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INDUSTRIAL BY-PRODUCTS AS SUSTAINABLE SOIL AMENDMENTS: IMPACTS ON SOIL HEALTH AND AGRICULTURAL PRODUCTIVITY: A REVIEW

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ABSTRACT

Industrial by-products are generated from a wide range of sectors, including textiles, distilleries, paper mills, tanneries, oil refineries, pesticide and fertilizer industries, and metallurgical processes. Conventional disposal practices such as landfilling, incineration, and direct discharge into water bodies are increasingly discouraged due to their adverse environmental, social, economic, and regulatory implications. As a result, sustainable management approaches such as recycling and beneficial land application are gaining global attention. The application of industrial by-products to agricultural soils has emerged as a promising strategy for improving soil quality, enhancing soil health, and increasing agricultural productivity. Materials such as fly ash, phosphogypsum, press mud, steel slag, and paper mill sludge have shown potential as soil amendments due to their ability to supply macro and micronutrients, improve soil physical structure, and enhance soil chemical properties. These amendments can contribute to enhanced plant growth, increased crop yields, and the reclamation of degraded or marginal soils while simultaneously reducing the burden on landfills and minimizing environmental pollution. However, the effectiveness of industrial by-products as soil amendments depends on their source, chemical composition, application rate, and interactions with specific soil types. In addition, the presence of potentially toxic elements, such as heavy metals and organic contaminants, in certain by-products necessitates careful assessment, appropriate treatment, and site-specific application strategies to avoid adverse environmental impacts. Overall, the judicious and integrated use of industrial by-products in combination with conventional fertilizers and organic manures can enhance soil fertility, improve crop productivity, and support sustainable agricultural systems. At the same time, improper or excessive application may lead to soil contamination, deterioration of soil health, and negative impacts on ecosystem functioning. Therefore, a balanced and scientifically guided approach is essential for the safe and effective utilization of industrial by-products in agriculture.

Keywords **:** Industrial By-products, Soil Health, Soil Quality, Agricultural Productivity, Circular Economy, Sustainable Soil Amendments.

Introduction

Waste is a by-product of population increase, urbanization, and economic growth. Approximately 2.59 billion tons of waste are projected to be generated globally by 2030, with this figure expected to reach 3.4 billion tons by 2050, doubling from 2016 levels and potentially tripling by 2100 (Abdollahi *et al.*, 2022).

The principles of waste classification are diverse, such as according to material, state, or source. Based on the source of generation, waste can be classified into municipal solid waste, agricultural solid waste, and industrial solid waste. Among the various categories of waste, industrial by-products have attracted considerable attention because of their potential for resource recovery and beneficial utilization in agriculture.

Municipal solid waste (MSW) is one of the fastest-growing waste streams worldwide due to rapid urbanization and population growth, comprising wastes generated from households, commercial establishments, institutions, and small industries (Tawfik *et al.*, 2022). By 2025, approximately 4.3 billion people are expected to reside in urban areas, generating about 1.42 kg of MSW per capita per day (Mandal, 2019). Similarly, the increasing demand for food has intensified crop and livestock production, resulting in the generation of substantial quantities of agricultural waste (Tripathi *et al.*, 2019).

In contrast, improper disposal of agricultural waste generates greenhouse gases such as carbon dioxide, nitrous oxide, and methane, threatening humans and the natural environment. In addition, worldwide industrial solid waste generation is substantial and continues to increase to meet human daily needs.

Industrial solid waste usually comprises steel slag, tailings, fly ash, red mud, waste tyres, and special wastes generated by industries, in addition to wastes from light and heavy manufacturing, fabrication, construction sites, power plants, and chemical plants (Li *et al*., 2021a). These wastes contain a large number of heavy metals and other hazardous substances and, if dumped or landfilled indiscriminately, can have severe adverse impacts on the environment. Furthermore, the disposal of industrial solid wastes occupies substantial amounts of scarce land resources (Kulkarni, 2020).

Solid waste management approaches include waste identification, reduction, recycling, storage, collection, transfer, transportation, effective treatment, reuse and disposal. Among several waste management options, landfill remains the most common waste disposal route globally (Das *et al.*, 2019). However, landfills take up many land resources and produce leachate and landfill gas that still negatively affect the atmosphere. About 3–4% of global greenhouse gases are generated due to irrational waste disposal (Abdollahi *et al.*, 2022).

Globally, waste disposal options such as landfill, incineration and discharge into water bodies, are not preferred long-term solutions due to their social, environmental, political, and economic implications (Cameron *et al.*, 1997). Expanding industrialisation, population growth, and growing consumer demand are placing stress on existing waste management strategies (Haynes, 2009). Across the world, more sustainable ways of handling industrial waste through increased recycling and reuse alternatives are being considered. Thus, there is potential for increasing the sustainability of industrial processes by considering land application of wastes. Land application of industrial wastes can provide several benefits, including reducing the amount of waste sent to landfills and supplying alternative sources of nutrients for agricultural and other primary production systems (Van Ewijk and Stegemann, 2020). Studies have shown that the functional benefits of waste application to land can range from increased plant growth and yield, to improved soil structure and alleviation of undesirable soil conditions such as acidity and erosion (Manoharan *et al.*, 2010).

