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Review Article

Sustainable Innovations in Mineral Fertilizer Production: Progress and Challenges

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Abstract

This study provides a comprehensive analysis of recent advancements in the production of nitrogen, potash, and phosphorus fertilizers, focusing on innovations that enhance both efficiency and environmental sustainability. Key technological breakthroughs discussed include low-energy ammonia synthesis through electrochemical and plasma-assisted processes, phosphate recovery from municipal and industrial wastewater, and the use of potassium-bearing industrial by-products such as mica, feldspar, and fly ash. The review highlights the development of green synthesis methods that minimize the environmental footprint and offer cost-effective routes to utilize secondary raw materials. Special attention is paid to the integration of circular economy principles and zero-waste approaches in fertilizer production, including the transformation of phosphogypsum and sludge into valuable fertilizer components. Moreover, the potential application of nanotechnology for nutrient delivery optimization and precision farming techniques for improving fertilizer use efficiency are critically examined. This paper provides a detailed overview of current trends and future perspectives in sustainable mineral fertilizer production. By emphasizing innovative strategies and emerging technologies, the article underlines the importance of environmentally responsible approaches to support global food security while preserving ecological balance.

Keywords: environmental sustainability, mineral fertilizers, nitrogen, phosphorus, potassium, waste management

1. INTRODUCTION

Currently, the chemical industry, in particular the segment of the production of mineral fertilizers, is undergoing a period of intensive development. This process is characterized not only by an increase in production volumes, but also by significant qualitative improvements [1]. They include the transition to a more advanced technical level, the use of new production methods and technologies, increased labor efficiency, expanding the range and sources of raw materials, as well as improving the quality of fertilizers produced.

Historically, people began to use naturally occurring salts for various practical needs. Over time, they switched to using salts obtained by processing natural minerals. Initially, the processing methods were quite simple, but these techniques gradually improved in parallel with cultural development [2]. Over time, especially with the development of industry, the variety of salts used for various purposes has increased significantly. Today, the number of types of salts has hundreds of names and continues to increase. Not all inorganic salts have the same importance in economic activity. Some of them are used only in small volumes, while the extraction and production of others reach millions, and sometimes tens of millions of tons per year. Among all artificially produced mineral salts, the largest volumes of production are those that are used as agricultural fertilizers. Fertilizers are materials designed to improve plant nutrition and increase soil fertility [3].

Most mineral fertilizers are salts extracted from natural minerals and atmospheric nitrogen. Among mineral fertilizers, commonly used products include superphosphates, potassium salts, sulfates, as well as ammonium nitrates and phosphates. Mineral fertilizers are salts and other inorganic industrial or natural products containing elements necessary for plant growth and increasing soil fertility, used to achieve high and stable yields [4]. These fertilizers are mainly applied to the soil before sowing, although some of them are also used for non-root nutrition of plants. Nitrogen plays a key role in the mineral nutrition of plants, it is part of proteins, protoplasm, cell nucleus and chlorophyll, which allows plants to assimilate carbon from atmospheric carbon dioxide and solar energy [5]. Alnaas et al. [6] believes that phosphorus, contained in vital substances of plant tissue such as enzymes and vitamins, and especially abundant in seeds, plays an important role in the respiration and reproduction of plants, increasing yields and improving resistance to drought and frost. Potassium, which is contained in significant amounts in plants and their ashes, significantly affects the water regime of the plant, metabolism and the formation of carbohydrates [7]. Elements needed by plants in small quantities, such as iron, are usually present in any soil. While the elements required in large volumes, especially nitrogen, phosphorus and potassium, are introduced into the soil in the form of fertilizers. In nature, there is a natural cycle of nutrients, where they return to the soil. For example, nitrogen from plant tissue in organic form is converted into ammonia during decomposition, and then, thanks to bacteria, into nitrite and nitrate forms, which are then absorbed by plants [8][9]. In addition, plants assimilate a certain amount of atmospheric nitrogen due to the activity of nodule bacteria on their roots [10]. Atmospheric nitrogen is also fixed during thunderstorms, forming nitrogen oxides, which turn into nitric acid when interacting with moisture and enter the soil with rains, forming nitrates.

Fertilizers are divided into categories depending on their origin, purpose, composition, characteristics and production methods. In recent years, key trends and innovations in fertilizer production have included the production of "green" and "blue" ammonia [11]-[13], which is growing due to global efforts to decarbonize the energy sector, making these types of ammonia more competitive. Also, the development of decarbonization technology, including the capture, utilization and storage of blue ammonia, as well as the development of green hydrogen production is relevant among researchers [14]-[16]. In addition, the search for new sustainable and effective types of fertilizers and, accordingly, raw materials for their production is considered a particularly important area in chemical technology. These trends reflect a shift in the fertilizer industry towards sustainable development and new technologies that meet changing regulatory, environmental and market requirements. The purpose of this review is to provide a comprehensive analysis of the latest scientific and technological achievements and innovative developments in the production of complex mineral fertilizers, to assess their impact on agriculture and the environment, as well as to explore current trends, challenges and possible directions for future research in this area.

2. NITROGEN FERTILIZERS

The nitrogen fertilizer industry covers the manufacture of synthetic ammonia, nitric acid, ammonium nitrate, and urea. Synthetic ammonia and nitric acid often serve as intermediates to produce ammonium nitrate and carbamide fertilizers. Nitrogen fertilizers include ammonia solution, ammonium nitrate, ammonium sulfate, anhydrous ammonia, various mixed fertilizers, nitric acid, solutions of nitrogen fertilizers, and urea (Table 1). Synthetic ammonia is produced from natural gas, and about 75% of it in the United States is used for fertilizer production [17]. Nitric acid is used in the production of ammonium nitrate for fertilizers and explosives. Ammonium nitrate is used for the production of fertilizers and explosives, and urea is used in fertilizers and in the production of plastics. Ammonium sulfate is a byproduct of other processes and is used as a fertilizer.

2.1. Chemical and Biological Approaches in Nitrogen Fertilizer Production

One of the promising methods of obtaining nitrogen fertilizers at this time is the use of liquid organic waste. The Crabtree development offers a method for preparing liquid fertilizer from organic waste, including the stages of obtaining liquid filtrate of organic waste, adding acid and evaporation [18]. The process begins with liquid organic waste (preferably from bird droppings), from which suspended solids are removed. This fertilizer contains at least 4% nitrogen, which is higher than in other organic fertilizers. The nitrogen in the fertilizer is ammonia nitrogen, which quickly dissolves in water and becomes available to plants. The use of organic waste is a promising area to produce biofertilizers.

Also, one of the directions of bio-nitrogen fertilizers is the use of bacteria. For example, the Ranka et al. [19] studied biofertilizer composition containing at least one microbiological element

Table 1. Structured nitrogen fertilizers data.

