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Sustainable Phosphogypsum Management in the Circular Economy: Innovations for Environmental Risk Mitigation and Resource Efficiency – Global Perspectives with Indian Insights

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Abstract
The rapid growth of the global population, coupled with the escalating demand for food, has led to increased reliance on phosphate-based fertilizers vital for ensuring sustainable agricultural productivity. However, the large-scale production of these fertilizers, particularly through the wet-process method for phosphoric acid manufacturing, generates significant volumes of phosphogypsum (PG), a byproduct primarily composed of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). For every ton of phosphoric acid produced, approximately 4 to 6 tons of PG are generated, resulting in a global annual output of over 300 million tons. India contributes significantly to this total, generating an estimated 11–12 million tons of PG each year. PG poses serious environmental and public health concerns due to the presence of hazardous impurities and naturally occurring radionuclides such as radium-226. A majority of this waste is stockpiled in vast, unprotected stacks, leading to soil degradation, water contamination, radon gas emissions, and long-term ecological risks. Despite its potential for reuse, only about 15% of PG is currently recycled, leaving the remainder as a growing liability due to inadequate disposal practices. This manuscript presents a comprehensive review of PG generation, its environmental implications, and the global and national regulatory frameworks governing its management. Emphasis is placed on sustainable research and development (R&D) initiatives aimed at safe handling and value-added utilization of PG. Case studies from India highlight key aspects of PG management, including its generation from phosphoric acid production, estimated output across the fertilizer industry, analysis of PG at selected plants, and industry-wise disposal practices across the country. The review also examines international and Indian guidelines such as those from the atomic energy regulatory board (AERB) and the international atomic energy agency (IAEA) which guide the safe use of PG in various sectors. Additionally, the economic aspects of PG stack maintenance and closure are discussed, highlighting the financial burden associated with long-term storage and the pressing need for circular economic solutions. The paper advocates for the adoption of pretreatment technologies, stricter regulatory enforcement, and broader recycling strategies aligned with circular economy principles to minimize the environmental footprint of PG and promote sustainability in the fertilizer industry.

Keywords: Phosphogypsum, hazardous impurities, environmental footprint, circular economy, sustainable development

1. Introduction

Since the post-industrial era, rising energy consumption has led to a sharp increase in greenhouse gas emissions, accelerating global warming, depleting natural resources, and causing widespread biodiversity and ecosystem loss all while fueling an ever-growing demand for materials (Bates et al., 2024; Sun et al., 2025; Koprić, 2024; Bose and Dhār, 2022; Bose et al., 2022b; Bose et al., 2021; Bose et al., 2019). The depletion of natural resources has become a critical challenge, driving the pursuit of alternatives such as green and sustainable materials and low-carbon processes, which are increasingly gaining global acceptance. In this context, the circular economic approach has emerged as a key sustainability strategy, emphasizing resource circulation and the regeneration of depleted reserves. Among the various industrial by-products, PG stands out as a significant waste material with considerable potential for producing value-added materials for diverse applications (Bates et al., 2024; Sun et al., 2025; Koprić, 2024; Bose et al., 2024; Bose et al., 2022a).

Globally, the exponential growth of population has significantly increased the demand for agricultural and food products. This rising demand, in turn, has necessitated the replenishment of essential plant nutrients primarily phosphorus (P), nitrogen (N), and potassium (K) through fertilizer application. Among these, phosphorus plays a critical role in enhancing agricultural productivity. Adequate phosphorus input is essential to maintain soil fertility and ensure optimal crop yields. A deficiency in phosphorus not only reduces crop output but also undermines the overall efficiency of agricultural systems (Hasan and Tarannum, 2025). Moreover, phosphorus is a vital element for all living organisms. Importantly, it is a non-renewable resource, primarily derived from mined phosphate rock (Tang et al., 2024). Since the last century, mineral phosphorus obtained from these sources has been widely used in agriculture as a key component of phosphate fertilizers.

Mined phosphate rock is primarily used in the production of agricultural fertilizers, accounting for approximately 80% of global consumption. The remaining 20% is distributed between animal feed supplements (5%) and various industrial applications (15%), such as detergents and metal treatment (Smit et al., 2009). The agriculture sector alone consumes 80–90% of the total global phosphorus demand (Greenpeace Research Laboratories, Technical Report, 2012).

