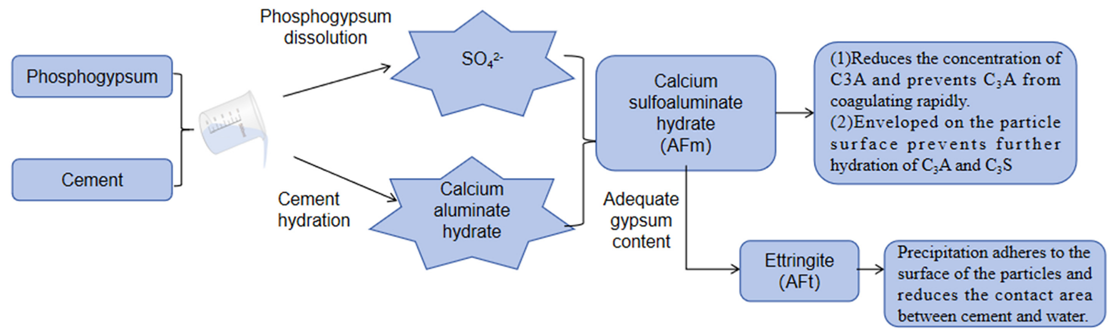


Figure 8. Mechanism diagram of phosphogypsum as cement retarder.

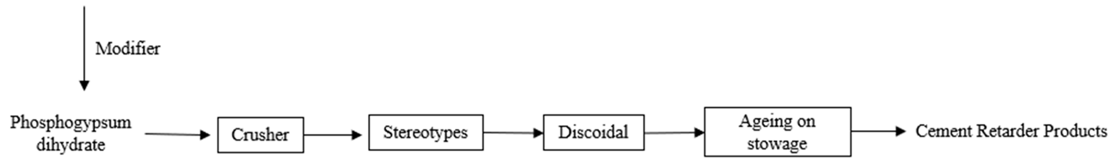


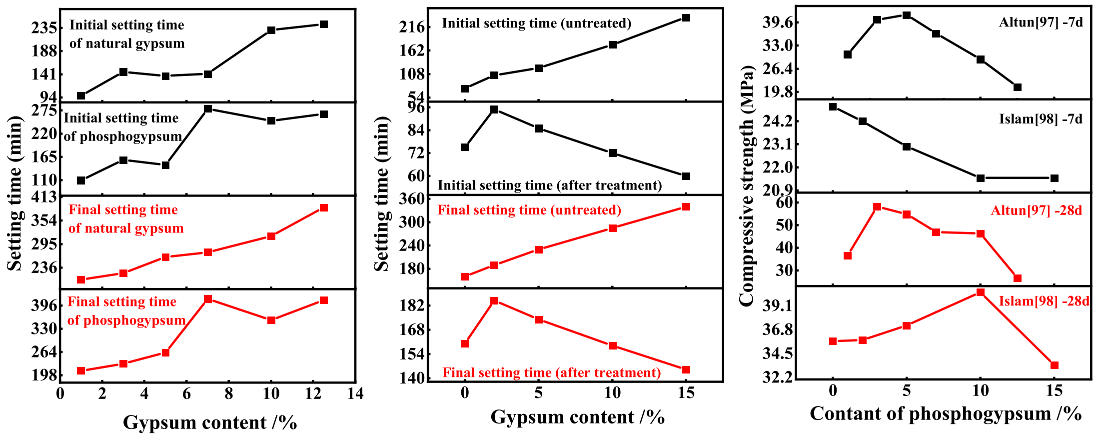
Figure 9. Flow chart of the new process of phosphogypsum balling for the preparation of cement retarder. Reproduced from [93]. CC BY 4.0. CNKI Literature Database.

promotes the use of phosphogypsum, improves the quality of the product and market competitiveness, reduces the cost of production, and can achieve energy saving and emission reduction [93] (figure 9).