Intensive agricultural practices are dependent on the routine use of fertilisers and liming agents to replenish nutrients and sustain high production. Utilising the beneficial properties of industrial wastes has the potential to provide alternatives to fertilisers and soil conditioners for farming systems. Using wastes instead of, or as a supplement to, commercial products could alleviate the financial pressures imposed on farmers by fluctuating global markets (ACCC, 2008).

In many countries, the acceptance of industrial waste as a soil amendment in agriculture is highly contentious and limited by uncertainty about the effects of contaminants on soil, water, food, and, subsequently, human health (Dessalew *et al.*, 2017). Consequently, the application of wastes as soil amendments must be in a way that ensures safe and sustainable outcomes. Velvizhi *et al.* (2020) argued that most solid waste fractions could be converted into resources rather than polluting elements through value-added technologies, which can reduce resource consumption, protect the environment, and ease the pressure on waste disposal.

Despite the growing interest in the agricultural utilization of industrial by-products, their effectiveness and environmental implications vary considerably depending on their origin, composition, and application practices. Therefore, a comprehensive evaluation of their potential benefits and associated risks is essential to promote their sustainable use in agricultural systems.

The objective of this review is to critically assess the role of major industrial by-products, including fly ash, phosphogypsum, press mud, steel slag, and paper mill sludge, in improving soil health and crop productivity. The review examines their sources, characteristics, nutrient composition, mechanisms of soil improvement, agronomic benefits, environmental concerns, and management strategies associated with their agricultural application. Furthermore, it highlights current research gaps and future prospects for the safe and sustainable utilization of industrial by-products in agriculture.

Unlike previous reviews focusing on individual industrial wastes, the present review provides a comprehensive comparative assessment of major industrial by-products including fly ash, press mud, distillery spent wash, paper mill sludge, phosphogypsum, and steel slag with emphasis on soil health indicators, soil quality improvement, crop productivity, environmental concerns, and future research needs.

Soil Health

Soil health refers to the capacity of soil to function as a living ecosystem that sustains plant and animal productivity, maintains environmental quality, and supports biological activity. It is governed by the physical, chemical, and biological properties of soil and is fundamental to sustainable agricultural production (Doran and Zeiss, 2000). Healthy soils exhibit efficient water infiltration and drainage, provide essential nutrients for plant growth, sequester carbon, and support diverse microbial communities. These attributes contribute to enhanced crop productivity, nutrient cycling, and environmental sustainability (Lal, 2015; Bünemann *et al.,* 2018).

Soil health management is based on four key principles that enhance soil functionality and agricultural sustainability. Maintaining living roots throughout the growing season provides a continuous supply of carbon compounds that support soil microbial activity and nutrient cycling (Fageria *et al.,* 2005). Minimizing soil disturbance through reduced tillage or no-till practices helps preserve soil structure, conserve organic matter, and protect beneficial soil organisms (Lal, 2004). Maximizing soil cover using crop residues, mulches, or cover crops protects the soil surface from erosion, conserves moisture, and promotes organic matter accumulation (Blanco-Canqui, 2015). Enhancing biodiversity through diversified crop rotations and cover-cropping systems improves ecosystem stability, nutrient availability, and resistance to pests and diseases (Altieri, 1999).

Agricultural systems with greater biodiversity are generally more productive, resilient, and sustainable than monoculture-based systems (Bender *et al.,* 2016).

The maintenance of soil health requires sustainable nutrient management practices, among which the agricultural utilization of industrial by-products has gained considerable attention due to its potential to improve soil quality while promoting resource recycling.

Types of Industrial By-products Used for Soil Application in Crop Production

Industrial by-products are increasingly utilized in agriculture as soil amendments and alternative nutrient sources. Their application improves soil fertility, enhances soil physical properties, increases crop productivity, and promotes the sustainable recycling of industrial wastes. Fly ash, a by-product of coal combustion, serves as a source of micronutrients and acts as a soil-conditioning material (Adriano *et al.*, 2002). Press mud, generated by the sugar industry, is rich in organic matter, phosphorus, and calcium, making it an effective organic amendment for crop production (Dotaniya *et al.,* 2016). Paper mill sludge contains substantial amounts of organic matter and plant nutrients, contributing to improved soil structure and water-holding capacity (Maiti, 2013).