Furthermore, the consumption of phosphate rock has been growing at a rate of over 2% per year (FAO, 2015; Powers and Liu, 2019). It is projected that the global population will reach nearly 10 billion by 2050 (Ghosh et al., 2024). To meet the corresponding increase in food demand and ensure sustainable living standards, agricultural activities are expected to expand by approximately 70% by that time. As a result, the demand for phosphate fertilizers will also rise significantly.

According to the U.S. Geological Survey (USGS), global phosphate fertilizer consumption is estimated to increase from 47 million metric tons in 2019 to 50 million metric tons by 2023 (Phosphate Investing News, 2020; Tayibi et al., 2009; Kumar et al., 2020). In India, fertilizer production grew from 414.85 lakh metric tons (LMT) in 2018–19 to 462.15 LMT in 2019–20, reflecting an annual consumption increase of over 11.4% (Annual Report 2019–20, Ministry of Chemicals and Fertilizers, Government of India). However, the production of phosphate fertilizers generates a significant amount of waste, particularly PG, a byproduct primarily composed of calcium sulfate dihydrate ($CaSO_4{\cdot}2H_2O$). PG is formed during the production of phosphoric acid, where phosphate rock is treated with sulfuric acid. This process produces phosphoric acid (H_3PO_4), the main component of phosphate fertilizers, while the residual waste is PG. Phosphate rock naturally contains trace amounts of radioactive elements such as uranium, thorium, and radium. During processing, these radionuclides are concentrated in the PG, making it more radioactive than the original rock. On average, the production of 1 ton of phosphoric acid generates about 5 tons of PG. Currently, the global cumulative stockpile of PG is approximately 6 billion tons (Seraya et al., 2023). Each year, around 300 million metric tons are generated worldwide (Awad et al., 2024). In India alone, an estimated 11–12 million tons of PG wastes are produced annually (Pratap et al., 2023). This waste is typically stored in large mounds or "stacks" that can exceed 100 feet in height, occupying vast land areas and posing significant environmental and health risks. Fig. 1 shows an example of a PG stack in the Florida region.

Fig. 1. PG stacks at Florida

1.1. Phosphate Production Process and Waste Generation (PG and Slag)

1.1.1. Phosphate Production Process (USEPA, 1993)

Phosphate ore is processed to produce phosphoric acid through two primary methods, the dry thermal method and the wet acid (or wet chemical) method (Zhao et al., 2025). The dry thermal method uses an electric arc furnace to produce elemental phosphorus. In contrast, the wet process—also known as the wet chemical phosphoric acid treatment is used to produce phosphoric acid along with calcium sulfate in the dihydrate form ($CaSO_4{\cdot}2H_2O$), as shown in *Equation 1*.

$$Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \longrightarrow 3H_3PO_4 + 5CaSO_4 \cdot 2H_2O + HF \quad (1)$$

A schematic flow diagram of these phosphate production processes is presented in Fig. 2 (USEPA, 1993). Although the wet process is more economically viable, it generates a significant quantity of PG approximately 5 tons of PG per ton of phosphoric acid produced (USEPA, 2002).

1.1.2. Industrial Production and Processing of phosphoric Acid

Phosphoric acid is produced primarily through two major processes:

I. Thermal Furnace Process
II. Wet Process

The wet process, which is more economically viable, is further classified into the following sub-types:

I. Di-hydrate Process (DH)
II. Hemi-hydrate Process (HH)
III. Hemi-hydrate–Di-hydrate Process with Intermediate Filtration (HDH)
IV. Di-hydrate–Hemi-hydrate Process
V. Three-Stage Re-crystallization Process

While the wet process is cost-effective, it leads to the generation of a substantial amount of PG approximately 5 tons of PG for every ton of phosphoric acid produced (USEPA, 2002).

2. Environmental Impacts Associated with PG

PG, a byproduct of phosphate fertilizer production, poses significant environmental and public health risks. The U.S. Environmental Protection Agency (USEPA) classifies PG as a technologically enhanced naturally occurring radioactive material (TENORM) (Tayibi et al., 2009; USEPA, 2002).