Category	Fertilizer Type	Description	Ref.
Synthetic nitrogen fertilizers	Ammonia solution	Synthetic ammonia-based solution for direct soil application.	[17]
	Ammonium nitrate	Used in fertilizers and explosives, highly soluble.	
	Ammonium sulfate	Byproduct of other processes, common nitrogen source.	
	Anhydrous ammonia	Gas-based nitrogen source, highly concentrated.	
	Nitric acid	Intermediate for ammonium nitrate production.	
	Urea	Widely used, also applied in plastics production.	
Organic and bio-nitrogen fertilizers	Liquid organic waste-based fertilizer	Extracted from organic waste with high nitrogen content.	[18]
	Organic waste-based biofertilizers	Uses liquid waste to create high-nitrogen fertilizers.	
	Microbial biofertilizers	Contains beneficial bacteria to enhance soil nitrogen fixation.	[19]
	Bacterial biofertilizers	Improves nitrogen fixation and availability in soil.	
	Polymer microgel-based biofertilizers	Enhances plant growth, flowering, and seed germination.	
	Bacterial inoculants	Uses pure bacterial cultures to improve nitrogen absorption.	[20]
	Solid carrier bacterial fertilizers	Applies soil bacteria in liquid medium to solid carriers.	[21]
	Azospirillum-based biofertilizers	Uses Azospirillum strains to fix atmospheric nitrogen.	[22]
	Azotobacter-based biofertilizers	Enhances nitrogen fixation and improves soil fertility.	[23]
Advanced nitrogen Fertilizers	Granular CAS fertilizer	Includes ammonium nitrate, urea, and sulfate additive.	[24]
	Granulated nitrogen fertilizers	Enhances production process and improves quality.	[25]
	Improved granulation processes	Improves drying and granulation of nitrogen fertilizers.	[26]
Environmental concerns	Urea environmental impact	Urea contributes to nitrogen oxides and water pollution.	[27]
	Greenhouse gas emissions	Nitrogen fertilizers contribute to climate change.	
	Microbial fertilizer limitations	Challenges in maintaining microbial fertilizers.	[28]
Alternative nitrogen sources	Nitrogen recovery from wastewater	Produces nitrogen fertilizer from ammonia wastewater.	[29]
	Biomass-based nitrogen fertilizers	Utilizes biomass (straw, willow) for nitrogen fertilizer.	[30]
	Manure-based nitrogen fertilizers	Manure provides ammonium and organic nitrogen.	[31]

from a group of bacteria and fungi or their combinations, as well as a polymer microgel. This microgel is capable of promoting plant growth, improving seed germination, accelerating and improving flowering, as well as increasing yield and crop quality. Biofertilizer can be applied directly in the soil, on natural or artificial substrates, or in the form of spraying plants. A similar method is proposed by Patel et al. [20] to improve nitrogen fixation in plants using cultures of pure bacteria, including *Azotobacter chrococcum, Azotobacter vinelandii, Acetobacter xylinum, Gluconacetobacter dizotropicus* and *Azospirillum Lipoferum*. These bacteria efficiently absorb atmospheric nitrogen, making it available to plants and increasing the effectiveness of chemical fertilizers. The method involves inoculation of these bacteria under aseptic conditions and their cultivation in a specialized agar medium to achieve optimal growth and nitrogen fixation activity (Figure 1).

Kutaisi et al. [21] proposed an advanced method for biofertilizer production that enhances microbial viability by immobilizing soil bacteria onto a solid carrier under optimized oxygen and temperature conditions. The process includes controlled drying to improve product stability and optional granulation for better handling. This approach ensures a favorable environment for beneficial microorganisms, enhancing the effectiveness and shelf-life of the fertilizer. A biofertilizer recipe was also proposed by Errakhi et al. [22], based on the *Azospirillum* strain, which is able to fix nitrogen from the atmosphere. This strain also stimulates the absorption of nutrients by plants and helps to increase yields. The invention includes a method for preparing biofertilizer, starting with the mass production of a bacterial strain, and checking its stability and effectiveness to increase yields. Biofertilizer consists of *Azospirillum sp.*, carboxymethylcellulose (CMC) in the range from 0.01% to 0.50%, preservative and stabilizer in the range from 2% to 5%, as well as sterile water. The composition of bio nitrogen fertilizer developed by Girennavar et al. is also known [23]. This method describes the composition of a bio nitrogen fertilizer to enhance nitrogen fixation from various sources, which aims to improve the sustainability and organic nature of agriculture. It includes nitrogen fixers such as *Azotobacter sp.*, *Azospirillum sp.*, *Rhizobium sp.*, and *Gluconacetobacter dizotropicus*, which helps reduce the use of chemical fertilizers and increase yields and soil fertility. The invention also describes a method for preparing biofertilizer, including mixing nitrogen-containing components, creating conditions for granulation and drying of granules at low temperature to preserve living and effective bacteria.

The use of microorganisms for soil cultivation and fertilizer production, although useful in many ways, has some disadvantages [24]. The effectiveness of these microorganisms can strongly depend on specific environmental conditions, such as soil pH, temperature and humidity levels, which makes them less versatile compared to chemical fertilizers. In addition, the introduction of foreign microorganisms in the ecosystem can potentially disrupt the natural microbial balance, which will lead to unforeseen environmental consequences. There is also the problem of constantly maintaining and cultivating these organisms in large-scale agricultural settings, which can be difficult and expensive. In addition, the slow release of nutrients from microbial fertilizers may not meet the immediate nutrient demand of fast-growing crops, which could potentially lead to lower yields compared to chemical fertilizers.

2.2. Advanced and Sustainable Nitrogen Fertilizer Technologies

Kiselevich et al. [25] introduced a novel method and composition for producing nitrogen fertilizer known as granular CAS, which integrates ammonium nitrate, carbamide, and a sulfate additive. The granules of this fertilizer consist of a core of ammonium nitrate, an outer shell of urea and an intermediate layer of ammonium sulfate, providing a nitrogen content of 37% to 41% and sulfated sulfur from 1% to 3%. Fertilizer production involves applying an aqueous suspension of ammonium sulfate to ammonium nitrate granules with simultaneous drying, and then melting carbamide and cooling the finished product. The amount of ammonium sulfate is 80–210 kg per ton of ammonium nitrate, and the concentration in the suspension is maintained at 55–70%. A similar method proposed by Luk et al. [26], describes a method for the production of granular nitrogen-containing fertilizer, the purpose of which is to simplify the production process and improve the quality of fertilizer. The method involves the addition of finely ground ammonium sulfate to a 72–80% aqueous urea solution and its subsequent concentration and granulation using aluminum sulfate. The resulting fertilizer contains from 71.7% to 79.0% urea, from 19.0% to 27.0% ammonium sulfate, from 1.0% to 2.0% aluminum sulfate and water. According to Serebryakov et al. [27], the key problem of the above-described method is the need to use finely ground ammonium sulfate. This process requires additional steps of grinding and sieving ammonium sulfate, which increases energy consumption and requires additional equipment at the concentration and granulation stages, where ammonium sulfate is used to dissolve in an aqueous urea solution. Another problem is the use of a fluidized bed device at the granulation stage, which has low productivity and creates a significant amount of dust per unit of production. At the same time, the authors propose their own method for obtaining a nitrogen-containing fertilizer by mixing a 14–50% mass fraction of a urea solution with an ammonium sulfate solution with a concentration of 50–80% by weight, followed by evaporation of the mixture and granulation at a temperature of 100–140 °C. The resulting nitrogen-sulfate fertilizer contains from 33.5% to 42.4% by weight. nitrogen and from 12.0% to 3.36% by weight. sulfur. This method simplifies the production process, and the fertilizer has good agrochemical properties and is suitable for a wide range of crops.