Phosphogypsum, a by-product of phosphate fertilizer manufacturing, is widely used as a source of calcium and sulfur and plays an important role in the reclamation of sodic soils (FAO, 2006). Spent wash, produced by distilleries, contains high concentrations of organic matter and plant nutrients and can enhance soil fertility when applied at appropriate rates (Pathak *et al.,* 1998). Steel slag, a by-product of the steel industry, supplies calcium, magnesium, silicon, and micronutrients while also helping to ameliorate soil acidity (Das *et al.*, 2007).

Impact of Industrial By-Products on Soil Properties and Crop Production

Industrial by-products can significantly enhance soil fertility by supplying essential plant nutrients and organic matter, thereby improving nutrient availability and promoting crop growth. The application of materials such as fly ash, press mud, paper mill sludge, and spent wash improves soil structure, aggregation, and porosity, resulting in better root development and soil aeration. All the physical, chemical and biological benefits are mentioned in the figure 1.

These materials can also increase the water-holding capacity of soils, enabling crops to better withstand moisture stress and improving water-use efficiency. Furthermore, several industrial by-products function as effective amendments for degraded or problematic soils. For example, phosphogypsum and steel slag help reclaim sodic soils and alleviate soil acidity through the addition of calcium and other beneficial elements.

The incorporation of organic-rich industrial wastes stimulates soil microbial biomass and enzymatic activities, thereby enhancing nutrient cycling and overall soil biological functioning. Consequently, improvements in soil physicochemical and biological properties often translate into increased crop yields and improved produce quality.

The use of industrial by-products also helps reduce soil erosion by improving soil aggregation and surface stability. Furthermore, these materials can partially substitute chemical fertilizers, lowering production costs and reducing environmental impacts associated with synthetic fertilizer use. Their agricultural utilization promotes a circular economy by recycling industrial wastes into valuable resources for crop production (De Silva *et al.*, 2023).

Table 1 : Effects of Industrial By-products on Soil Physicochemical Properties

Soil property	Waste type	Outcome	Reference
Soil moisture, water movement, and retention	Fly ash	Increased bulk density, porosity, and hydraulic conductivity	Young *et al.* (2008); Zhai and Horn (2018)
	Dairy effluents, meat processing effluents	Altered or reduced hydraulic conductivity	Sparling *et al.* (2015)
Soil pH	Fly ash, dairy waste, steel slag, and paper pulp	Acts as a liming agent and reduces soil acidity	Qing *et al.* (2015); Spark and Swift (2008)
Organic matter	Fly ash, tannery sludge, dairy effluents	Generally increased soil organic matter, although reductions were reported in some cases	Singh *et al.* (2011); Spark and Swift (2008)
Soil salinity and sodicity	Pulp and paper mill effluent, fly ash	Increased soil salinity and/or sodicity under excessive application rates	Roy and Joy (2011); Singh *et al.* (2012)

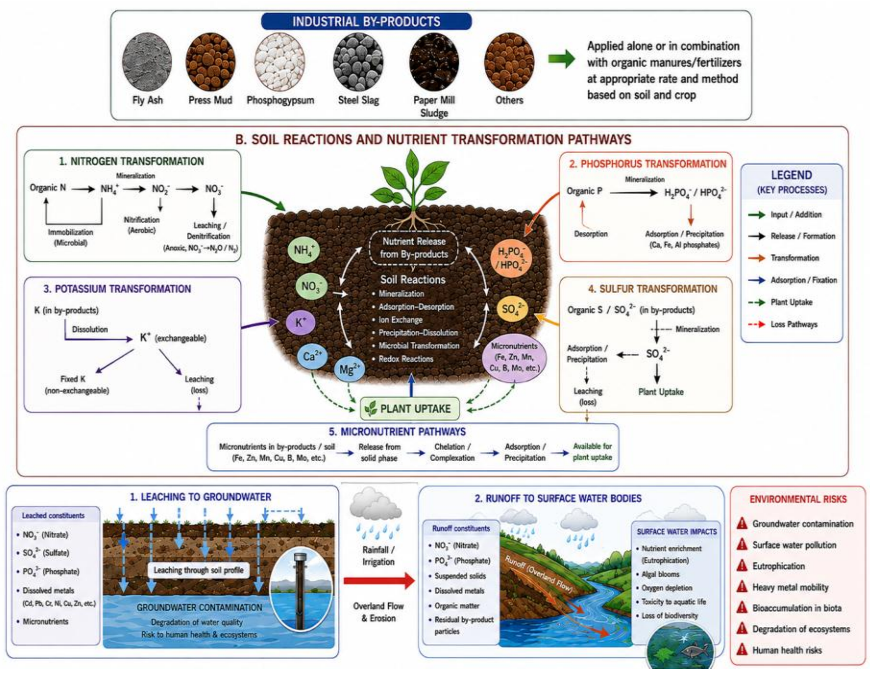

Fig. 1 : Role of industrial by product application in soil for nutrients transformation pathways

Fly ash can improve soil water movement and retention by increasing bulk density, porosity, and hydraulic conductivity. In contrast, dairy and meat-processing effluents may alter or reduce hydraulic conductivity depending on application rates and soil conditions. The effects of industrial by-products on soil physicochemical properties are summarized in Table 1.