Managing PG remains one of the most critical environmental challenges facing the phosphate industry today. Globally, only about 15% of PG is recycled, the remaining 85% is typically stockpiled near production facilities, often in coastal regions. These stockpiles require vast land areas and pose long-term ecological threats. Untreated PG storage contributes to soil degradation, water contamination, and air pollution. Chemical composition analysis offers insight into the constituents of PG.

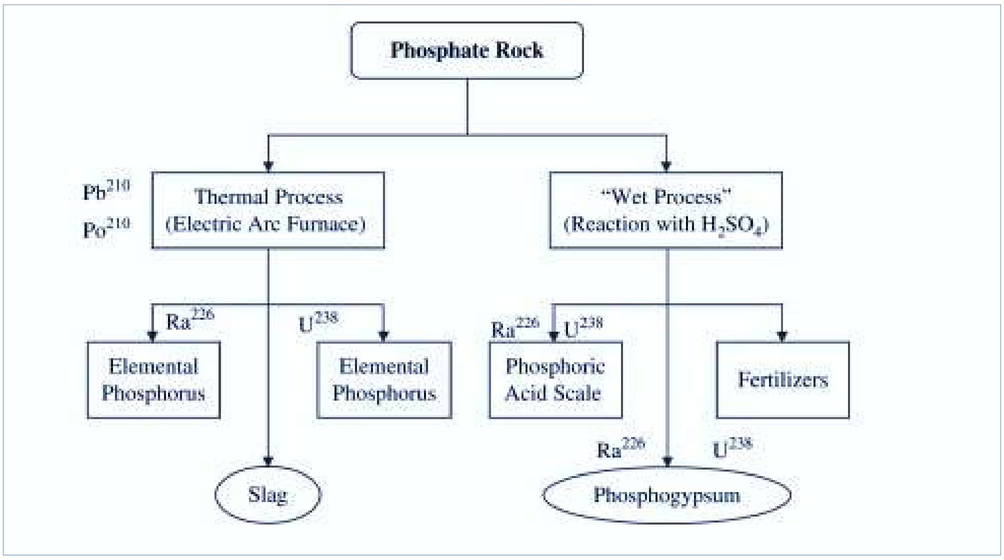

Fig. 2. Schematic flow line of phosphate processes (USEPA, 1993)

Table 1 presents the results of the chemical analysis, revealing potentially hazardous components. Furthermore, radio-nuclide leaching is a major environmental concern. Tables 2 and 3 provide radionuclide activity concentration in PG samples and its reference value in human body. Erosion caused by wind and rain can disperse toxic substances such as heavy metals, sulfates, fluorosilicates, hydrogen fluoride, and other harmful vapors (Szlauer et al., 1990).

PG also contains hazardous elements including phosphorus, cadmium, and radioactive isotopes like radium-226 (^{226}Ra), compounding its environmental burden (Marovic and Sencar, 1995). These pollutants can spread through air and water pathways, contaminating nearby ecosystems and human settlements. The cumulative effect is a significant threat to biodiversity, ecological integrity, and public health (Maina et al., 2025; Wu, 2024; Awad et al., 2024). The leaching of radio nuclides and heavy metals into soil and groundwater undermines agricultural productivity, endangers wildlife and compromises water safety.

Additionally, the release of radon gas from PG particularly in enclosed or poorly ventilated spaces poses a serious respiratory hazard (Wu, 2024). Fig. 3 presented the potentially toxic elements in PG due to the weathering process and anthropogenic activities and the potential exposure risks (Liu et al., 2024; Bose, 2024).

The primary environmental concerns associated with PG stem from its chemical composition and long-term behavior in the environment (Chen et al., 2025). One major issue is the leaching of contaminants such as fluoride, sulfate, total dissolved solids, trace elements, and radionuclides from the uranium-238 decay series into surrounding groundwater supplies, particularly from beneath PG stacks. Another significant concern is the exhalation of radon-222 gas, which poses potential health risks to workers at storage sites and to nearby residents. Additionally, the material's inherent acidity can adversely affect soil and water quality. Further risk arises when agricultural land, previously treated with PG, is later repurposed for residential development this can lead to radon-222 exhalation from the soil into homes, creating potential indoor air quality and public health issues (Akfas et al., 2024; Li et al., 2024).