Li *et al* [94] studied the effect of calcium carbide slag dosing, reaction temperature, and reaction time on phosphogypsum modification, respectively, and found that the addition of calcium carbide slag to phosphogypsum modification is not only conducive to the utilization of solid wastes but also the phosphogypsum modified with calcium carbide slag is applied to cement as a retarder with good results, optimizing the performance of cement. Hu *et al* [95] investigated the effect of phosphogypsum added to cement after three modification processes on cement properties, and it can be seen by comparison that phosphogypsum after autoclaving treatment is better than the other two modification processes as a retarder, and even better than natural gypsum in the application of cement. Luo *et al* [96] studied the effect of phosphogypsum modified by asphalt solid waste composite as a cement retarder, and it was found that this modified phosphogypsum can effectively retard the setting of cement, and its effect is the best under the ratio of one, which can be used instead of natural gypsum in cement. Altun [97] and Islam [98] investigated the effect of modified phosphogypsum incorporated into cement at different contents on setting time and compressive strength of silicate cement, and the results showed that phosphogypsum can replace natural gypsum as a cement retarder (figures 10(a), (b)), and weathered phosphogypsum added to silicate cement at an amount of 3% had the highest 28-day compressive strength; before and after the treatment, the phosphogypsum was significantly shorter than that before treatment. Compared with the amount of treated phosphogypsum at greater than 5%, the setting time of treated phosphogypsum was significantly shorter than that before treatment, which may be related to the formation of early dehydration [99], and the effect of 5–10% of treated phosphogypsum in cement clinker was better (figures 10(b), (c)). The impurities contained in phosphogypsum seriously affect the performance of cement, in which phosphate impurities will excessively prolong the cement setting time and damage the early strength of cement [100]. Therefore, phosphogypsum requires modification before application. Comparing the performance of cement retarders prepared using untreated and treated phosphogypsum reveals that the performance of those made with treated phosphogypsum is significantly improved.

5.1.2. Preparation of soil conditioners from phosphogypsum

Phosphogypsum i.e. can be used to regulate saline soils as well as acidic soils [101], phosphogypsum used in saline soils will invert the chemical reaction, which can effectively reduce the carbonate ions in the soil, produce soluble salts, and exchange the sodium ions in the soil with the phosphogypsum calcium ions, thus reducing the soil pH and effectively improving the soil properties [102] (figure 11). Phosphogypsum is usually used in a co-production process to prepare acidic soil conditioners (figure 12), and this process produces silica-calcium–potassium-magnesium fertilizers, which are alkaline fertilizers that can be used both to correct soil acidity and to improve soil fertility and promote crop growth.



(a) Effect of phosphogypsum and natural gypsum contents on cement setting time[97]

(b) Effect of phosphogypsum contents before and after treatment on cement setting time[98]

(c) Effects of phosphogypsum contents on compressive strength of cement [97, 98]

Figure 10. Effect of content on setting time and compressive strength.

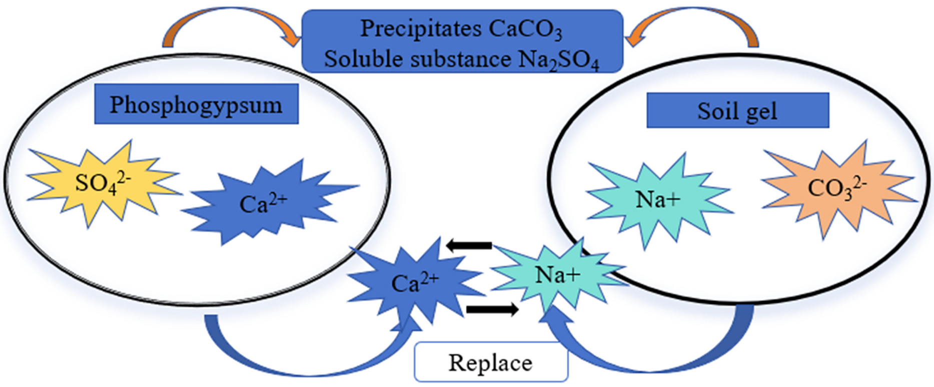


Figure 11. Mechanism diagram of phosphogypsum as a soil conditioner in saline-alkali land. Reproduced with permission from [102]. CC BY-NC-ND 4.0.