Ouadday et al. [28] developed a granular chemical fertilizer aimed at enriching agricultural soils with nitrogen. It addresses a number of important problems faced by the chemical fertilizer industry, such as the use of fertilizers in the production of explosives for terrorist purposes, emissions of harmful and greenhouse gases, groundwater pollution and restrictions on the fixed nitrogen content of fertilizers. This fertilizer, being safe to use, can contain nitrogen in concentrations from 30% to 40%. The authors suggest using a mixture of ammonium nitrate and carbamide. However, recently the use of urea for agricultural

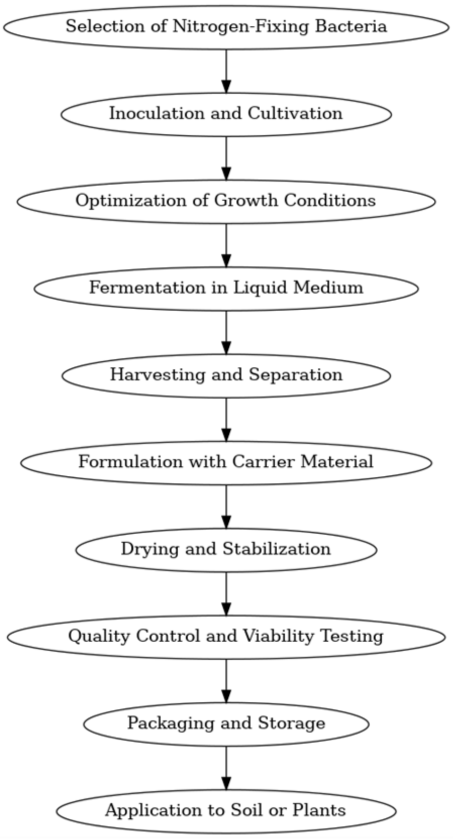

Figure 1. The main steps of the method for preparing bacterial formulations using nitrogen-fixing bacteria [20].

purposes has been limited. Since its decomposition produces nitrogen oxides, which are powerful greenhouse gases [20]-[28][32][33]. They contribute to climate change and can lead to ozone pollution. In addition, urea can be easily washed out of the soil, leading to an increased concentration of nitrates in water sources. These nitrates in water can be converted into nitrogen oxides, enhancing the greenhouse effect [34]. Rosenthal et al. [29] proposed a method for obtaining nitrogen fertilizer from wastewater from ammonia production. The process consists of five stages: removal of ammonia, its extraction, granulation of the product, wax coating on the granules and their encapsulation (Figure 2).

The goal is to create a sustainable, slow-release nitrogen fertilizer produced from wastewater rather than fossil sources, which reduces environmental pollution and overall wastewater treatment costs. This method also reduces nutrient runoff into the environment and provides more cost-effective wastewater treatment, helping to offset operating costs and the cost of consumables. The manufactured product uses environmentally friendly ammonia derived from wastewater nitrogen, which distinguishes it from traditional nitrogen fertilizers and reduces the need for additional wastewater treatment.

Ahlgren et al. [30] proposed a method for obtaining nitrogen fertilizer from biomass. A study of environmental impacts, fossil energy consumption and land use has shown that the use of biomass (straw and short willow Salix) as raw materials reduces the potential for global warming by up to 22–30% compared with traditional natural gas production. However, the potential for eutrophication is higher due to nutrient leaching during biomass cultivation. The use of primary fossil energy for Salix and straw was 1.45 and 1.37 MJ/kg of nitrogen, respectively, which is significantly lower than 35.14 MJ for natural gas. It is assumed that biomass production will provide itself with nutrients by returning part of the nitrogen obtained during the gasification process. From Salix, 3,914 kg of nitrogen can be produced annually from 1 ha of land (with a return of 1.6% nitrogen to production), and from wheat straw — 1,615 kg of nitrogen (with a return of 0.6% nitrogen).

In Italy, an experiment was conducted on the use of manure as a source of nitrogen for agricultural land. Cavalli et al. [31] found that in the first year of use, nitrogen in slurry is mainly available in ammonium form, since the mineralization of organic nitrogen in the short term is usually low. A two-year experiment in Italy compared the effectiveness of various types of manure and mineral fertilizers, including raw and digested manure of dairy cows, as well as their liquid and solid fractions. It turned out that the extraction of ammonium was higher with the use of mineral fertilizers (75%) compared with slurry (30%), except for the use of digested manure (65%). The application of ammonia with organic materials turned out to be less effective than with mineral fertilizers. When using digested slurry and its liquid fraction, most of the ammonium was available during the year of its application (55%) due to the low ratio of carbon to organic nitrogen. However, in the case of the untreated suspension and the solid fraction of the fermented suspension, there was a significant increase in nitrogen availability between the first and second years, due to the high ratio of carbon to organic nitrogen, causing temporary immobilization of nitrogen and residual effects during the cultivation of ryegrass and corn.

Recent advancements in nitrogen fertilizer production highlight a clear shift toward sustainability, efficiency, and reduced environmental impact. Traditional synthesis methods using fossil resources are increasingly being supplemented or replaced by alternative approaches, such as the recovery of nitrogen from wastewater, the utilization of organic and biological waste, and the integration of nitrogen-fixing bacteria. Innovations like slow-release formulations, microbial encapsulation techniques, and bio-based inputs significantly enhance nutrient availability while minimizing runoff and greenhouse gas emissions. Despite challenges such as variable microbial efficacy and production scalability, these developments reflect a strong global trend toward circular economy principles and environmentally conscious fertilizer technologies. Collectively, these innovations mark a transformative phase in nitrogen fertilizer manufacturing, aligning agricultural productivity with ecological responsibility.

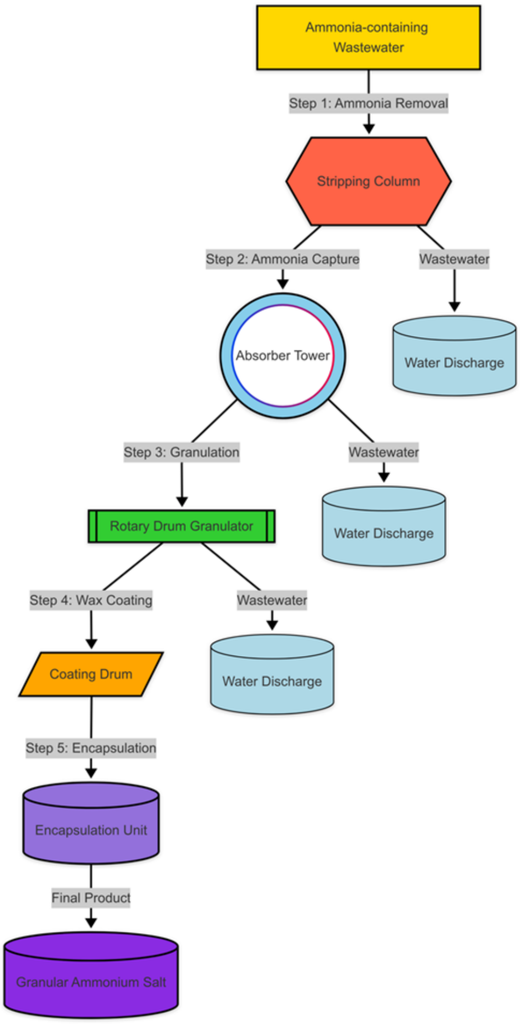

Figure 2. Production of nitrogenous fertilizer from wastewater [29].