3. Sustainable Approaches for Recycling and Utilization of PG

The utilization of PG represents a sustainable approach to reducing environmental contamination and associated health risks (Gao et al., 2025; Awad et al., 2024; Maina et al., 2025; Bose, 2023; Bose, 2022). Additionally, recycling and repurposing PG can partially supplement renewable resources, thereby enhancing the overall sustainability of products such as plaster, plasterboards, gypsum fiberboards, and gypsum blocks. Table 4 summarizes the current state-of-the-art applications of PG across various domains.

3.1. Prerequisites for the Utilization of PG

The utilization of PG is largely determined by the presence of toxic elements and impurities, including radioactive substances, fluoride, and residual phosphoric acid. To enable its safe application across various sectors, pretreatment is essential to reduce these contaminants to within permissible limits. Additionally, the safe and secure management of PG including its storage, handling, and transportation by rail or road must strictly comply with regulatory standards and guidelines to ensure environmental and public safety.

Table 1. Chemical composition of PG

Constituent (%)	Degirmenci et al., 2007	Saadaoui et al., 2017	Nizeviciene et al., 2018
SiO_2	3.44	0.5–18	0.37
Al_2O_3	0.88	0.05–0.6	0.13
Fe_2O_3	0.32	0.01–0.25	0.03
CaO	32.04	24–34	38.60
MgO		0.01–0.54	0.04
SO_3	44.67		53.48
SO_4		48–58	
K_2O			
Na_2O	0.13	0.12–10	
P_2O_5	0.50	0.5–0.82	0.82
F	0.79	0.1–1.8	0.14
CaO_{free}	0.81		
Loss on ignition	21.06		6.4

Table 2. Radionuclide activity concentration in tested samples $Bq.kg^{-1}$

Sample description	Nizeviciene et al., 2018	BARC Mumbai, India	BARC Mumbai, India
^{238}U		581 ± 5.3	737± 8.0
^{226}Ra	50.9 ± 5.7	606± 19	759± 24
^{228}Ra	71.6 ± 9.9		
^{228}Th	65.2 ± 6.4		
^{210}Pb	57 ± 19		
^{40}K	<40		
I	0.51		

Table 3. Reference values of natural radionuclides in human $Bq.kg^{-1}$

Sample description	Global value		
	Average activity concentration in soil (UNSCEAR, 2000)	Maximum reported for soil (UNSCEAR, 2008)	Maximum reported for buildings materials (UNSCEAR, 2008)
^{238}U (parent radionuclide for $_{226}Ra$ and ^{210}Pb)	33	1000	
^{226}Ra	32	1000	310
^{232}Th (parent radionuclide for ^{228}Ra, ^{228}Th)	45	258	556
^{40}K	420	3200	1860

3.2. Review of International Regulations and Practices on the Use of PG

The regulatory landscape concerning the use of PG, a by-product of phosphoric acid production containing naturally occurring radioactive materials (NORM), has been shaped by international guidance rooted in radiological protection principles. The International Atomic Energy Agency (IAEA) Safety Series No. 115 (1996) defines an exemption level of 10 Bq/g for radium-226, based on an annual individual dose of 10 μSv. However, this exemption specifically excludes bulk quantities of material, recognizing the potential for cumulative exposure in large-scale applications. The European Commission's Radiation Protection Report (RP112, 1999) advances this framework by recommending an incremental effective dose limit of 0.3 mSv/year as the criterion for exemption and clearance, particularly in the context of building materials.

This threshold is supported by Part II RP122 (2001), which extends the 0.3 mSv/year dose criterion to a broader range of occupational and work-related activities involving NORM. Further guidance is provided in the IAEA Safety Standards Series No. RS-G-1.7 (2004), which establishes 1 Bq/g as the reference activity concentration for individual radionuclides in the uranium and thorium decay series as a general regulatory entry point for bulk materials.

According to this standard, materials with activity concentrations below 1 Bq/g typically do not require regulatory control, whether in their natural state or after processing. This is further elaborated in the IAEA Safety Reports Series No. 49 (2006), which clarifies that radiation protection measures are generally unnecessary below this threshold. Nevertheless, the use of such materials, especially in construction, may still warrant regulatory attention based on exposure scenarios and long-term usage patterns.

