QO‘QON DAVLAT PEDAGOGIKA INSTITUTI ILMIY XABARLARI
(2026-yil 6-son)

TABIIY FANLAR

NATURAL SCIENCES

https://doi.org/10.70728/a.series.tab.v08.i06.015

UDC 631.842.4

SCIENTIFIC AND TECHNOLOGICAL FOUNDATIONS FOR WASHING-BASED PURIFICATION OF PHOSPHOGYPSUM

Namazov Shafoat Sattarovich
Dr. Tech. Sc., Prof., Academician, Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan
Tel: +998 91 162 3846
E-mail: erkinovichjamshid@mail.ru
Radjabov Ruzmat
cand. tech. Sc., Senior Researcher, Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan
Tel: +998 90 530 4981
E-mail: radjabov.r@yandex.com
Kholmurodov Jamshid Erkinovich
[1]Doctor of Philosophy in Technical Sciences, Senior Researcher, Institute of General and Inorganic Chemistry, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan, [2]Doctoral student, Namangan State Technical University, 160115, Namangan, Uzbekistan
Tel.: (+99895) 801-07-91,
E-mail: erkinovichjamshid@mail.ru
Karshiev Bekzod Nosirovich
Doctor of Philosophy in Technical Sciences, Doctoral student, Institute of General and Inorganic Chemistry, Academy of Sciences of the Republic of Uzbekistan
Tel.: (+99893) 009-86-88,
E-mail: erkinovichjamshid@mail.ru
Khudayberdiyev Jaloliddin Khasanovich
Acting Associate Professor of the Department of Chemistry and Ecology, Kokand State University
Tel.: (+998903078586)
E-mail: Ximik_uz@mail.ru

Abstract. This article examines the ecological and technological foundations of purifying phosphogypsum from harmful impurities. Phosphogypsum is a technogenic waste generated in large quantities during the production of wet-process phosphoric acid from phosphate raw materials. In addition to calcium sulphate dihydrate, it contains phosphates, fluorides, silicon, iron and aluminium compounds, soluble salts, and other impurities. These impurities limit the use of phosphogypsum in the production of construction materials, mineral fertilizers, and chemical products. In this study, the potential to improve the physicochemical and morphological properties of phosphogypsum samples was evaluated by first washing them with ordinary water, then with weakly acidic water, using a counter-current washing method. During the washing process, partial removal of soluble phosphate and fluoride ions, residual acids, and finely dispersed impurities was observed. SEM analysis revealed uneven layers and adhered impurities on the surface of unwashed phosphogypsum, whereas the washed sample exhibited relatively cleaner crystal surfaces. The results substantiate the necessity of a washing stage before using phosphogypsum as a secondary mineral raw material for subsequent chemical conversion, the production of ammonium sulfate and calcium carbonate, and the manufacture of construction materials.

Keywords: phosphogypsum, washing, weakly acidic medium, harmful impurities, phosphate, fluoride, SEM, secondary raw material.

Аннотация. В данной статье рассматриваются экологические и технологические основы очистки фосфогипса от вредных примесей. Фосфогипс представляет собой техногенный отход, образующийся в больших количествах при производстве экстракционной фосфорной кислоты из фосфатного сырья. Наряду с дигидратом сульфата кальция он содержит фосфаты, фториды, соединения кремния, железа и алюминия, растворимые соли, а также другие примеси. Наличие указанных компонентов ограничивает применение фосфогипса при производстве строительных материалов, минеральных удобрений и химической продукции. В настоящем исследовании оценена возможность улучшения физико-химических и морфологических свойств образцов фосфогипса путем их последовательной промывки сначала обычной водой, затем слабокислой водой с применением противоточного метода промывки. В ходе процесса промывки установлено частичное удаление растворимых фосфат- и фторид-ионов, остаточных кислот и тонкодисперсных примесей. SEM-анализ показал, что поверхность непромытого фосфогипса характеризуется неровными слоями и наличием прилипших примесей, тогда как промытый образец имеет относительно более чистую поверхность кристаллов. Полученные результаты обосновывают необходимость включения стадии промывки перед использованием фосфогипса в качестве вторичного минерального сырья для последующей химической конверсии, получения сульфата аммония и карбоната кальция, а также производства строительных материалов.