Industrial by-products such as fly ash, dairy waste, steel slag, and paper pulp residues can increase soil pH and act as liming agents, thereby reducing soil acidity. The application of fly ash, tannery sludge, and dairy effluents generally increases soil organic matter content. However, some by-products, particularly pulp, paper mill effluents and fly ash, may increase soil salinity and sodicity if applied excessively, highlighting the need for careful management (Das *et al*., 2007).

Contaminants Associated with Industrial By-products

Despite their agronomic benefits, industrial by-products may contain various contaminants that pose potential environmental and human health risks. Tannery wastes are often enriched with heavy metals such as chromium (Cr), copper (Cu), lead (Pb), strontium (Sr), and vanadium (V), whereas dairy industry wastes and paper pulp residues may contain arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb). The major contaminants commonly associated with industrial by-products used in agricultural applications are summarized in Table 2.

Besides inorganic contaminants, several industrial by-products may also contain organic pollutants. Fly ash can contain polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs). Likewise, tannery wastes may contain chlorinated phenols, dyes, PCBs, and per- and polyfluoroalkyl substances (PFAS), while dairy industry wastes may carry residual hormones, antibiotics, and disinfectants. Consequently, comprehensive characterization, regular monitoring, and strict compliance with environmental regulations are essential to ensure the safe and sustainable agricultural utilization of industrial by-products (De Silva *et al.*, 2023).

Fly Ash

Fly ash is a by-product generated during coal combustion in thermal power stations and contains silica (50–62%), alumina, iron oxides, calcium, magnesium, macro- and micronutrients, along with trace amounts of heavy metals such as Pb, Hg, As, Cd, Se, and Ni (Yao *et al*., 2015). The application of fly ash to agricultural soils improves soil texture, porosity, aeration, and water-holding capacity while reducing soil compaction, thereby enhancing crop growth and yield (Pandey and Singh, 2010). Its nutrient-rich composition contributes to improved soil fertility by supplying several essential elements required for plant growth (Ram and Masto, 2014).

However, the presence of trace heavy metals in fly ash may result in their accumulation and transfer through the soil–water–plant continuum, posing potential environmental and human health risks if not properly managed (Adriano, 2001). Therefore, fly ash should be applied judiciously according to soil and crop requirements, preferably in combination with organic amendments, with continuous monitoring of soil properties and heavy metal concentrations (FAO, 2018).

Bhoyar *et al.* (2011) evaluated the effects of different fly ash application rates (20, 40, 60, 80, 100, and 120 t ha^{-1}) on the physical and chemical properties of black soil. The study demonstrated that fly ash improved soil properties up to an optimum level, whereas excessive application adversely affected soil quality. Among the treatments, 60 t ha^{-1} of fly ash was found to be the most effective, significantly increasing maximum water-holding capacity (70.98%) and hydraulic conductivity (1.52 cm h^{-1}), while reducing bulk density to 1.60 Mg m^{-3}. Furthermore, soil pH shifted towards neutrality (7.63), and organic carbon content increased to 0.69%, indicating enhanced soil quality and fertility.

Malakar *et al.* (2016) conducted an incubation study in a Vertisol at the Indian Institute of Soil Science to assess the effects of organic amendments, including farmyard manure (FYM), biochar, and poultry manure (25 t ha^{-1}), applied with or without fly ash (22.4 t ha^{-1}). Soil quality parameters measured after ten weeks of incubation revealed that the combined application of organic amendments and fly ash significantly improved soil physical and chemical properties compared with the individual application of the respective amendments. Treatments involving FYM or poultry manure in combination with fly ash exhibited the greatest improvements in soil quality indicators.

Table 2 : Major contaminants present in industrial by-products used for agricultural applications

Sr. No.	Contaminant Type	By-product Type	Typical Contaminants Present	References
1	Inorganic contaminants	Tannery waste	Chromium (Cr), Copper (Cu), Lead (Pb), Strontium (Sr), Vanadium (V)	Gowd *et al.* (2010)
		Dairy industry waste	Arsenic (As), Cadmium (Cd), Chromium (Cr)	Cameron and Di (2019)
		Paper pulp waste	Arsenic (As), Cadmium (Cd), Lead (Pb)	Shakil and Mostafa (2021)
2	Organic contaminants	Fly ash	Polycyclic aromatic hydrocarbons (PAHs), Polychlorinated biphenyls (PCBs), Polychlorinated dibenzo-p-dioxins (PCDDs), Polychlorinated	Shaheen *et al.* (2014)

			dibenzofurans (PCDFs), dimethyl and monomethyl sulphate	
		Tannery waste	Chlorinated phenols, phenol, various dyes, and PCBs	Chowdhary *et al.* (2020); Rigueto *et al.* (2020)
3	Emerging contaminants	Dairy industry waste	Hormones, antibiotics, udder-cleaning antiseptics, and topical veterinary pharmaceuticals	Fisher and Scott (2008)
		Paper pulp waste	Hydroxy furanones with mono-, di-, and trichloromethyl groups	Franzén and Kronberg (1994)
		Tannery waste	Per- and polyfluoroalkyl substances (PFAS), mainly linear perfluorooctane sulfonate (L-PFOS)	Flores *et al.* (2013)