3. POTASSIUM FERTILIZERS

To overcome the agronomic and environmental drawbacks of conventional potassium fertilizers—such as excessive chloride content, nutrient leaching, and limited bioavailability—researchers have sought to develop innovative potassium-based formulations. These efforts focus on improving efficiency, minimizing environmental harm, and adapting fertilizers to diverse crop requirements and soil conditions. The following overview presents both traditional and emerging potassium fertilizer types, along with their sources, agronomic roles, and associated limitations. Potassium fertilizers (Table 2), which are key to maintaining plant health and productivity, are usually extracted from natural minerals such as sylvinite (a mixture of potassium and sodium chloride), carnallite (a mixture of potassium chloride and magnesium chloride), and potassium salts from marine reservoirs [35][36].

Common types of potash fertilizers include potassium chloride, potassium sulfate, and potassium nitrate. Potassium chloride is the most common and economical, but contains chlorine, which can be harmful to some crops. Potassium sulfate, suitable for chlorine-sensitive crops, has fewer side effects, but its cost is higher. Potassium nitrate enriches the soil with nitrogen, but is expensive and can contribute to the leaching of nutrients from the soil. These fertilizers improve the water balance of plants, strengthen stems, increase resistance to drought and diseases, but excessive use of them can lead to soil and water pollution, deterioration of crop quality and disruption of the balance of nutrients in the soil [37].

3.1. Technological Innovations in Potassium Fertilizers

Among the recent developments in potassium fertilizers, one approach focuses on improving nutrient delivery and environmental safety through advanced liquid formulations. For instance, Roach et al. [38] proposed a development that is an environmentally friendly high-K liquid fertilizer for crops with a high potassium content (10–27% by weight in the form of K_2O). High-K consists of potassium derivatives, including potassium acetate, potassium formate and other organic sources, and may also contain additional metal additives (up to 25% by weight). The fertilizer maintains a pH in the range of 7.0–10.5, optimally from 8.5 to 10.0. In addition, additional nutrients such as sulfur, zinc, boron, calcium and others can be included in its composition, often in the form of complexes with ethylenediaminetetraacetic acid. This fertilizer provides a nutrient-rich environment for plants, maintaining their health and productivity, while minimizing environmental damage. The same authors also proposed a method for producing liquid potash fertilizers [39]. This development describes an aqueous composition of a fertilizer with an organic potassium source, which has good storage stability, a neutral to slightly alkaline pH (from 6.0 to 8.0) and a low salt content (salt index no more than 40). This composition retains its properties for at least 12 months at room temperature and may contain other nutrients and additives such as nitrogen, phosphates, sulfur, zinc, boron and other trace elements, as well as acetic acid and inoculants. The potassium source is obtained from potassium phosphate, potassium carboxylic salts, potassium silicate or combinations thereof, which reduces phytotoxicity compared to other potassium fertilizers. Although additional research is required for such a statement.

A similar development is available from Qinghuai et al. [40], the purpose of which is to create an environmentally safe nitrogen-potassium complex fertilizer based on sulfur with slow release. This fertilizer provides effective and delayed release of nutrients, has high availability and is used in a wide range of conditions, while its production process is simple and economical. The fertilizer coating material is easily decomposed by microorganisms in the soil, contributing to the environmental protection of soil, air and water. The fertilizer is produced by cooking granules of nitrogen-potassium fertilizer based on sulfur, coating with stearic acid and secondary dusting of the surface with modified zeolite powder. The granules consist of urea, ammonium sulfate, potassium sulfate and a granulating adjuvant (a mixture of bentonite and powdered bauxite). Stearic acid and modified zeolite powder (containing magnesium stearate and zeolite powder) ensure slow release and high fertilizer efficiency. However, both of the above works use organic acids and compounds, which have a number of limitations. For example, their high cost and limited availability, problems with storage and use. These disadvantages undoubtedly affect the cost and quality of agricultural products in the long run.

In the invention of Monesini et al. [41], a method for the production of mineral fertilizers based on the exchange reaction between potassium chloride and ammonium sulfate is described. This process makes it possible to obtain a crystalline product with a high potassium content (from 40% to 50% K_2O of dry weight), low chlorine content (less than 3% of dry weight) and ammonia nitrogen (less than 5% of dry weight). The efficiency of potassium conversion in this method is high, which makes it possible to maximize the use of the source material. In addition, the process produces a by-product that can be used as an NK fertilizer (containing nitrogen and potassium oxide) or as a raw material for the production of complex fertilizers (Figure 3).

One of the potential disadvantages of the described method of production of mineral fertilizers may be the limited use of a by-product arising in the process. Since the by-product contains ammonia nitrogen and chloride, its direct application as an NK fertilizer may not be suitable for all types of soils or crops, especially those that are sensitive to chlorine or excess nitrogen. In addition, the need for additional processing of this by-product for the production of complex fertilizers may entail additional costs and technological difficulties. There is a development by Fairweather et al. [42], where a new liquid fertilizer containing potassium sulfite and bisulfite with a pH in the range from neutral to slightly alkaline was obtained. This fertilizer has a relatively low salt index and lower cytotoxicity compared to other potash and sulfur fertilizers, making it safer to use, especially as a starter fertilizer. The fertilizer is applied in various ways, including application to grooves, lateral fertilization, scattered application and

Table 2. Potash fertilizer production methods.