Ключевые слова: фосфогипс, промывка, слабокислая среда, вредные примеси, фосфат, фторид, SEM, вторичное сырье.

Annotatsiya. Ushbu maqolada fosfogipsni zararli aralashmalardan tozalashning ekologik va texnologik asoslari o‘rganildi. Fosfogips fosfat xomashyosidan ekstraksion fosfat kislota ishlab chiqarish jarayonida katta miqdorda hosil bo‘ladigan texnogen chiqindi bo‘lib, uning tarkibida kalsiy sulfat digidrat bilan bir qatorda fosfatlar, ftoridlar, kremniy, temir, alyuminiy birikmalari, eruvchan tuzlar va boshqa aralashmalar uchraydi. Mazkur aralashmalar fosfogipsdan qurilish materiallari, mineral o‘g‘itlar va kimyoviy mahsulotlar olish imkoniyatini cheklaydi. Tadqiqotda fosfogips namunalarini dastlab oddiy suvda, so‘ngra kuchsiz kislotali suvda qarama-qarshi oqim usulida yuvish orqali uning fizik-kimyoviy va morfologik xususiyatlarini yaxshilash imkoniyati baholandi. Yuvish jarayonida eruvchan fosfat va ftorid ionlari, qoldiq kislotalar hamda mayda dispers aralashmalarning qisman ajralishi kuzatildi. SEM tahlillari yuvilmagan fosfogips yuzasida notekis qatlamlar va yopishgan aralashmalar mavjudligini, yuvilgan namunada esa kristall yuzalar nisbatan tozalanganini ko‘rsatdi. Natijalar fosfogipsni keyingi kimyoviy konversiya, ammoniy sulfat va kalsiy karbonat olish, shuningdek, qurilish materiallari ishlab chiqarishda ikkilamchi mineral xomashyo sifatida qo‘llashdan oldin yuvish bosqichining zarurligini asoslaydi.

Kalit so‘zlar: fosfogips, yuvish, kuchsiz kislotali muhit, zararli aralashmalar, fosfat, ftorid, SEM, ikkilamchi xomashyo.

Introduction. Phosphogypsum is a high-volume technogenic waste produced during the extraction of phosphoric acid from phosphate raw materials. The decomposition of phosphate raw materials with sulphuric acid yields phosphoric acid as the primary product and generates significant quantities of phosphogypsum, which consists mainly of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), as a by-product. Annually, global phosphogypsum production is estimated at 200-280 million tonnes, with total accumulated volumes reaching several billion tonnes. The open storage of such large quantities of waste leads to environmental challenges, including land occupation, dust generation, filtrate water production, and the migration of soluble phosphate and fluoride ions into the environment [1,2].

While calcium sulfate dihydrate is the principal mineral component of phosphogypsum, the material may contain various impurities depending on production conditions, the type of phosphate raw material, and the technological regime. Impurities can include free phosphoric acid, water-soluble phosphates, fluorides, silicon, iron, aluminum, and potassium compounds, organic residues, and certain heavy metal ions. These contaminants alter the physicochemical properties of phosphogypsum, reduce its environmental safety, and limit its direct industrial applications. Specifically, phosphate and fluoride compounds can adversely affect the setting process in building material production, the hydration of cement systems, and the strength of the final product. In chemical processing, such impurities may destabilize the reaction medium, lower precipitate quality, or become incorporated into the final product [3,4].

In recent years, interest in considering phosphogypsum has been increasing. Recently, phosphogypsum has increasingly been regarded as a potential secondary mineral resource rather than merely waste. Numerous studies have explored its use in producing gypsum binders, cement additives, construction materials, soil ameliorants, ammonium sulfate, calcium carbonate, and other valuable products. However, effective utilization of phosphogypsum requires reducing harmful impurities and appropriately preparing the raw material for subsequent technological processes. Consequently, preliminary purification, particularly the removal of soluble and surface impurities through washing, represents a significant scientific and practical challenge [2-4]. Water washing is the simplest, most economical, and technically easiest to implement at the initial preparation stage. During water washing, part of the free acids, water-soluble phosphates, fluorides, and other salts present in phosphogypsum pass into the solution. As a result, the acidity of phosphogypsum decreases, while the electrical conductivity of the washing solution is initially high and gradually decreases in subsequent stages. This indicates the gradual removal of soluble impurities. The scientific literature reports the potential use of water-washed phosphogypsum as a cemented filler or as a component of construction materials, noting that the reduction of PO_4^{2-} and F^- ions resulting from washing improves the material's technological properties [5].