Tripathi *et al.* (2020) investigated the effects of different fly ash application rates (0–50 t ha^{-1}) in combination with vermicompost (2 t ha^{-1}) and recommended doses of NPK fertilizers on the physico-chemical properties, microbial population, and growth of chickpea (*Cicer arietinum* L.) under field conditions. The results showed that fly ash application increased soil water-holding capacity, moisture content, pH, porosity, organic carbon, electrical conductivity, and available phosphorus and potassium contents. In contrast, bulk density and total nitrogen content decreased with increasing fly ash application rates. The study concluded that the integrated use of fly ash and organic amendments can improve soil quality and support sustainable crop production.

Press Mud

Press mud, a by-product of the sugar industry, is generated in large quantities during sugarcane processing, with India producing approximately 8.5 million tonnes annually. It is rich in organic matter and contains moisture (50–65%), fiber (15–30%), crude wax (5–14%), sugar (5–15%), protein (5–15%), CaO (1–4%), MgO (0.5–1.15%), ash (9–10%), nitrogen (2–2.5%), phosphorus (1.8%), and potassium (0.9%). In addition, press mud serves as an important source of secondary and micronutrients, including calcium, zinc, iron, copper, manganese, and silicon.

Owing to its nutrient-rich composition, press mud is widely used as an organic fertilizer and soil conditioner, improving soil organic matter content, nutrient availability, aggregation, and overall soil structure. Its high calcium content also makes it effective for the reclamation of sodic soils. However, prolonged and excessive application may increase the accumulation of certain heavy metals, particularly cadmium (Cd), chromium (Cr), and copper (Cu), in soil. Therefore, pretreatment techniques such as composting and vermicomposting are recommended to stabilize organic matter, reduce heavy metal bioavailability, and ensure the sustainable and environmentally safe utilization of press mud in agriculture (Dotaniya *et al*., 2016; Kumar and Chopra, 2014).

Prabhavathi *et al.* (2019) evaluated the effects of press mud biocompost (press mud + spent wash) and farmyard manure in combination with recommended fertilizer doses on finger millet under field conditions in Karnataka. Application of press mud biocompost at 10 t ha^{-1} along with recommended fertilizers significantly reduced soil bulk density and increased maximum water-holding capacity. Furthermore, improvements in soil organic carbon content and other physicochemical properties were observed, indicating enhanced soil quality and crop productivity.

Poonkodi *et al.* (2016) investigated the combined effects of inorganic fertilizers and press mud compost on soil properties, yield, and quality of bhendi (*Abelmoschus esculentus* L.) in Tamil Nadu. The application of the recommended fertilizer dose along with 15 t ha^{-1} of press mud compost produced the highest fruit and stover yields and significantly improved quality attributes, including crude protein, ascorbic acid, and crude fiber contents. The treatment also resulted in the highest post-harvest availability of nitrogen, phosphorus, potassium, and sulfur, highlighting the potential of press mud compost to enhance soil fertility, crop productivity, and produce quality.

Distillery Spent Wash (DSW)

Distillery spent wash (DSW) is a nutrient-rich liquid by-product generated during alcohol production. It is acidic (pH 3.5–4.5) and contains high levels of organic matter, resulting in elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD). DSW supplies essential macronutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and sulfur (S), as well as micronutrients such as iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn), making it a valuable source of plant nutrients. When applied at recommended rates, DSW improves soil physicochemical properties, enhances microbial activity, and promotes crop growth and yield. However, excessive application may lead to salt accumulation and environmental pollution owing to its high organic load. Bio-composting of DSW with organic residues is an effective management strategy that reduces its pollution potential and converts it into a valuable organic fertilizer for sustainable agriculture (Pant and Adholeya, 2007; Kaushik *et al.*, 2005).

Ransing *et al.* (2018) evaluated the effects of various sulfur-containing amendments on pearl millet at the Micronutrient Research Farm, Mahatma Phule Krishi Vidyapeeth, Rahuri. The study demonstrated that the application of post-bio-methanated spent wash (PBSW) at 80 m^3 ha^{-1}, along with the general recommended dose of nutrients (GRDN), significantly increased grain and stover yields of pearl millet. These findings suggest that PBSW can serve as an effective nutrient source and soil amendment for enhancing crop productivity.