Category	Method / Fertilizer Type	Description	Ref.
Natural sources	Sylvinite	Natural mineral containing potassium and sodium chloride.	[35] [36]
	Carnallite	Natural mineral consisting of potassium and magnesium chloride.	
	Potassium salts from marine reservoirs	Potassium salts extracted from marine evaporation pools.	
Common potash fertilizers	Potassium chloride	Most common and economical, but contains chlorine, which can harm some crops.	[37]
	Potassium sulfate	Chlorine-free, suitable for sensitive crops, but more expensive.	
	Potassium nitrate	Contains nitrogen, improves soil enrichment, but expensive and prone to leaching.	
Advanced potash fertilizers	High-K liquid fertilizer	High potassium content (10-27% K_2O), includes organic potassium derivatives.	[38]
	Liquid potash fertilizer with organic acids	Neutral pH, low salt index, stable for 12 months, includes microelements.	[39]
	Sulfur-coated slow-release potash fertilizer	Sulfur-based, slow-release, environmentally friendly.	[40]
Liquid potash fertilizers	Environmentally safe liquid potash fertilizer	Contains potassium acetate, potassium formate; stable at pH 6.0-8.0.	[41]
	Potassium sulfite and bisulfite fertilizer	Low salt index, safer than potassium chloride, prevents seed damage.	[42]
Slow-release potash fertilizers	Hydrothermal treatment of potassium ores	Improves potassium release from silicate rocks, enhances plant uptake.	[43]
	Hydrothermal treatment of potassium silicate rocks	Greenhouse experiments confirm its agronomic effectiveness.	[44]
Exchange reaction-based fertilizers	Potassium fertilizers from exchange reaction	Potassium chloride reacts with ammonium sulfate, yielding NK fertilizer.	[45]
Liquid sulfur-potash fertilizers	Low-cytotoxicity potash fertilizer	Contains potassium sulfite and bisulfite, safer alternative to KCl.	[46]
Hydrothermal conversion	Hydrothermal conversion of kalishpate ore	Environmentally friendly method using mild hydrothermal conditions.	[47]
	Slow-release potassium from green sands	Uses green sands as slow-release potassium fertilizers.	[48]
Alternative potash sources	Silicate minerals as potassium source	Silicate minerals (biotite, vermiculite) studied for potassium efficiency.	[49]
	Potassium from Nepheline rocks	Nepheline rocks dissolve faster than feldspar, improving yield.	[49]
Alternative potash sources	Potassium from sugar cane molasses	Sugar cane molasses processed into potassium-rich syngenite.	[50]
Bioactivation of potassium minerals	Microbial bioactivation of potassium minerals	Microorganisms enhance potassium release from minerals.	[47]
	Biotechnological and mechanochemical potassium extraction	Organic acids improve dissolution of potassium from minerals.	[48]
Nanotechnology in potash fertilizers	Nanofertilizer with potassium and biomass	Nanoparticles extracted from banana peels increase seed germination.	[51]
Wastewater-based potash fertilizers	Potassium fertilizers from agro-industrial wastewater	Agro-industrial wastewater processed for potassium recovery.	[52]

fertigation. Experiments have shown that potassium sulfite and bisulfite are less prone to damage germinating seeds compared to other potassium fertilizers such as thiosulfate, sulfate and potassium chloride, and almost do not cause phytotoxicity with reasonable use. The fertilizer contains high levels of potassium and sulfur, while maintaining a neutral or moderately alkaline pH. The main disadvantage of a liquid fertilizer consisting of potassium sulfite and bisulfite may be its limited effectiveness in certain soil and climate conditions. Despite the low salt index and phytotoxicity, such fertilizers may not be suitable for all types of soils, especially for those that already have high levels of sulfur or alkaline reaction. In addition, the pH from neutral to slightly alkaline may not meet the needs of some crops that prefer a more acidic soil environment. This limits the versatility of using this fertilizer in various agricultural systems.

Ciceri et al. [43] developed a method for obtaining potash fertilizers by hydrothermal conversion of kalishpate ore. According to this study, a new calcium-containing material has been developed in the presented work, synthesized in accordance with the principles of green chemistry from local kalishpate ore and CaO under mild hydrothermal conditions. The material is characterized by X-ray diffraction, electron microscopy and other methods, demonstrating a significantly higher potassium content compared to crude ore. This study suggests an environmentally sustainable approach to potash fertilizer production that can overcome the limitations of KCl. However, the paper does not provide data on the presence of fluorine in the feedstock and in the resulting product.

Experiments on hydrothermal treatment of potassium-containing ores were conducted in Morocco. Mbissik et al. [44] the fertilizing properties of both untreated and hydrothermally treated potassium-containing silicate rocks were evaluated. In a greenhouse experiment with ryegrass on potassium-deficient soils, the effectiveness of stone powders was compared with a control without potassium and a standard potassium fertilizer (KCl). Using different doses of fertilizer, the reaction of ryegrass biomass was studied, evaluating the absorption of K, apparent recovery of K (AKR) and relative efficiency of K (RKE). The optimal economical rate of fertilizer application was about 230 kg K/ha, which corresponds to the optimal yield of ryegrass of 44,000 kg/ha. The treated potassium silicate rocks showed a positive result, achieving an optimal yield, although potassium absorption was only half of that provided by the crushed rock. As a result, a mixture of raw materials and hydrothermal materials is evaluated as a suitable option for long-term agronomic use.

3.2. Alternative and Natural Sources of Potassium

A study by Franzosi et al. [45] evaluated the green sands of the Salamanca formation (Argentina) as an alternative source of potassium compared to KCl. Glauconite pellets from this formation, concentrated in fractions of 600–250 microns (GL250c) and 250–125 microns (GL125c), showed an increase in K_2O content by 27% and 60%, respectively. These fractions have undergone chemical analysis, leaching analysis and agronomic assessments. Potassium release from GL250c was more effective in the first 15 days, while GL125c continued to release potassium after 15 days. After leaching, the specific area increased by 27% and 16% for GL125c and GL250c, respectively. In agronomic analyses, the first four harvests showed the best results for KCl, but the overall effectiveness of GL250c and GL125c was similar or slightly higher than KCl after five harvests. This suggests that the green sands of the Salamanca formation represent an effective alternative source of slow-release potassium for fertilizers, with advantages in production and processing costs compared to the cost of extraction of soluble potassium salts.

In a study by Li et al. [46] the potential of potassium-containing layered silicate minerals in China as alternative sources of potassium to combat potassium deficiency in the soil and reduce agricultural costs was studied. Using the methods of extraction of sodium tetraphenylborate and intensive cultivation of agricultural crops, optimal indicators of the rate of potassium release and its concentration in the leaves were determined. The effectiveness of various minerals varied: biotite and vermiculite showed the highest amounts of released potassium (27.80 and 5.58 g/kg, respectively), followed by illite, smectite and muscovite with lower values. Ryegrass grown on phlogopite was deficient in potassium throughout the experiment. The conclusions state that biotite and vermiculite can be used both directly and as an alternative to traditional potash fertilizers, illite in combination with soluble potassium fertilizers, while muscovite, phlogopite and smectite may be less effective for plant growth. Additional field experiments are required to evaluate the use of these minerals as potassium sources.

The above studies show the agrochemical value of alternative potassium sources. Natural potash fertilizers (NPF) represent a new approach to the sustainable development of agriculture using microbes for the bioactivation of natural minerals that contribute to the dissolution of potassium [47]. This technology improves the availability of potassium in the soil by activating natural potassium sources such as biotite, muscovite, feldspar, illite, orthoclase and mica with the help of microorganisms. These include *Bacillus mucilaginosus, Bacillus edaphicus, Bacillus circulans, Paenibacillus spp, Acidothiobacillus ferrooxidans* and other bacteria known as potassium solubilizing microorganisms (KSM), which play a key role in increasing the availability of potassium to plants. Organic acids produced by soil microorganisms can promote the release of potassium from potassium minerals, although the low reactivity of some minerals limits their effectiveness. A study by Lodi et al. [48] showed how gluconic, oxalic and citric acids can improve the solubilization of potassium from various types of minerals, including polyhalite (sedimentary mineral), feldspar (igneous mineral) and KCl (industrial fertilizer). Solubilization was complete for polyhalite and KCl using all organic acids, and the highest solubility of potassium from feldspar was achieved using oxalic acid. Additionally, the solubility of feldspar was studied using the fungus Aspergillus niger and mechanochemical treatment. The biotechnological method increased the dissolution of potassium to 63.2 mg/L, while the mechanochemical approach increased the release of potassium by about 8.6 times (to 993 mg/L), due to an increase in the surface area of the particles. These results demonstrate the potential of biotechnological and mechanochemical methods with organic acids to improve the dissolution of potassium in minerals with low reactivity, which may contribute to the use of these minerals in more sustainable agricultural practices.