At the same time, washing with water alone does not eliminate all harmful impurities. Some phosphate and fluoride compounds may be adsorbed onto particle surfaces, bound within the solid phase, or present as insoluble silicates, calcium phosphates, and calcium fluorides. Effective removal of these impurities requires pH control of the washing medium, the use of a weakly acidic solution, or additional physicochemical treatments. Employing a weakly acidic medium facilitates the transfer of residual phosphate and fluoride compounds from the particle surface into solution, separates finely dispersed impurities, and yields a cleaner phosphogypsum surface [6,7]. The gypsum washing process should be evaluated not only by changes in chemical composition, but also by changes in its morphological and phase structure. SEM analysis enables the identification of uneven layers, finely dispersed impurities adhered to the surface, and mechanical contamination on unwashed phosphogypsum particles. After washing, the particle surface becomes relatively cleaner, crystal forms become more clearly visible, and the amount of finely dispersed impurities decreases. XRD analysis is used to determine whether $CaSO_4 \cdot 2H_2O$ remains the primary mineral phase after washing. EDS or XRF analyses may also show a reduction in the proportion of P_2O_5, F, SiO_2, Fe_2O_3, and other impurities. The thesis you submitted also emphasises that, after washing, the pH is expected to become relatively neutral, electrical conductivity is expected to decrease, SEM images are expected to show a reduction in finely dispersed impurities on the particle surface, XRD is expected to confirm the preservation of $CaSO_4 \cdot 2H_2O$ as the main phase, and EDS/XRF analyses are expected to show a decrease in the proportions of P_2O_5 and F.

Water consumption and the generation of waste solutions during phosphogypsum washing are critical technological considerations. A simple single-stage washing process may require substantial volumes of water and yield low-concentration waste solutions. In contrast, a counter-current washing scheme offers environmental and economic advantages. In this approach, fresh washing solution contacts the already-purified phosphogypsum, while the used washing solution is applied to the raw phosphogypsum. This configuration reduces water usage, concentrates soluble impurities in the waste solution, and simplifies subsequent neutralization or utilization processes. The initial thesis also identifies the counter-current method as a technologically, economically, and environmentally sound solution for washing phosphogypsum with water and weakly acidic water.

An additional key benefit of preliminary phosphogypsum washing is the preparation of the raw material for subsequent chemical conversion processes. For instance, reacting washed phosphogypsum with ammonium carbonate yields ammonium sulfate and calcium carbonate:

$CaSO_4 \cdot 2H_2O + (NH_4)_2CO_3 \rightarrow (NH_4)_2SO_4 + CaCO_3 + 2H_2O$.

During this process, residual phosphates, fluorides, and other impurities in phosphogypsum can influence the conversion rate, solution composition, and the quality of the calcium carbonate precipitate. Consequently, washing phosphogypsum prior to conversion stabilizes the reaction medium, enhances product quality, and increases process efficiency. Additionally, washed phosphogypsum can be considered a safer and more reactive secondary mineral raw material for producing construction materials, gypsum binders, and other chemical products.

This study aims to investigate the ecological and technological principles underlying the counter-current washing of phosphogypsum using both ordinary and weakly acidic water. It seeks to assess the reduction of harmful impurities achieved through washing and to justify the use of washed phosphogypsum as a prepared raw material for subsequent chemical conversion processes. The evaluation of washing efficiency will be based on pH, electrical conductivity, phosphate and fluoride ion content, and SEM analyses.

Methods and Materials

This research focused on phosphogypsum, a byproduct from phosphoric acid production at “Ammofos-Maksam” JSC. Phosphogypsum forms during the decomposition of phosphate raw material by sulphuric acid, with calcium sulfate dihydrate as its main mineral component. Depending on the production process, it may also contain free acidity, water-soluble phosphates, fluoride compounds, siliceous materials, and other inorganic impurities.