Biswas *et al.* (2009) investigated the long-term effects of spent wash (SW) and post-methanated effluent (PME) on soil organic carbon and aggregate stability in a soybean–wheat cropping system grown on a Vertisol in central India. After five years of application, soils receiving SW or PME exhibited significantly higher organic carbon content and greater macro- and microaggregate-associated carbon than the control and conventional fertilizer treatments. The increase in soil organic carbon improved aggregate stability, indicating that the judicious application of distillery effluents can enhance soil structure, soil quality, and crop productivity.

Paper Mill Sludge (PMS)

Paper mill sludge (PMS) is a by-product generated during the treatment of effluents from the pulp and paper industry. Globally, the industry produces approximately 400 million wet tonnes of sludge annually. PMS is rich in organic matter and contains appreciable amounts of essential plant nutrients, including nitrogen (N), phosphorus (P), and potassium (K), along with varying proportions of inorganic constituents depending on the manufacturing process. The application of PMS to agricultural soils improves soil physical properties such as aeration, porosity, and water-holding capacity, while also enhancing nutrient cycling and microbial activity. Due to its high calcium carbonate content, PMS can serve as an economical liming material for ameliorating acidic soils. Although PMS generally contains low concentrations of potentially toxic elements such as cadmium (Cd), copper (Cu), lead (Pb), and nickel (Ni), factors such as odor, phytotoxicity, unfavorable C:N ratio, and the accumulation of trace contaminants may limit its large-scale agricultural utilization. Nevertheless, composted PMS has been recognized as an effective soil amendment and nutrient source for sustainable crop production (Meyer and Edwards, 2007; Norrie and Muhammad, 1993).

Numerous studies have highlighted the beneficial effects of PMS on soil quality and crop productivity. Dalei *et al.* (2016) reported that the combined application of PMS and recommended doses of fertilizers significantly enhanced growth parameters, yield attributes, and fresh rhizome yield of turmeric. Improvements in plant height, tiller production, leaf growth, and rhizome development indicated enhanced nutrient availability and better soil conditions resulting from PMS application.

Similarly, Kar *et al.* (2014) demonstrated the effectiveness of PMS as a low-cost liming material for acid soils. Application of PMS increased soil pH, improved nutrient uptake, biomass accumulation, leaf area development, and groundnut yield, while simultaneously reducing the water footprint of crop production. The study further revealed that the beneficial effects of PMS increased with application rate up to an optimum level, beyond which no significant additional advantages were observed.

Overall, the available literature suggests that PMS has considerable potential as a sustainable soil amendment for improving soil health, correcting soil acidity, enhancing nutrient availability, and increasing crop productivity. Its utilization in agriculture also offers an environmentally sound approach for recycling industrial waste and promoting circular resource management.

Phosphogypsum (PG)

Phosphogypsum (PG) is the major industrial by-product generated during the production of phosphate fertilizers. It is composed primarily of calcium sulfate and contains appreciable amounts of calcium (Ca), sulfur (S), and residual phosphorus (P), along with varying concentrations of trace elements depending on the source of phosphate rock. Owing to its high calcium and sulfur content, PG is widely used as a soil amendment and secondary nutrient source in agriculture. It is particularly effective in the reclamation of saline and sodic soils, where it improves soil structure, enhances water infiltration, reduces exchangeable sodium, and increases nutrient availability. Application of PG has also been reported to promote root development, improve nutrient uptake, and enhance crop productivity in degraded and nutrient-deficient soils. However, the presence of potentially toxic elements such as arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni), selenium

(Se), mercury (Hg), and lead (Pb) necessitates careful management and optimized application rates to minimize environmental risks associated with long-term use (Rutherford *et al.*, 1994; FAO, 2004).

Several studies have highlighted the beneficial effects of PG on crop growth and soil fertility. Meena *et al.* (2019) reported that the integrated application of phosphogypsum, fly ash, and chemical fertilizers significantly improved growth parameters, yield attributes, grain and straw yields, and nutrient uptake of wheat grown in an Inceptisol. The study demonstrated that PG can effectively complement fertilizer inputs, thereby improving nutrient-use efficiency and sustaining crop productivity.

Likewise, Ransing *et al.* (2021) observed significant improvements in yield-contributing characters, pod yield, and haulm yield of summer groundnut with phosphogypsum application. The positive response was attributed to the enhanced availability of calcium and sulfur, which play crucial roles in pod development and overall crop growth. These findings indicate that PG can serve as an effective alternative source of secondary nutrients for oilseed crops.

Overall, phosphogypsum has considerable potential as a sustainable soil amendment for improving soil physicochemical properties, enhancing nutrient availability, and increasing crop productivity, particularly in salt-affected and nutrient-deficient soils. Its agricultural utilization not only contributes to improved soil health and crop performance but also offers an environmentally sustainable approach for the recycling and beneficial use of industrial by-products.