Modern research shows that nepheline-containing rocks can be more effective sources of potassium for plant growth than granite rocks, since nepheline dissolves 100 times faster than potassium feldspar [49]. This is especially true for rapidly leaching soils such as tropical ones, where potash feldspar and granite rubble can increase yields, but not as effectively as conventional fertilizers. It is

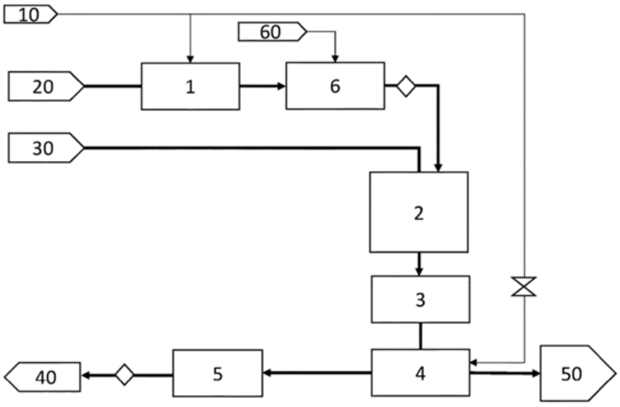

Figure 3. Process for the production of potassium sulphate based fertilizers [41]: **1** - Initial reaction vessel (where raw materials react); **2** - Crystallization unit (potassium sulfate formation); **3** - Filtration unit (solid-liquid separation); **4** - Drying and granulation unit (final processing); **5** - Waste treatment or recovery system; **6** - Secondary reaction or purification step; **10** - Primary raw material; **20** - Sulfuric acid feed; **30** - Additional reactants or additives; **40** - Waste stream or by-product; **50** - Final potassium sulfate fertilizer product; **60** - Recycled stream or process additive.

also mentioned that experiments with other types of rocks, such as basalt and andesite, can improve yields, but the relationship between this and their mineralogical composition is ambiguous. As an alternative raw material for the production of potash fertilizers, researchers Otani et al. [50] suggested using sugar cane molasses. Sugar cane molasses, a potassium-rich byproduct of sugar production, has significant potential as a source of potash fertilizers. In the study, a simple two-step precipitation method was developed to extract potassium as a syngenite from molasses. The first stage of water deposition allowed to recover more than 30% of potassium from the initial molasses, and the second stage using calcium acetate and sulfuric acid — about 40%. As a result, the method made it possible to extract more than 70% of potassium. The effectiveness of the method was confirmed on eight different molasses samples from Japan, showing successful extraction of syngenite with an efficiency of more than 70% without difficulties in processing. Thus, the proposed method can meet the growing demand for potash fertilizers and increase the sustainability of sugar production from sugar cane.

Nanofertilizer containing potassium, iron, tryptophan, urea, amino acids, protein and citric acid was extracted using biomass such as banana peel [51]. The size of fertilizer nanoparticles ranges from 19 to 55 nm, and most of them are about 40 nm in size. This fertilizer was used in the cultivation of tomatoes and fenugreek, showing an increase in the percentage of germination for both crops. For tomatoes, germination increased from 14% (without nano-fertilization) to 97% at 7 days after planting, and for fenugreek - from 25% to 93.14%. This highlights the potential of processing banana peels into useful materials for agriculture. However, the use of various biological masses to produce fertilizers has a number of disadvantages and limitations: heterogeneity of composition, presence of harmful substances, high cost of their processing, etc.

Wastewater from agro-industrial enterprises can serve as another raw material resource for potassium-containing fertilizers [52]. They often contain high levels of potassium. Potassium concentrations in these effluents are significantly higher than in domestic wastewater. For example, wastewater from olive oil mills contains 10,000–20,000 mg of potassium per liter, which is significantly higher than in wastewater from pigsties (500–1,000 mg/L) or wineries (up to 1,000 mg/L). The use of such wastewater for irrigation can improve soil fertility, however, prolonged use can lead to potassium accumulation and deterioration of soil hydraulic conductivity.

3.3. Comparative Evaluation of Potassium Fertilizer Innovations

A variety of potassium fertilizer innovations have been developed to address the limitations of conventional formulations such as high chloride content, nutrient leaching, and poor uptake efficiency. To assess the practical potential of these technologies, it is important to evaluate them across key dimensions: nutrient-use efficiency, cost-effectiveness, environmental sustainability, scalability, and crop suitability. Sulfur-coated and slow-release potassium fertilizers demonstrate improved nutrient-use efficiency and reduced leaching losses, especially in sandy soils and high-rainfall regions. However, their production involves higher costs, and scalability may be limited by coating technology requirements. Nanofertilizers, incorporating potassium into nanoscale carriers, offer targeted delivery and enhanced uptake by plant roots, often resulting in higher efficiency with lower application rates. These fertilizers show great promise in sustainability and minimizing runoff. Yet, their cost and regulatory uncertainty regarding nanomaterials may hinder widespread adoption.

Hydrothermally treated potassium ores represent an innovative approach for utilizing low-grade or alternative mineral sources. This method offers cost benefits in resource-rich regions and avoids dependence on high-quality potassium chloride imports. While environmentally favorable due to reduced chemical processing, the technology is still under development and requires further optimization for consistent agronomic performance. Liquid organic-based potassium fertilizers, derived from biomass or waste streams, contribute to circular economy goals and can be suitable for organic farming systems. However, they often show variability in nutrient concentration and may not be suitable for large-scale mechanized farming.

Each of these technologies has strengths aligned

Figure 4. Molten phosphorus-potassium fertilizer preparation process [74].

with specific agricultural contexts and policy priorities. While nanofertilizers and sulfur-coated products are advantageous in terms of precision and efficiency, hydrothermal processing and organo-mineral options emphasize cost and sustainability. A balanced approach considering regional soil conditions, crop types, and economic feasibility will be key in selecting the most appropriate potassium fertilizer technology.

4. PHOSPHORUS FERTILIZERS

Another important macronutrient for plants and soil is phosphorus. Phosphorus fertilizers are obtained mainly from phosphate rocks, including apatites and phosphorites, as well as from animal bones and manure [53]-[55]. Among the types of phosphorus fertilizers, superphosphate, triple superphosphate, ammophos and diammonium phosphate are common (Table 3). The advantages of these fertilizers are their effectiveness in improving soil fertility and accelerating plant growth, especially in phosphorus-deficient conditions. However, significant disadvantages are the risk of environmental pollution due to leaching of phosphates, potential deterioration of soil structure and the possibility of accumulation of toxic elements such as cadmium in phosphate rocks [56][57]. In addition, the extraction of phosphate rocks is limited and can lead to depletion of natural resources.