Phosphogypsum was washed using two methods: ordinary water and a weakly acidic aqueous medium. The primary goal was to reduce water-soluble impurities, free acidity, phosphate compounds, and other fine additives.

Five washing variants were tested: W-1 (ordinary water), A-1 (0.3% H_2SO_4), A-2 (0.5% H_2SO_4), A-3 (0.75% H_2SO_4), and A-4 (1.0% H_2SO_4). The liquid-to-solid ratio was

2.5-3.5:1, the temperature was 25-35 °C, the washing time was 10-20 minutes, and the stirring speed was 250–300 rpm.

In each experiment, the phosphogypsum was mechanically mixed with the designated washing solution. After processing, the suspension was filtered to separate the solid and liquid phases. The pH and P_2O_5 content of the washed samples were measured and compared with those of the initial unwashed material. Washing efficiency was assessed by the reduction in P_2O_5 content, calculated as follows:

$$R = \frac{C_0 - C_1}{C_0} \times 100$$

where R is the degree of P_2O_5 reduction, %; C_o is the P_2O_5 content in the initial phosphogypsum, %; and C_1 is the P_2O_5 content in the washed phosphogypsum, %.

Washing with ordinary water reduced P_2O_5 content from 3.23% to 1.79%, a 44.60% reduction. Using weak sulphuric acid solutions further improved removal efficiency: 58.80% for A-1, 78.02% for A-2, 86.06% for A-3, and 89.78% for A-4. These results show that washing phosphogypsum in a weakly acidic medium effectively reduces phosphate impurities and can serve as a preparatory step for further chemical processing.

Results and Discussion

Experiments on phosphogypsum washing employed both plain water and weak sulphuric acid solutions with different concentrations. As detailed in Table 1, the washing parameters varied across the medium, H_2SO_4 concentration, liquid-to-solid ratio, temperature, time, and stirring speed. W-1 involved washing with plain water, while the other variants-A-1, A-2, A-3, and A-4-used 0.3%, 0.5%, 0.75%, and 1.0% H_2SO_4 solutions, respectively.

Table 1.

Selected experimental conditions for the preliminary washing of phosphogypsum

Variant	Washing medium	H2SO4 concentration, %	Liquid-to-solid ratio (L/S ratio)	Temperature, °C	Time, min	Stirring speed, rpm
W-1	Water	0	2.5:1	25	15	250
A-1	Weakly acidic water	0.3	2.5:1	30	10	250
A-2	Weakly acidic water	0.5	3.0:1	30	15	300
A-3	Weakly acidic water	0.75	3.0:1	35	20	300

A-4	Weakly acidic water	1.0	3.5:1	35	20	300
W-1	Water	0	2.5:1	25	15	250

As shown in Table 1, several technological parameters gradually intensified with increasing H_2SO_4 concentration during the washing process. In the W-1 variant, which involved washing with plain water, the liquid-to-solid ratio was set to 2.5:1, the temperature to 25 °C, the washing duration to 15 minutes, and the stirring speed to 250 rpm. In the acidic washing variants, the H_2SO_4 concentration increased from 0.3% to 1.0%, the liquid-to-solid ratio increased from 2.5:1 to 3.5:1, the temperature was set to 30-35 °C, and the washing time ranged from 10 to 20 minutes. These parameters were chosen to gradually reduce phosphate impurities in phosphogypsum and produce washed phosphogypsum suitable for subsequent chemical conversion.

Table-2.

Reduction of impurity content in phosphogypsum under various washing regimes

Variant	Washing conditions	Washing solution pH	Washed phosphogypsum pH	P2O5 %	P_2O_5 reduction, %
PG-0	Unwashed phosphogypsum	-	3.4-3.6	3.23	-
W-1	Washing with water, L:S = 2.5:1, 25 °C, 15 min	6.5-7.0	4.6-4.8	1.79	44.60
A-1	0,3% H2SO4, L:S = 2.5:1, 30 °C, 10 min	2.2-2.5	5.4-5.6	1.33	58.80
A-2	0,5% H2SO4, L:S = 3.0:1, 30 °C, 15 min	1.9-2.2	5.9-6.2	0.71	78.02
A-3	0,75% H2SO4, L:S = 3.0:1, 35 °C, 20 min	1.6-1.9	5.5-5.8	0.45	86.06
A-4	1,0% H2SO4, L:S = 3.5:1, 35 °C, 20 min	1.4-1.7	5.1-5.4	0.33	89.78

Table 2 shows that the original, unwashed phosphogypsum had an acidic pH, ranging from 3.4 to 3.6. Its P_2O_5 content was 3.23%, indicating the presence of residual phosphoric acid, water-soluble phosphates, and various other acidic impurities.