Steel Slag

Steel slag is a major industrial by-product generated during steel manufacturing. India currently produces approximately 19 million tonnes of steel slag annually, and its generation is projected to increase substantially with the expansion of the steel industry. Steel slag is rich in essential plant nutrients and beneficial elements, including calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), iron (Fe), and manganese (Mn), making it a valuable soil amendment and mineral fertilizer. Owing to its alkaline nature, steel slag is particularly effective in ameliorating acidic soils by neutralizing soil acidity and improving soil physicochemical properties. Its application has been reported to enhance soil structure, increase nutrient availability, stimulate microbial activity, and improve crop growth and productivity. However, steel slag may contain trace amounts of potentially toxic elements such as vanadium (V) and chromium (Cr), necessitating careful monitoring and appropriate application rates to avoid environmental contamination. The integration of steel slag with organic amendments and biofertilizers is considered an effective strategy for maximizing agronomic benefits while minimizing potential environmental risks (O'Connor *et al*., 2021; Tozsin and Öztaş, 2023).

Several studies have demonstrated the beneficial effects of steel slag on soil health and crop performance. Singh *et al.* (2015) evaluated the impact of Linz–Donawitz (LD) steel slag applied alone and in combination with reduced doses of recommended fertilizers across several crops, including wheat, rice, maize, brinjal, tomato, amaranthus, and mustard. The results indicated that slag application alone was insufficient to sustain soil quality and crop productivity. However, when combined with 80% of the recommended NPK fertilizer dose, LD slag significantly improved soil pH, electrical conductivity, organic carbon content, and enzymatic activities such as urease and phosphatase. The integrated application also enhanced plant biomass and crop yield in several crops, demonstrating its potential to improve nutrient-use efficiency and soil biological activity while reducing fertilizer requirements.

These findings suggest that steel slag can serve as a promising soil amendment for improving soil fertility, soil health indicators, and crop productivity. Its utilization in agriculture not only supports sustainable nutrient management and soil quality enhancement but also provides an environmentally sound approach for the recycling and beneficial use of industrial by-products within a circular economy framework.

Table 3 : Comparative Summary of Major Industrial By-products Used as Soil Amendments

By-product	Major Constituents	Soil and Crop Benefits	Potential Concern	Recommended Use
Fly Ash (FA)	Silicon (Si), Calcium (Ca), Magnesium (Mg), Iron (Fe)	Improves soil porosity, water-holding capacity, and nutrient availability	Heavy metal accumulation	Apply with organic manures and fertilizers

By-product	Major Constituents	Soil and Crop Benefits	Potential Concern	Recommended Use
Press Mud (PM)	Organic Matter (OM), Nitrogen (N), Phosphorus (P), Calcium (Ca)	Enhances soil organic carbon, aggregation, and fertility	Long-term metal buildup	Compost or vermicompost before application
Distillery Spent Wash (DSW)	Organic Matter, Nitrogen (N), Potassium (K), Sulfur (S)	Improves soil fertility, microbial activity, and crop growth	Salinity and high biological oxygen demand	Use at recommended rates
Paper Mill Sludge (PMS)	Organic Matter, Calcium Carbonate ($CaCO_3$), Nitrogen (N), Phosphorus (P)	Improves soil structure, water retention, and acidity correction	High carbon-to-nitrogen ratio	Suitable for acidic soils after stabilization
Phosphogypsum (PG)	Calcium Sulfate ($CaSO_4$), Calcium (Ca), Sulfur (S)	Reclaims saline and sodic soils; improves root growth	Trace toxic elements	Recommended for salt-affected soils
Steel Slag (SS)	Calcium (Ca), Magnesium (Mg), Silicon (Si), Iron (Fe)	Reduces soil acidity and improves nutrient availability	Chromium (Cr) and Vanadium (V) contamination	Apply with fertilizers and organic amendments

Salient Findings

- Fly ash application significantly influences soil physicochemical properties, microbial populations, and crop productivity. However, excessive application may induce toxicity, whereas its integrated use with fertilizers and organic manures enhances soil fertility and crop yield.
- Press mud, an organic industrial by-product, improves soil physical, chemical, and biological properties and increases crop productivity. Its combined application with chemical fertilizers can reduce dependence on synthetic nutrient inputs while maintaining soil health.
- Optimum application of spent wash can partially substitute chemical fertilizers without adversely affecting crop yield. Its use as a soil amendment provides an environmentally sound disposal strategy while improving soil fertility and agricultural productivity.
- Paper mill sludge improves soil physicochemical properties, microbial activity, nutrient availability, and crop growth. Its liming effect makes it particularly useful for ameliorating acidic soils, although supplemental fertilization may be required for optimum crop performance.
- Phosphogypsum serves as an important source of calcium and sulfur and contributes to improved soil structure and nutrient availability. It is particularly effective in reclaiming saline and sodic soils and enhancing crop productivity.
- Steel slag can improve soil fertility, soil health indicators, and crop yield when applied in conjunction with recommended fertilizer doses. However, its sole application is generally inadequate for crop production due to nutrient imbalances and the potential presence of trace heavy metals such as vanadium and chromium.
- The integrated use of industrial by-products with conventional fertilizers, organic manures, and biofertilizers offers a sustainable approach to improving soil quality, enhancing soil health indicators, increasing nutrient-use efficiency, and boosting agricultural productivity.
- Recycling industrial by-products in agriculture supports circular economy principles by converting waste materials into valuable soil amendments, thereby reducing environmental pollution and promoting sustainable soil management.