The history of phosphorus fertilizers began in the early 19th century, although phosphorus was discovered as early as 1669 [58]. Initially, natural sources of phosphorus, such as bone meal, were used. The first commercial method for the production of phosphorus fertilizers was developed in 1840 by John Bennet Lawes, who used sulfuric acid to process bone meal, creating superphosphate [59][60]. In the following years, fertilizer production evolved with the development of new forms, including ammophos and diammonium phosphate, providing higher concentrations and digestibility of phosphorus by plants. This development included the beginning of the extraction of phosphate rocks as the main source of phosphorus.

The main methods of production of phosphorus fertilizers include the following key processes. Wet process one of the most common method used for the production of phosphorus fertilizers. It involves treating phosphate ore with sulfuric acid to produce phosphoric acid, which can then be used to produce various phosphate fertilizers such as diammonium phosphate (DAP) and monoammonium phosphate (MAP) [61]-[64]. Thermal process: In this method, phosphate ore is mixed with silica and coke, and then subjected to high-temperature reduction in an electric arc furnace. The result is elementary phosphorus, which can be converted into phosphoric acid or other phosphorus-containing compounds [65][66]. Nitric acid process: This method involves treating phosphate ore with nitric acid. The product is calcium phosphate, which can then be converted into various phosphorus fertilizers [67]-[69].

4.1. Innovative and Low-Phosphorus Fertilizer Technologies

The invention of Sheppardson et al. [70] presents an innovative concentrated phosphorus fertilizer in the form of a liquid suspension, the purpose of which is to improve the absorption of phosphorus by plants and accelerate their growth. The fertilizer has a number of advantages: it consists of soluble forms of phosphorus, which facilitates its assimilation by plants; contains a suspending agent that prevents the precipitation of potassium monophosphate; has a pH acceptable for phosphorus absorption in the range from 5.0 to 7.5; and is a stable suspension that is easily diluted with water immediately before use. The suspension composition contains phosphoric acid or its salts, as well as phosphoric acid or its salts, and provides homogeneous mixing without the need for additional preparation. The total acid and salt content in the fertilizer ranges from about 50% to about 80% by weight. A similar work by Lovatt [71] provides a method for producing a concentrated phosphorous fertilizer with a buffer composition containing organic acids and their salts, as well as phosphorous-containing acids and their salts, which is diluted with water to obtain a completely soluble fertilizer with a pH optimal for phosphorus absorption. According to the author, this fertilizer provides effective fertilizer for plants with improved phosphorus absorption. The main disadvantages of the proposed method of production of concentrated phosphorus fertilizer may be related to its stability and storage. Firstly, the presence of suspending agents can cause difficulties in storage and transportation, especially if long-term storage is required, because it can affect the homogeneity of the suspension. Secondly, a high concentration of active ingredients requires precise dilution before use, which can be problematic for end users without appropriate equipment or experience.

While phosphorus-free fertilizers such as those containing polyaminoacid salts aim to enhance plant resilience under nutrient stress, other approaches seek to directly optimize phosphorus uptake and utilization. Funk et al. [72] suggest to use phosphorus-free or low-phosphorus fertilizers containing a polyaminoacid salt to compensate for low phosphorus levels and improve nutrient absorption by plants. These fertilizers promote the development of roots and root hairs, and also help plants cope with stress such as high temperatures or drought. Both powder and liquid forms of fertilizers with different ratios of nitrogen and potassium, including mixtures with slowly and rapidly released nitrogen, are proposed. Fertilizers are also characterized by a low salt index, which prevents the risk of "burning" plants. They are suitable for underground injection and long-term exposure, especially effective for woody perennial plants. The main disadvantage of the proposed method of fertilizers without phosphorus or with a low phosphorus content containing polyaminoacid salt is the potentially insufficient supply of phosphorus to plants, which is critically important for their growth and development. Although the polyamide acid salt can compensate for some disadvantages, it cannot completely replace phosphorus in its key biological functions such as photosynthesis, energy transfer and cell division. In addition, special application methods may be required for the effective use of such fertilizers, which complicates their use for the average farmer. There may also be problems with the solubility and stability of fertilizers during storage and transportation, especially with a high content of organic components. These factors may limit the widespread use of these fertilizers in agriculture.

Scientists from China Agricultural University present a new sugar and phosphorus-containing fertilizer designed to improve the use of phosphate fertilizers in agriculture [73]. This fertilizer combines water-soluble carbon-containing compounds such as glucose, sucrose or molasses with phosphorus-containing compounds, including phosphoric acid and various types of phosphates (for example, monoammonium phosphate or diammonium phosphate). The fertilizer promotes the activity of microorganisms in the soil and increases the efficiency of phosphorus use. The carbon and phosphorus in the fertilizer are in a mass ratio from 1:1 to 15:1, with low- and high-carbon variants. This combination of carbon and phosphorus provides effective nutrition for plants, improving their growth and health. However, the potential risk of excessive carbon entrainment into the soil can lead to undesirable changes in the soil microbiome and a possible nutrient imbalance. High sugar content can also attract pests or contribute to the development of pathogens.

The Brazilian company Mineracao Curimbaba Ltda. offers a method for producing phosphorus-potassium fertilizer produced by melting raw materials containing phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O), as well as materials providing SiO_2 [74]. Preferably, these components are obtained from phosphate minerals (apatite, phosphorite) and potassium minerals (potassium rocks, phonolite), with additional inclusion of materials such as sands, dunites or serpentinites, manganese and dolomites (Figure 4).

To create the fertilizer described in this invention, mixtures of alkaline rocks from the territory of Planalto de Pocos de Calda and natural phosphate rocks from various sources can be used as starting materials, for example. The fertilizer helps to correct the acidity of the soil and provides plants with amorphous vitreous SiO_2. In the process of creating fertilizer, the raw material melts and then quenches in water, turning into an amorphous material with phases of potassium, phosphorus and silicon, soluble in weak acids, but not soluble in water. The method involves homogenization and melting of raw materials, followed by quenching in water, drying and grinding to a particle size of about 100 mesh. The composition of the fertilizer may vary, but is not limited to certain ratios of components. A potentially complex and energy-intensive production process requiring high temperatures for melting and subsequent quenching is the main disadvantage of the proposed method. This approach can entail significant energy and specialized equipment costs, increasing overall

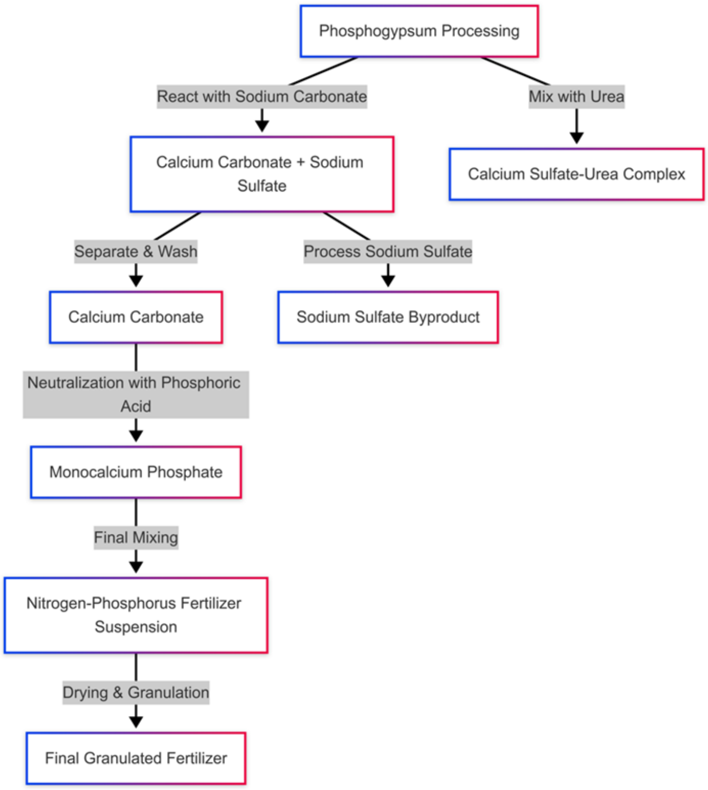

Figure 5. Chemical reaction flowchart for processing phosphogypsum into nitrogen-phosphorus fertilizer [83].

production costs.