Washing with plain water slightly lowered the acidity of the phosphogypsum. In the W-1 variant, the pH of the washing solution ranged from 6.5 to 7.0, while the pH of the washed phosphogypsum ranged from 4.6 to 4.8. This shows an increase in pH compared to

the unwashed sample. Under these conditions, the P_2O_5 content dropped from 3.23% to 1.79%, a reduction rate of 44.60%. Thus, washing with ordinary water removes some soluble phosphate impurities, but a significant amount of P_2O_5 remains in the solid phase.

Washing with weak sulphuric acid solutions resulted in a much greater reduction in P_2O_5 content than washing with plain water. In the A-1 variant, a 0.3% H_2SO_4 solution was used at an L:S ratio of 2.5:1, at 30 °C, for 10 minutes with stirring at 250 rpm. Under these conditions, the pH of the washed phosphogypsum ranged from 5.4 to 5.6, and the P_2O_5 content decreased to 1.33%. The rate of P_2O_5 reduction was 58.80%, demonstrating that a weak acidic medium is more effective at removing phosphate impurities than water.

In the A-2 variant, the H_2SO_4 concentration was increased to 0.5%, with a liquid-to-solid phase ratio of 3.0:1, a temperature of 30 °C, a washing time of 15 minutes, and stirring at 300 rpm. Under these conditions, the pH of the washed phosphogypsum ranged from 5.9 to 6.2, making it among the most neutral of the variants. The P_2O_5 content dropped to 0.71%, achieving a reduction rate of 78.02%. Consequently, the A-2 variant showed significantly higher purification efficiency compared to washing with plain water or 0.3% H_2SO_4.

In the A-3 variant, washing involved a 0.75% H_2SO_4 solution. The process used an L:S ratio of 3.0:1 and was conducted at 35 °C for 20 minutes with stirring at 300 rpm. This resulted in a washed phosphogypsum pH ranging from 5.5 to 5.8. The P_2O_5 content dropped to 0.45%, a reduction of 86.06%. These findings show that increasing acidity, temperature, and washing duration improve the transfer of phosphate impurities from solid to liquid.

In the A-4 variant, the most rigorous acidic washing conditions were used: 1.0% H_2SO_4, an L:S ratio of 3.5:1, 35 °C, 20 minutes, and a stirring speed of 300 rpm. Under these conditions, the P_2O_5 content dropped to 0.33%, representing an 89.78% reduction. This achieved the highest purification efficiency among all variants. Additionally, the pH of the washed phosphogypsum ranged from 5.1 to 5.4, slightly lower than in the A-2 and A-3 variants.

In general, the results in Table 2 show that the P_2O_5 reduction rate increased in the following order:

W-1 = 44.60%; A-1 = 58.80%; A-2 = 78.02%; A-3 = 86.06%; A-4 = 89.78%.

This sequence shows that increasing the H_2SO_4 concentration and washing conditions consistently reduced the P_2O_5 content in phosphogypsum. Washing with tap water lowered it to 1.79%, while washing with weakly acidic solutions reduced it to between 1.33% and 0.33%. Thus, an acidic wash is more efficient than water for removing phosphate impurities from phosphogypsum.

When choosing the best washing method, it's important to consider not only the degree of P_2O_5 reduction but also the pH of the washed phosphogypsum, acid consumption, liquid-to-solid ratio, and overall process convenience. Although the A-4 variant achieved the highest P_2O_5 removal at 89.78%, it required a 1.0% H_2SO_4 concentration and an L:S ratio of 3.5:1, leading to higher reagent and liquid consumption. Conversely, the A-3 variant used a 0.75% H_2SO_4 solution and a 3.0:1 L:S ratio, reducing P_2O_5 to 0.45% with an 86.06%

purification efficiency. Thus, the A-3 variant can be seen as a relatively optimal choice, balancing efficiency with lower technological costs.