Collectively, these international recommendations provide a risk-based approach to the management and potential reuse of PG, balancing safety considerations with the practicality of large-scale material utilization.

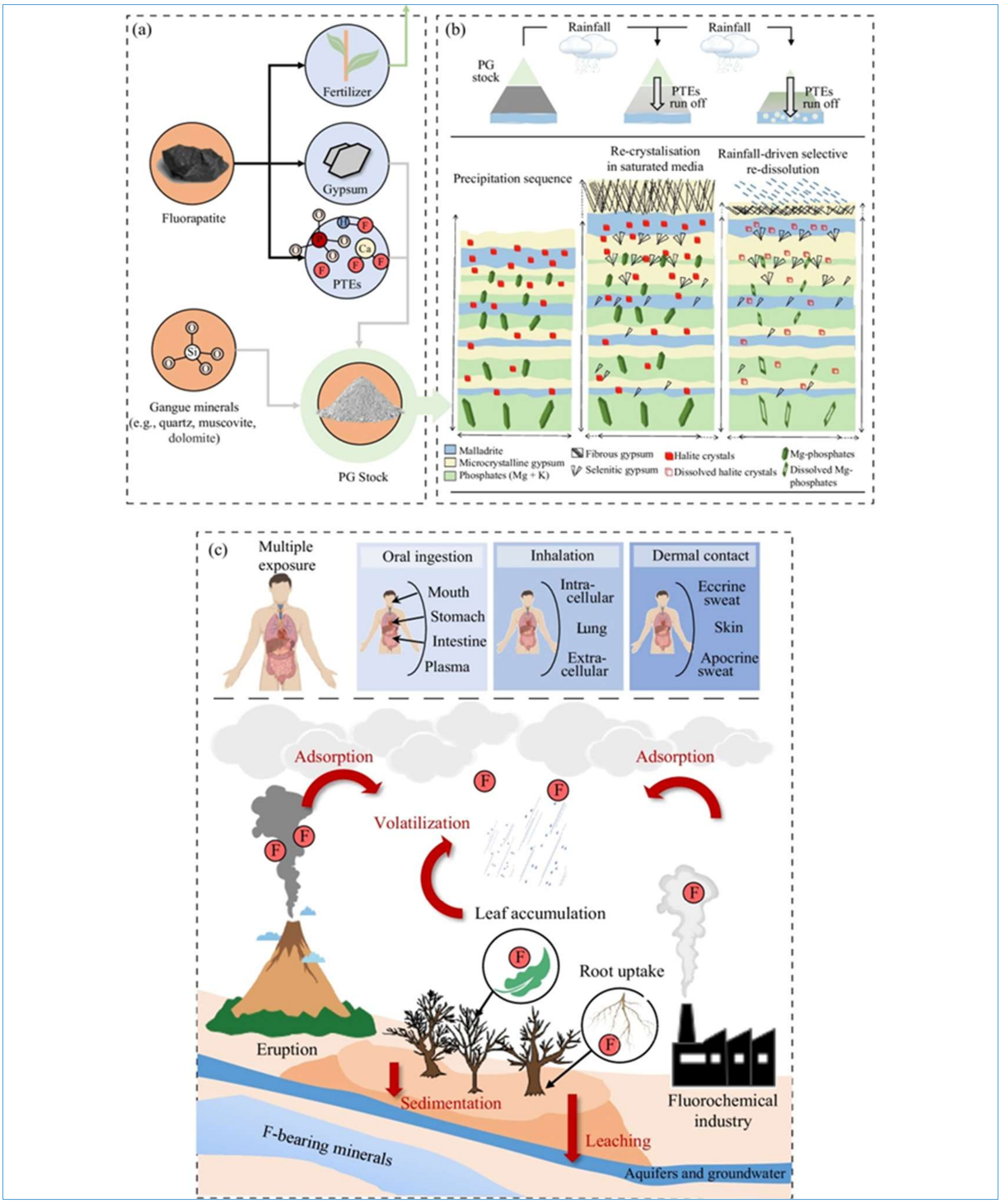

Fig. 3. Spatial distributions of PTEs in PG due to the weathering process and anthropogenic activities and the potential exposure risks: (a) fluoride and phosphate transformation from phosphate ores to PG stock, (b) mechanisms controlling the evolution of the brine-evaporation deposits system and (c) major natural and anthropogenic fluxes in the biogeochemical cycle of fluorides and in-vitro bio accessibility of fluorides posed by multiple exposure routes (Liu et al., 2024)