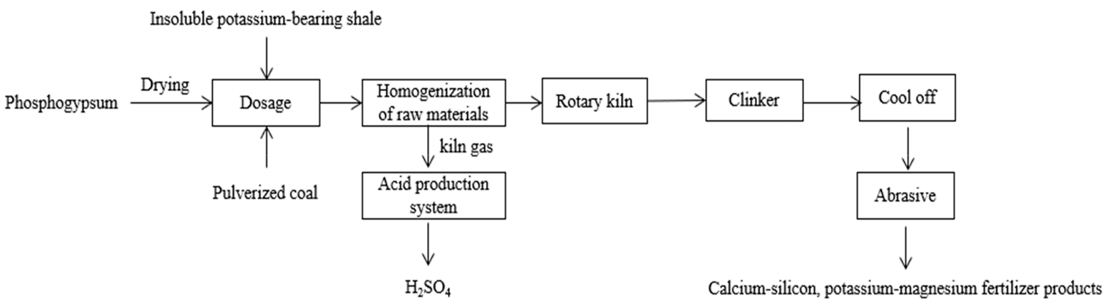


Figure 12. Mechanism diagram of phosphogypsum as acid soil conditioner. Reproduced from [103]. CC BY 4.0. CNKI Literature Database.

Lu *et al* [104] analyzed the improvement of the performance of phosphogypsum by harmless modification measures, and modified phosphogypsum can improve the soil pH and repair the soil environment in soil, and phosphogypsum application in agriculture is one of the effective ways of resource utilization. Hanafi *et al* [105] added organic phosphogypsum on sandy soil and conducted a multi-crop field trial for 23 months, the cumulative yield of plots intercropped with ragweed, teak, and sisal increased with the use of phosphogypsum organic fertilizers as compared to the control, therefore, the application of phosphogypsum organic fertilizers improves the soil environment and thus promotes plant growth. Han *et al* [106] conducted a three-year trial on

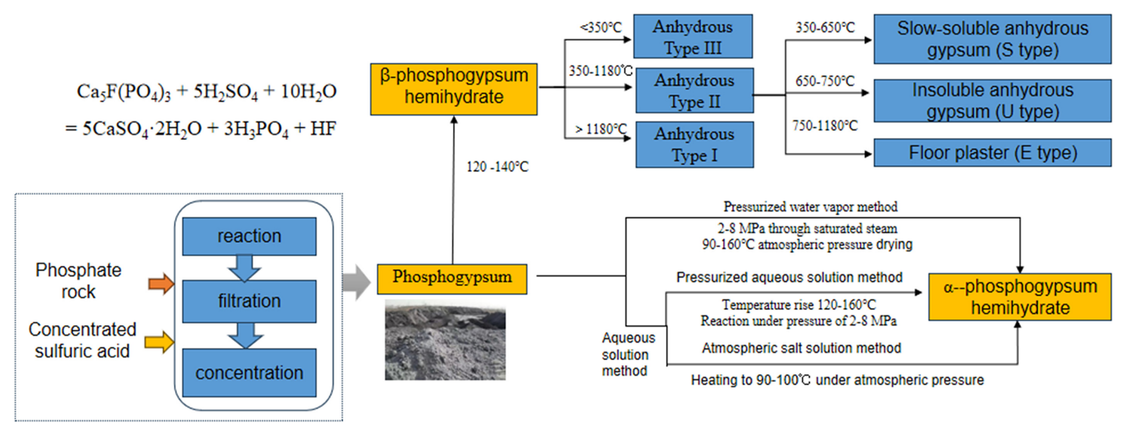


Figure 13. Process route of phosphogypsum preparation of hemihydrate phosphogypsum. Reproduced from [116, 118, 119]. CC BY 4.0. CNKI Literature Database. Reprinted from [117], Copyright (2018), with permission from Elsevier.