Data from Tables 1 and 2 show that washing phosphogypsum with plain water is effective as an initial step. For more thorough purification, a weak sulphuric acid solution is necessary. Using 0.75–1.0% H_2SO_4 solutions reduces P_2O_5 levels to 0.45–0.33%, enabling the production of phosphogypsum as a purer raw material for subsequent processes such as ammonium carbonate conversion or other chemical treatments.

The morphological state of phosphogypsum before and after washing was studied using scanning electron microscopy. The SEM images are presented in Figure 1.

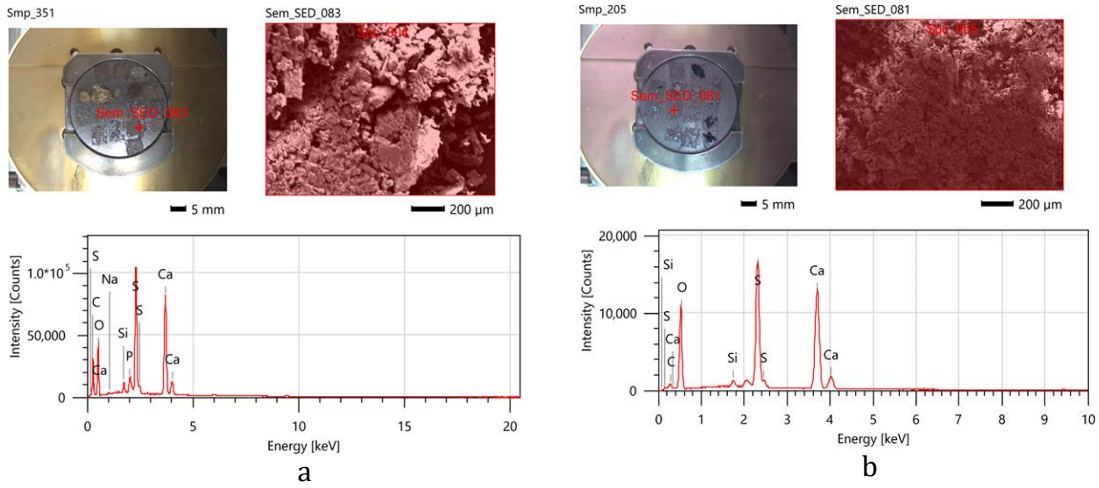


Figure 1. SEM images of the phosphogypsum sample:

a - unwashed phosphogypsum; b - phosphogypsum washed in a counter-current mode.

The unwashed phosphogypsum sample showed particles with uneven, porous surfaces coated with fine impurities. Some regions exhibited particle aggregation and secondary layers on the crystal surfaces. This morphology suggests that impurities from phosphate, fluorine, and related processes persisted in the phosphogypsum throughout the extraction and phosphoric acid production.

In the washed phosphogypsum sample, the crystal surfaces appeared cleaner, with more distinct particle boundaries and fewer fine particles of phosphoric acid. Extraction washing with water and weak acidic solutions effectively removed soluble and mechanical impurities from the phosphogypsum surface. Consequently, the crystals became more reactive during the subsequent conversion process using an ammonium carbonate solution.

The morphological changes seen in the SEM images align with the SEM–EDS findings. Phosphorus was present in the unwashed phosphogypsum, but it was not detected in the washed sample. This suggests that washing effectively removes phosphorus and improves the morphology of phosphogypsum, making it more suitable for the next conversion stage.

Conclusion

Washing phosphogypsum before further processing is a crucial step for both ecological safety and technological efficiency. Water washing reduces residual acids, phosphates, and

fluorides, while mild acidic washing helps remove surface-adsorbed impurities. The counter-current washing method reduces water use and helps concentrate impurities in the washing solution. Evaluating the effectiveness of washing using SEM-EDS, XRD, and ionic analyses enables assessment of phosphogypsum as a raw material for producing ammonium sulfate, calcium carbonate, building materials, and other useful products.