3.3. Maintenance Cost of PG Stack

The long-term management of PG stacks involves significant expenditure across various stages of their lifecycle (Chen et al., 2025; Tang et al., 2025). Initially, the stack area requires proper lining, typically at a cost of around $1 per ton of stacked PG to ensure environmental safety and containment. Ongoing maintenance costs including monitoring, repair of containment systems and erosion control are estimated to be around $25 per ton. Additionally, the lifetime storage cost can amount to up to $25 per ton, depending on site-specific factors and regulatory requirements. When a PG stack reaches the end of its usable life, full closure and capping operations may incur further costs, approaching $5 per ton. These figures highlight the considerable financial commitment required for responsible PG stack management.

4. PG in the Indian Context: A Sustainability Lens

In India, PG is classified as an industrial byproduct generated mainly from phosphate fertilizer production, particularly during the manufacture of phosphoric acid. With an estimated annual generation of over 12 million tonnes, India faces significant challenges in its safe handling, storage, and disposal. Large quantities are currently stockpiled near fertilizer plants, posing risks related to land use, groundwater contamination, and radiation due to naturally occurring radionuclides like radium-226. However, increasing attention is being given to its potential utilization, particularly in agriculture, cement manufacturing, road construction, and as a soil conditioner. The Central Pollution Control Board (CPCB), India and the Department of Fertilizers (India) have issued guidelines promoting its safe and regulated use, and several R&D initiatives are underway to assess its long-term environmental impact and explore sustainable applications.

Table 4. Recycling and utilization of PG across various applications

Utilization and existing practice of PG	References
for use as soil conditioning (for alkaline soil) or as fertilizer in agriculture	CPCB, India , 2015
In cement manufacturing to control the setting time of cement (as a retardant) and	CPCB, India , 2015
Small quantity is used in the production of plaster, plaster boards, gypsum fiber boards, and gypsum blocks	CPCB, India , 2015
Production of gypsum binder	Chernysh et al., 2021
Production of building materials using unprocessed PG	Rashad, 2017; Ajam et al., 2019; Chernysh et al., 2021
Production of building brick	Ajam et al., 2019; Kuzmanović et al., 2021
Production of thermal insulation materials	Chernysh et al., 2021
Asphalt addition and component for road construction	Abramenko et al., 2019
Pain and coating filler	Chernysh et al., 2021
Cement production	Chernysh et al., 2021
Production of plastic and glass	Chernysh et al., 2021
Production of sulfuric acid and certain products (Portland cement , lime, silicate materials)	Kuzmanović et al., 2021
Production of fertilizer and salt, Reclamations of saline soils in agriculture	Chernysh et al., 2021
Components of composite organic fertilizer instead of phosphorite flour	Chernysh et al., 2021
Production of sulfuric acid and certain products (Portland cement , lime, silicate materials)	Kuzmanović et al., 2021; Chernysh et al., 2021

Table 5. PG generation and utilization in India (IFA Paris, 2020)

Years	PG Generation (MT)	Utilization of PG (MT)			
		Cement	Agriculture	Others	Total
2017-2018	7.79	2.67	0.42	2.21	5.30
2018-2019	8.27	3.96	0.59	1.82	6.37

Table 6. Phosphoric acid production and estimated PG generation in the Indian fertilizer industry (in '000 Tonnes) (CPCB New Delhi, 2014)

Year	Phosphoric acidproduction	Estimated PG generation
2000-01	1042.4	4690.80
2001-02	1134.7	5106.15
2002-03	1085.6	4885.20
2003-04	990.1	4455.45
2004-05	1242.5	5591.25
2005-06	1067.8	4805.10
2006-07	1331.8	5993.10
2007-08 (P)	1206.5	5429.25
2008-09 (P)	1201.7	5407.65
2009-10 (P)	1160.0	5220.00
2010-11 (P)	1544.6	6950.70
2011-12 (P)	1740.4	7831.80
2012-13 (P)	1394.7	6276.15

Despite these efforts, large-scale utilization remains limited, and regulatory, technical, and public perception barriers continue to hinder its widespread adoption. As per the report published by IFA Paris (2020). Table 5 presents data on the generation and utilization of PG in India, based on information from ten fertilizer plants.