Table 5. Effects of 3-year application of silica-calcium–potassium-magnesium fertilizer on crops.

Crop	Yield/%	Soluble sugar/%	Soluble solids	w(VC)/mg·kg-1	Total acid/%
Shandong oilseed rape [107]	13	−0.03	—	18.03	—
Shandong grapes [108]	27.44 ~ 39.97	—	0.43 ~ 1.33	—	−0.09 ~ −0.01
Fujian honey pomelo [109]	4.40 ~ 11.70	−0.20 ~ 0.70	—	3.50 ~ 26.00	0.01 ~ 0.06
Guangdong bananas [110]	3.82 ~ 5.64	−0.72 ~ 0.94	−0.23 ~ 0.87	−5.10 ~ 11.90	—

Zhejiang rice, and the results showed that phosphogypsum conjugate products of silica-calcium–potassium-magnesium (SCPM) fertilizers were able to promote the growth of rice, reduce the amount of exchanged hydrogen ions and aluminum ions present in the acidic soils, increase the soil pH, and enhance the overall fertilizer retention of the soil. Through a three-year experiment, the effects of silica-calcium–potassium-magnesium fertilizer on the growth of rape, grape, honey, grapefruit, and banana were studied (table 5). It was found that the yield of Shandong rape, Shandong grape, Fujian honey grapefruit, and Guangdong banana could reach 13%, 27.44%, 4.40%, and 3.82% after three years of application of phosphogypsum co-production process product silica-calcium–potassium-magnesium fertilizer, and the overall quality of crops was improved.

5.1.3. Preparation of calcium sulfate whiskers from phosphogypsum

Calcium sulfate whisker is a kind of green material, and calcium sulfate whisker prepared by phosphogypsum is a high replication plus value product, calcium sulfate whisker has good performance and high cost-effectiveness [111, 112]. Natural gypsum is a non-renewable resource, and phosphogypsum instead of natural gypsum for the preparation of calcium sulfate whiskers has good economic benefits [113]. The hardness and strength of calcium sulfate whiskers hemihydrate are better than calcium sulfate whiskers dihydrate [114, 115]. Most studies have used purified phosphogypsum or natural gypsum as raw materials to prepare calcium sulfate whisker hemihydrate, but none of these studies have directly prepared calcium sulfate whisker hemihydrate from raw materials. Phosphogypsum is modified after treatment and purification through different control conditions. Crystal conversion agent is added to the calcium sulfate dihydrate in different modification processes to lose crystal water to form hemihydrate phosphogypsum. Products with different properties can be formed after modification under different control conditions. Currently, phosphogypsum is mainly prepared through calcination-dehydration transcrystallization and liquid-phase transcrystallization for β-hemihydrate gypsum, anhydrous type II gypsum, and α-hemihydrate gypsum, respectively (figure 13) [116].

α-hemihydrate gypsum crystals show relatively regular hexagonal prisms, β-hemihydrate gypsum crystals are similar to phosphogypsum in morphology showing plates or flakes, and anhydrous type II gypsum belongs to the orthorhombic crystal system also showing flakes [120]. Due to differences in crystal morphology, these forms of gypsum exhibit distinct characteristics, allowing them to serve different purposes (table 6). α-Hemihydrate gypsum, known for its high strength and excellent fluidity, is suitable for applications such as gypsum reinforcement and self-leveling mortar. In contrast, β-hemihydrate gypsum has lower strength and poor fluidity but is more cost-effective, making it ideal for use in gypsum building materials, line caulking, and similar applications. Anhydrous gypsum can be prepared by further calcination of β-hemihydrous gypsum and can be used in chemical fillers. The current process of preparing hemihydrate gypsum whiskers from

Table 6. Characteristics and uses of downstream products formed by phosphogypsum calcination [121, 124, 125].