REFERENCES

1. Bilal, E., Bellefqih, H., Bourgier, V., Mazouz, H., Dumitraş, D. G., Bard, F., ... & Haneklaus, N. (2023). Phosphogypsum circular economy considerations: A critical review from more than 65 storage sites worldwide. Journal of Cleaner Production, 414, 137561.

2. Guan, Q., Wang, Z., Zhou, F., Yu, W., Yin, Z., Zhang, Z., ... & Zhou, J. (2024). The impurity removal and comprehensive utilization of phosphogypsum: a review. Materials, 17(9), 2067.

1. Li, X., Lv, X., & Xiang, L. (2023). Review of the state of impurity occurrences and impurity removal technology in phosphogypsum. Materials, 16(16), 5630.

2. Ennaciri, Y., & Bettach, M. (2024). The chemical behavior of the different impurities present in Phosphogypsum: a review. Phosphorus, Sulfur, and Silicon and the Related Elements, 199(2), 129-148.

3. Dong, W., Sun, N., Deng, X., Chen, Z., Zhang, Y., Chi, R. A., & Hu, L. (2024). Study on the occurrence state of main components of phosphogypsum dihydrate and its impurity distribution. *RSC advances*, *14*(31), 22280-22291.

4. Zhou, Y., Li, X., Shi, Y., Zhu, Q., & Du, J. (2022). Reuse of phosphogypsum pretreated with water washing as aggregate for cemented backfill. *Scientific Reports*, *12*(1), 16091.

5. Zhou, Y., Shi, Y., & Zhu, Q. (2023). Control of fluoride pollution in cemented phosphogypsum backfill by citric acid pretreatment. *Materials*, *16*(19), 6493.

6. Cai, Q., Jiang, J., Ma, B., Shao, Z., Hu, Y., Qian, B., & Wang, L. (2021). Efficient removal of phosphate impurities in waste phosphogypsum for the production of cement. *Science of the Total Environment*, *780*, 146600.

7. Chanouri, H., Agayr, K., Mounir, E. M., Benhida, R., & Khaless, K. (2024). Staged purification of phosphogypsum using pH-dependent separation process. *Environmental Science and Pollution Research*, *31*(7), 9920-9934.

8. Wang, M., Yuan, X., Dong, W., Fu, Q., Ao, X., & Chen, Q. (2023). Gradient removal of Si and P impurities from phosphogypsum and preparation of anhydrous calcium sulfate. *Journal of Environmental Chemical Engineering*, *11*(3), 110312.

9. Chen, S., Fan, J., He, X., Su, Y., Chen, J., Cao, Y., ... & Li, Y. (2025). Single-Step Efficient Purification of Phosphogypsum via Wet Grinding and Microenvironmental Treatment. *Fluid Dynamics & Materials Processing*, *21*(7).

10. Zhao, H., Li, H., Bao, W., Wang, C., Li, S., & Lin, W. (2015). Experimental study of enhanced phosphogypsum carbonation with ammonia under increased CO2 pressure. *Journal of CO2 Utilization*, *11*, 10-19.

11. Idboufrade, A., Bouargane, B., Ennasraoui, B., Biyoune, M. G., Bachar, A., Bakiz, B., ... & Mançour-Billah, S. (2022). Phosphogypsum two-step ammonia-carbonation resulting in ammonium sulfate and calcium carbonate synthesis: Effect of the molar ratio OH−/Ca2+ on the conversion process. *Waste and Biomass Valorization*, *13*(3), 1795-1806.

12. Su, Y., Li, Y., Zhou, W., Jie, W., Zhang, H., & Ni, H. (2025). A green integrated process for phosphogypsum recycling: CO2 sequestration combined with SO2 recovery. *Journal of Environmental Management*, *373*, 123707.

13. Orabi, A. S., Ismail, A. H., Abou El-Nour, K. M., Atia, B. M., Gado, M. A., Cheira, M. F., & Goda, A. E. S. (2024). The employing of pure calcium sulfate extracted from phosphogypsum for composing highly pure ammonium sulfate and calcium carbonate. *Canadian Metallurgical Quarterly*, *63*(4), 1554-1571.