In India, phosphoric acid (H_3PO_4) serves as a crucial intermediate in the manufacture of phosphate fertilizers such as Di-Ammonium Phosphate (DAP) and single super phosphate (SSP). The wet process is predominantly employed for phosphoric acid production, which generates PG as a byproduct.

Table 6 presents the phosphoric acid production and the corresponding estimated PG generation within the Indian fertilizer industry. PG generated at selected phosphoric acid plants in India refers to the byproduct formed during the wet-process production of phosphoric acid at specific fertilizer manufacturing facilities across the country. Composed mainly of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), it is formed when phosphate rock reacts with sulfuric acid.

Table 7. A summary of the analysis report on PG generated at select phosphoric acid plants in India (CPCB New Delhi, 2014)

No	Name of theindustry	Type ofProcess	Characteristics (in %)				
			Insoluble P_2O_5	Insoluble F	Soluble P_2O_5	Soluble F	Moisture
1	TCL, Haldia, WB	DH	0.50	0.25	0.30	0.60	15
2	PPL, Orissa.	DH	0.75	-	0.30	0.80	20
3	GSFC, FertilizerNagar, Gujarat	DH	0.80 to0.85	0.20-0.50	0.5-1.0	-	20-24
4	Hindalco Industries Ltd.(HIL) P.O. Dahej, Gujarat	DH	0.50-1.60	0.45-0.65	0.05-0.60	0.03-0.06	18-22
5	Indian FarmersFertilizer Co-Operative Ltd.(IFFCO) Musadia, Orissa	DH	0.70-0.90	0.20-0.50	0.04-0.10	0.04-0.06	6-12
6	Rashtriya Chemicals and Fertilizers Ltd. (RCFL), Chembur,Mumbai	HDH	0.20-1.20	0.06-0.20	0.05-0.60	0.02-0.16	15-20
	Range		0.2-1.6	0.06-0.65	0.04-1.0	0.02-0.16	6 -24

Table 8. Industry-wise PG disposal practices across Indian phosphoric acid plants

No	Name of industry	PG generation		PG management practices		
		Net quantity from 2006–2011 (MT)	Rate of PG generation (MT/MT of P_2O_5)	Dry disposal	Wet disposal	Intermediate storage
1	TATA Chemicals Ltd. Haldia, WB	478591.52	4.5	Dry PG is directly delivered to the gypsum storage area for curing and further sale	Only at the time of startup and shut down of the plant	There is no intermediate storage facility
2	Paradeep Phosphates Limited, Paradeep, Orissa.	6229900	5	During the year 2011- 2012, about 5.09 Lac Tonnes of PG sold to cement plant and other use.	From Phosphoric Acid Plant PG is transported as slurry containing 10-15% through HDPE pipelines to gypsum stack. PG is excavated and transported to railway storage site	One intermediate storage shed of area 700 x 15 m with 25000 MT capacity has been provided
3	Gujarat State Fertilizer & Chemicals Limited Vadodara, Gujarat.	2043233.4	5.5 – 5.9	During 2011-2012, 6106 tonnes of PG sold to cement plant.	PG in slurry form is sent to the 'PG pond' through pipelines which is located within the plant and then PG is dispatched in loose/ bagged form to farmers on continuous basis. Surplus quantity is repulped and sent to the pond.	There is no intermediate storage facility
4	Hindalco Industries Ltd. Bharuch, Gujarat	2215198	5	PG transportation from plant to the storage yard directly through conveyor belt. Till now 3905808 MT of PG has been disposed off.		There is no intermediate storage facility
5	Indian Farmers Fertilizer Cooperative Ltd. Musadia	10922885	4.5 – 5	During the year 2011- 2012, about 3.11 Lac Tonnes of PG sold to the Cement Plants	Wet PG is being sent to the PG pond area through HDPE pipeline. There are 2 nos. of gypsum ponds of 200 acres and 85 acres area, respectively.	There is no intermediate storage facility
6	Sterlite Industries (I) Ltd., SIPCOT Industrial Complex, Tuticorin	4171306	4.7	Through conveyor system, PG is getting transferred and stored in lined PG pond. There are 07 conveyors and through tippers the PG is shifted to the designated location.		There is no intermediate storage facility
7	Coromandel International Limited, Vishak-hapatnam AP	3349334	4 – 4.5	Dry PG is directly disposed to the HDPE lined gypsum handling area before its final disposal		
8	Coromandel International Limited, Ennore, Chennai	1576933	5.83	Transported through conveyor belts, toppers and trucks stored in impervious layer pond.		There is no intermediate storage facility
9	Greenstar Fertilizers Limited Tuticorin, TN	83200 MTPA	5		Wet disposal is being followed by the unit. PG is first collected in the tank and slurry was pumped to the disposal pond.	There is no intermediate storage facility
10	Fertilizers and Chemicals Travancore Ltd., Ambalmedu Kerala	1316319	6	PG produced in the plant is conveyed to PG pond and the earmarked area for PG disposal, through tippers/trucks.		There is no intermediate storage facility
11	Rashtriya Chemicals And Fertilizers Ltd., Chembur, Mumbai	561819	5.1	During 2011-2012, 1.06 Lac MT of PG was used in house gypsum board manufacturing.	Wet disposal of PG is being conducted by the industry through pipeline	There is no intermediate storage facility