Type	Characteristic
Alpha-hemihydrous phosphogypsum	High strength, good hardness and stability, good fluidity, fast set hardening
Beta-phosphogypsum hemihydrate	Relatively low strength and relatively poor mobility
Anhydrous phosphogypsum type I	It exists when the calcination temperature is higher than 1180 °C and does not have hydration activity.
Anhydrous phosphogypsum type II	Almost no crystallization and difficult to dissolve in water, the increase in calcination temperature is conducive to the densification and stability of the crystalline form, but it will reduce the hydration activity and be transformed into gypsum dihydrate after the activity excitation.
Anhydrous phosphogypsum type III	Honeycomb structure with strong vapor adsorption capacity, which can be transformed into β-hemihydrate gypsum after adsorption of vapor.

phosphogypsum has received much attention, and phosphogypsum is a high-performance material with good potential for development [121]. The mechanical properties of α-hemihydrate gypsum are better than those of β-hemihydrate gypsum. However, its preparation is limited by a complex process, high production costs, and challenges in achieving large-scale continuous production. Therefore, the process of preparing α-hemihydrate gypsum from phosphogypsum needs to be further developed to realize the development of phosphogypsum with high value. Chen *et al* [122] improved the mechanical properties of α-hemihydrate gypsum made from phosphogypsum by adding compounds such as fluorine and aluminum. In phosphoric acid solution, the properties of α-hemihydrate gypsum varied by adding different amounts of modifiers. Wet phosphoric acid solution was used to synthesize morphologically controllable and mechanically excellent α-hemihydrate gypsum. Lin *et al* [123] proposed an efficient and simple method for the preparation of α-hemihydrate gypsum whiskers to study the effect of phosphogypsum on the preparation of α-hemihydrate gypsum whiskers under different experimental parameters, and the results showed that at the concentration of HCl, the reaction temperature, and the reaction time of 6 mol l^{-1}, 80 °C, and 30–60 min, respectively, the purity of α-hemihydrate gypsum whisker can reach 100%, which provides a new idea for the sustainable development of phosphogypsum.

5.2. New advances in phosphogypsum utilization pathways

Phosphogypsum and red mud (RM)are two typical types of bulk industrial wastes, which are difficult to reuse due to their large emission, complex composition and high environmental risk. RM is a kind of solid waste produced in the process of alumina production, which has various hazards. RM is alkaline slag, the main chemical composition of Fe_2O_3, Al_2O_3, SiO_2, Na_2O, CaO and so on. Phosphogypsum is an acidic slag, the main chemical composition contains CaO and SO_3. Therefore, the mineral properties of RM d and phosphogypsum can be used to realize the synergistic utilization of phosphogypsum and RM based on the principle of acid–base neutralization (figure 14). Al, Fe, and Na are currently extracted from phosphogypsum and red mud by sintering mainly through soda-lime. Phosphogypsum can be decomposed at high temperatures into CaO, which allows phosphogypsum to be used instead of quicklime. Therefore, the extraction of valuable metals from red mud and phosphogypsum is a viable approach. This method can facilitate the high-value utilization of these two types of industrial solid waste, mitigate environmental pollution, and achieve the objective of utilizing waste to treat waste.

Lu *et al* [126] used two slag synergistic treatments to realize the technological idea of calcium recycling and simultaneous recovery of aluminum and sodium, and the small pilot test showed that under the conditions of a sintering temperature of 850 °C, two times the theoretical additive amount of reductant, C/S = 2.1, N/A = 1.1, and a sintering time of 7 min, the recovery of aluminum and sodium was 82.14% and 83.48%, which were the most suitable process conditions. A pilot test was also carried out under this condition, and the results showed that the aluminum and sodium recoveries obtained in the pilot test were slightly lower (76.32% for Al_2O_3 and 81.25% for Na_2O) compared with the small pilot test. Lei *et al* [127] used high-temperature sintering-alkali leaching to extract aluminum-magnetic separation to extract iron process to synergistically treat three kinds of solid wastes to recover aluminum and iron and investigated the effect of process conditions of sintering process on the recovery rate of aluminum and iron. Under the conditions of sintering temperature of 1100 °C, holding time of 30 min, and calcium ratio of 2.0, the iron recovery rate reached 79.2% and the aluminum dissolution rate reached 75.9%. Xiao and coworkers [128] adopted a three-step method of alkali lime sintering-leaching-magnetic separation. Under the conditions of sintering temperature 1100 °C, sintering atmosphere N_2, sintering time 30 min, C/S =2.0, N/A =1.3, aluminum recovery, iron recovery, and iron grade are 69%, 78%, and 83.8%, respectively. The feasibility of the high-temperature collaborative treatment of phosphogypsum and red mud resource utilization technology is verified through experiments. Through testing, the feasibility of high-