Challenges

Limited awareness and lack of standardized guidelines: Insufficient farmer awareness and the absence of well-defined recommendations for application rates and management practices restrict the safe and effective agricultural utilization of industrial by-products.

Requirement for pre-treatment: Many industrial by-products require pre-treatment processes such as composting, stabilization, or detoxification to reduce toxicity, immobilize contaminants, and improve nutrient availability before field application.

Variability in composition: The chemical, physical, and biological characteristics of industrial by-products vary considerably depending on their source, production process, and storage conditions, making it difficult to establish universal application guidelines.

Potential accumulation of heavy metals and toxic compounds: Some industrial by-products may contain trace amounts of heavy metals and other harmful substances that can accumulate in soils and crops under prolonged or excessive application, posing risks to soil health, food safety, and the environment.

Need for long-term monitoring: Continuous monitoring of soil properties, crop quality, and contaminant levels is essential to evaluate the long-term sustainability and environmental impacts of industrial by-product application.

Economic and logistical constraints: The adoption of industrial by-products is influenced by factors such as transportation costs, handling requirements, processing expenses, and overall cost-effectiveness relative to conventional soil amendments and fertilizers.

Regulatory and environmental concerns: Inadequate regulatory frameworks and environmental risk assessments may limit the large-scale adoption of industrial by-products in agriculture, highlighting the need for clear policies and quality standards.

Site-specific management requirements: The effectiveness of industrial by-products depends on soil type, climate, crop species, and application rates, necessitating location-specific recommendations for optimum benefits.

Conclusion

Industrial by-products have emerged as valuable resources for sustainable soil management and agricultural production. Their judicious application can improve soil physicochemical and biological properties, enhance nutrient availability and nutrient-use efficiency, and increase crop productivity. Furthermore, these materials contribute to the reclamation of degraded, acidic, saline, and sodic soils, thereby supporting sustainable agricultural development.

The integrated use of industrial by-products with conventional fertilizers, organic manures, and biofertilizers has demonstrated significant potential for improving soil fertility, stimulating microbial activity, and sustaining crop yields while reducing dependence on chemical fertilizers. In addition, the beneficial utilization of industrial wastes in agriculture promotes circular economy principles by transforming waste materials into valuable soil amendments and reducing environmental pollution.

However, the agronomic benefits of industrial by-products depend on their source, composition, processing, and application rates. Excessive or indiscriminate use may lead to the accumulation of heavy metals and other toxic substances, posing risks to soil health, crop quality, environmental safety, and human health. Therefore, site-specific recommendations, appropriate pre-treatment, and regular monitoring of soil and crop quality are essential to ensure their safe and sustainable utilization.

Overall, the integrated and regulated use of industrial by-products represents a promising approach for enhancing soil quality, improving soil health indicators, increasing agricultural productivity, and promoting environmentally sustainable farming systems.

Future Research Needs and Prospects

Industrial by-products have considerable potential as sustainable soil amendments for improving soil quality, soil health indicators, nutrient availability, and agricultural productivity. However, further research is needed to evaluate their long-term effects on soil properties, crop performance, environmental quality, and ecosystem sustainability across diverse agro-climatic conditions. Special emphasis should be placed on understanding the fate, mobility, and bioavailability of potentially toxic elements to ensure their safe and sustainable agricultural use.

The development of site-specific application strategies based on soil characteristics, crop requirements, and the composition of industrial by-products is essential for maximizing agronomic benefits while minimizing environmental risks. Moreover, the integration of industrial by-products with organic manures, biofertilizers, and precision nutrient management practices may improve nutrient-use efficiency, enhance soil biological activity, and sustain crop productivity.

Future studies should also focus on developing advanced pre-treatment and stabilization technologies to improve the quality, safety, and agronomic effectiveness of industrial by-products. Additionally, the establishment of standardized quality standards, regulatory frameworks, and evidence-based application guidelines will be critical for their wider acceptance and adoption in agriculture. Collectively, these efforts will contribute to sustainable soil management, efficient waste recycling, resource conservation, and the promotion of circular economy principles in modern agricultural systems.

The successful integration of industrial by-products into agricultural systems can simultaneously address waste management challenges, improve soil resilience, enhance resource-use efficiency, and contribute to climate-smart sustainable agriculture. “The sustainable utilization of industrial by-products can contribute to climate-smart agriculture, resource conservation, and circular economy-based soil management.”

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