MT: Metric tonnes

The quantity and properties of PG vary depending on factors such as plant capacity, processing technology, and the quality of raw materials used. These selected plants contribute significantly to India's total PG output, making it a major source of industrial solid waste. However, it also presents considerable potential for large-scale recycling and utilization in sectors like construction, agriculture, and infrastructure. Table 7 provides detailed data on PG generation at selected phosphoric acid plants across India. In India, PG disposal practices across the phosphoric acid industry vary significantly depending on plant capacity, technological advancement, and adherence to environmental regulations. Large, integrated fertilizer complexes generally employ engineered landfills or dedicated stacking yards to ensure safe storage and minimize environmental impact.

4.1. Regulatory Framework Governing the Use of PG in Indian Construction Sector

The Atomic Energy Regulatory Board (AERB), Mumbai, India, has issued specific guidelines regarding the use of PG in building and construction materials. As per the AERB, no prior approval is needed if the activity concentration of Radium-226 (Ra-226) in PG is less than or equal to 1 Bq/g. In cases where the concentration exceeds 1 Bq/g, the PG must be diluted with other materials to ensure the final mixture stays within the 1 Bq/g limit. Similarly, the manufacture and use of PG panels or blocks do not require AERB approval, provided the Ra-226 activity is below 40 kBq per square meter of any surface area. These guidelines help promote safe recycling and reuse of PG in construction while adhering to radiological safety standards (Source: Proceedings of the International Symposium, Marrakesh, Morocco, 22–26 March 2010).

5. Conclusion

PG, an inevitable by-product of phosphate fertilizer production, poses serious environmental and health risks due to its hazardous elements and radionuclides, with only about 15% of global production currently being recycled. Vast quantities remain stockpiled, leading to soil degradation, groundwater contamination, radon emissions, and long-term ecological hazards. Research and development efforts have demonstrated the potential of PG as a resource in agriculture, cement, construction, and soil reclamation, but widespread application is hindered by technical, regulatory, and public perception challenges. International and Indian regulations such as IAEA guidelines and AERB standards provide frameworks for safe reuse, while pretreatment technologies and strict compliance can further mitigate risks. Given the high cost of PG stack maintenance and the pressing need for sustainable waste management, adopting a circular economic approach is essential. By promoting resource recovery, innovative applications, and broader utilization of PG, this strategy can significantly reduce environmental impacts while contributing to the replenishment of natural resources and the creation of a more sustainable industrial ecosystem. In contrast, smaller or older plants often continue with traditional open dumping due to inadequate infrastructure and weaker regulatory oversight, raising environmental concerns. However, growing regulatory pressure and a stronger focus on sustainability are steadily pushing the industry toward more secure, resource-efficient disposal and utilization methods. By promoting resource recovery, innovative applications, and broader utilization of PG, this strategy can significantly reduce environmental impacts while contributing to the replenishment of natural resources and the creation of a more sustainable industrial ecosystem.

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