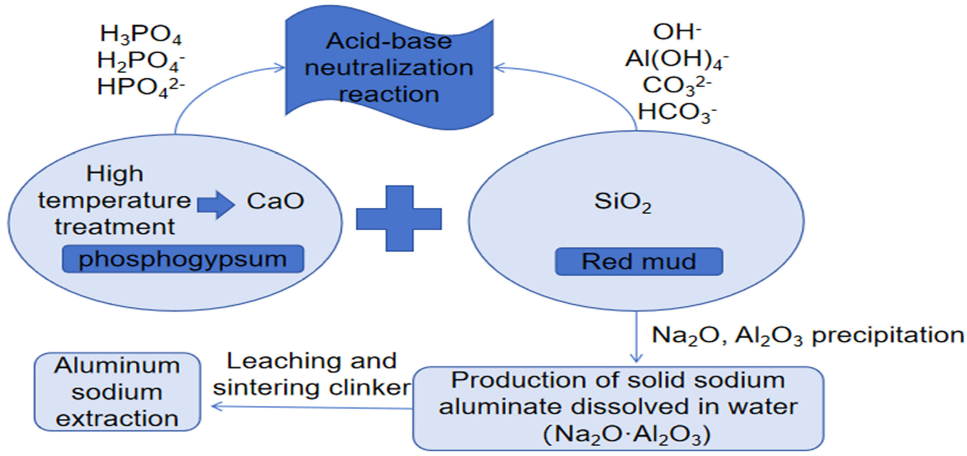


Figure 14. Mechanism of recovery of valuable components by alkali lime sintering. Reproduced from [126]. CC BY 4.0. CNKI Literature Database.

temperature synergistic treatment and resource utilization of phosphogypsum and red mud has been verified. This process enables the green, synergistic elimination of multiple solid wastes, reduces environmental pollution, and effectively promotes comprehensive resource utilization. The synergistic use of various solid wastes is expected to become a new direction in solid waste resource management.

5.3. Future direction of phosphogypsum application

Phosphogypsum, a solid waste generated from the wet phosphoric acid process, holds significant development potential for resource utilization due to its chemical composition and inherent properties. The accumulation of phosphogypsum, however, can cause a series of environmental issues. Under the current context of the 'double carbon' and 14th Five-Year Plan development background, the resource utilization of phosphogypsum and other solid wastes has attracted widespread attention from both society and the government. Although the production of phosphogypsum has been somewhat regulated through policy implementation, these measures have also constrained the growth of the phosphorus industry.

The key to the resource utilization of phosphogypsum lies in eliminating the impact of impurities and exploring high-value utilization pathways. Chemical, physical, and thermal pretreatment methods are commonly used to address specific impurities, but phosphogypsum contains diverse and complex impurities. As a result, pretreatment using a single method often leaves behind residual impurities. Additionally, the pretreatment process faces challenges such as incomplete impurity removal, complex procedures, and high costs, making it difficult to meet the quality standards required for comprehensive product utilization. To enhance the utilization of pretreated phosphogypsum, researchers have conducted in-depth studies on fundamental pretreatment methods, aiming to develop comprehensive and efficient technologies for the removal of phosphogypsum impurities. The building materials sector is currently the primary means of consuming large quantities of phosphogypsum, providing a quick solution to the stockpiling problem . However, in the long run, with the overcapacity of China's cement industry, the scale of phosphogypsum application in the construction industry is gradually declining, and the building materials field is not a long-term solution to phosphogypsum stockpiling [32]. Although phosphogypsum has been applied in agriculture, the chemical industry, and environmental management, with its utilization pathways showing diversified potential, challenges such as high costs, secondary pollution, and product instability have prevented the establishment of large-scale, high-value-added resource utilization routes. As a result, the comprehensive utilization of phosphogypsum in China remains in its early developmental stage. Effective utilization of phosphogypsum to realize zero emissions and eliminate stockpiles is the inevitable requirement for sustainable development of the industrial economy and environmental protection in China.

In recent years, under the joint promotion of the government and industry, the comprehensive utilization rate of phosphogypsum has been improved. However, it still cannot meet the current utilization requirements of phosphogypsum. By means of physical, chemical and solid-waste coupling, a variety of solid wastes can be treated as resources and the cost of pollution control can be reduced. At present, the resource utilization rate of phosphogypsum has been low; unstable product performance and other problems always exist. To address this issue, it is essential to focus on the ecological value of phosphogypsum, following the concept of 'curbing waste with waste and achieving clear waters and green mountains.' This involves an in-depth exploration of the development status of the phosphogypsum industry, technological breakthroughs in its comprehensive utilization, and the extension of the industrial chain. Collaborative efforts are needed to identify a green development pathway for phosphogypsum resource utilization. Additionally, the synergistic development of multiple solid wastes is expected to become a key trend in the future.

6. Conclusion and outlook

Phosphogypsum is a renewable solid waste, and its resource utilization has good economic and social benefits. The resource utilization rate of phosphogypsum in China reaches 55.6% in 2023, and the production of phosphogypsum and the utilization of phosphogypsum cannot reach a balance. The key to large-scale utilization of phosphogypsum lies in the reduction and removal of impurities, and harmless treatment will be the basis of comprehensive utilization of phosphogypsum. Although China's phosphogypsum used as soil conditioner, cement retarder, and building materials in the field of technology is more mature, the added value of the products produced by this technology is low, the and utilization rate of phosphogypsum is not high, these technologies are no longer applicable to the current economic and social development, phosphogypsum used in the preparation of whiskers and fixation of radioactive elements, and other new technologies will be the hot spot of the research on the utilization of phosphogypsum resources. This paper summarizes the research progress of phosphogypsum in the current resource utilization, focusing on the summary of phosphogypsum pretreatment methods and utilization pathways. Through the synergistic effect of solid waste, Treating waste with waste will be the new direction of industrial solid waste resource utilization.

At present, China's phosphogypsum is mainly facing the following problems in resource utilization:

(1) The wet phosphoric acid process adopts a more dihydrate method, and its by-product phosphogypsum has more impurity content and poor quality, and the impurities contained impede the process of phosphogypsum resource utilization.

(2) The components of phosphogypsum are complex, and the impurity content and types of phosphogypsum in different regions are different, which leads to the influence of the quality and application effect of the comprehensive utilization products of phosphogypsum in different regions when treating phosphogypsum with the same process.

(3) The current comprehensive utilization of phosphogypsum lacks the application technology of large dosage, large scale, and high value, and the development of the phosphogypsum utilization pathway is limited by cost factors.

Effective measures should be taken to address the above problems:

(1) Increase the use of α-gypsum method of phosphoric acid process, optimize the phosphoric acid leaching process, greatly reduce the impurity content of phosphorus gypsum, as far as possible to recover valuable elements, and promote the development of efficient phosphorus gypsum treatment technology.

(2) Enterprises around the world should coordinate with each other to develop testing methods and phosphogypsum quality evaluation systems in line with industry conditions, to fully understand the quality of the phosphogypsum used.

(3) To enhance the high-value and large-scale development of phosphogypsum, the company has joined hands with enterprises, research institutes, and universities to formulate a comprehensive utilization plan for phosphogypsum, intensify research and development efforts, and develop products with high value-added. Multi-solid waste synergistic use will be an effective way of phosphogypsum resource utilization.

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Data availability statement

No new data were created or analysed in this study.

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