4.2. Phosphorus Fertilizers from Industrial Waste

The development of phosphorus fertilizers accelerated significantly in the 20th century, when many of their formulations were developed. Rocks such as apatites and phosphorites have become the main source of phosphorus for these fertilizers, but the gradual depletion of these natural resources has led to scientific and technological interest in finding alternative sources of phosphorus. This research area includes exploring the possibilities of recycling agricultural, livestock and industrial waste, as well as developing more efficient ways to recycle and reuse existing phosphate resources. Such approaches are aimed at reducing the environmental impact and ensuring the sustainability of the supply of phosphorus fertilizers in the future.

One of the by-products formed during the production of phosphoric acid from phosphate ores is phosphogypsum. Phosphate ore is usually treated with sulfuric acid, which leads to the formation of phosphoric acid and gypsum as a by-product. Chemically, phosphogypsum consists mainly of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), that is, it is similar to gypsum used in construction, but may also contain various impurities, including small amounts of radionuclides, heavy metals and other pollutants that may limit its use [75]-[78]. Phosphogypsum is often considered as a waste requiring safe disposal or storage, however, research is aimed at finding ways to process and use it, for example, as a raw material for the production of building materials, in agriculture or in soil restoration [79]-[82].

For example, a method of processing phosphogypsum into nitrogen-phosphorus fertilizer is known [83]. The process involves the conversion of phosphogypsum in a solution of sodium carbonate at 70–100 °C with constant stirring, which leads to the formation of a suspension with calcium carbonate and sodium sulfate solution (Figure 5). The separated and washed calcium carbonate is used to neutralize phosphoric acid, forming a suspension of monocalcium phosphate. This suspension is mixed with a suspension of the chemical compound $CaSO_4 \cdot 4CO(NH_2)_2$, obtained from phosphogypsum and carbamide, resulting in a suspension of nitrogen-phosphorus fertilizer. The resulting slurry of fertilizer with a humidity of 44–54% is then dried and granulated, producing granules of 2-4 mm in size with a content of CaO 16.5–20%, P_2O_5 10.5–33.5%, N 13.5–24.7%, S 3.9 –7.0% and pH 5.2–6.5. This method makes it possible to efficiently process phosphogypsum and produce nitrogen-phosphorus fertilizers.

In a similar method, Gorbachev et al. [84] proposes to carry out the conversion of phosphogypsum in a solution of sodium carbonate with a concentration of 152–156 g/L in Na_2O at 60–70°C. At a temperature of 75–80°C and a ratio of phosphogypsum to a solution of sodium carbonate of 24.0–25.0% to 75.0–76.0%, calcium carbonate and a solution of sodium sulfate are formed. Under these conditions, the phosphogypsum conversion process is completed by reaction Equation (1):

$$Na_2CO_3 + CaSO_4 \cdot 2H_2O + H_2O \rightarrow Na_2SO_4 + CaCO_3 + 3H_2O \quad \mathbf{(1)}$$

The washed calcium carbonate is used to neutralize phosphoric acid with a content of 35.0–37.0% P_2O_5, resulting in a suspension of phosphorus fertilizer with a moisture content of 57–60%, which is then subjected to drying and granulation as shown in Equation (2):

$$CaCO_3 + 2H_3PO_4 \rightarrow Ca(H_2PO_4)_2 + CO_2 + H_2O \quad \mathbf{(2)}$$

This method makes it possible to effectively convert phosphogypsum into a phosphorus fertilizer with a high content of digestible and water-soluble form of P_2O_5. In addition, rare earth elements [85]-[87] and various salts [88][89] can be isolated from phosphogypsum. Another by-product formed during the production of phosphorus is cottrel dust. It is a finely dispersed residue that is collected in flue gas purification systems of phosphorus plants [90]. This process involves the roasting of phosphate ore, in which phosphorus is released, as well as other gases and impurities, which are then captured in Cottrell electrofilters or similar devices.

The composition of cottrel dust in the production of phosphorus, in addition to phosphorus oxides, may include various impurities such as phosphates, fluorides, sulfur, metal oxides, as well as heavy metals and other elements, depending on the characteristics of the feedstock. Dust often contains

Table 3. Phosphorus fertilizer production methods.

Category	**Method / Fertilizer Type**	**Description**	**Ref.**
Natural sources	Apatites	Natural phosphate mineral used as raw material for phosphorus fertilizers.	[53]-[55]
	Phosphorites	Sedimentary rock rich in phosphates, another primary source of phosphorus.	
	Animal bones and manure	Organic source of phosphorus from livestock waste.	
Common phosphorus fertilizers	Superphosphate	Traditional phosphate fertilizer produced by treating phosphate rock with sulfuric acid.	[56][57]
	Triple superphosphate	More concentrated than superphosphate, providing higher phosphorus content.	
	Ammophos	Ammonium phosphate fertilizer with balanced nitrogen and phosphorus.	
	Diammonium phosphate	Highly concentrated ammonium phosphate fertilizer.	
	Wet process	Phosphate rock treated with sulfuric acid to produce phosphoric acid.	[61]-[64]
	Thermal process	High-temperature reduction of phosphate ore with silica and coke.	[65][66]
	Nitric acid process	Treatment of phosphate rock with nitric acid, producing calcium phosphate.	[67]-[69]
Liquid phosphorus fertilizers	Concentrated phosphorus suspension	Liquid suspension fertilizer with high phosphorus solubility.	[70]
	Buffer-based liquid phosphorus fertilizer	Contains organic acids and buffers to enhance phosphorus absorption.	[71]
Low-phosphorus fertilizers	Low-phosphorus fertilizers with polyaminoacid salt	Polyaminoacid salts replace phosphorus, promoting root growth.	[72]
Sugar-phosphorus fertilizers	Sugar-containing phosphorus fertilizers	Combines carbon sources like glucose with phosphorus to enhance microbial activity.	[73]
Phosphorus-potassium fertilizers	Phosphorus-potassium fertilizer via high-temperature fusion	Fusion of phosphate and potassium minerals, forming an amorphous fertilizer.	[74]
Phosphogypsum recycling	Phosphogypsum-based nitrogen-phosphorus fertilizer	Phosphogypsum processed with sodium carbonate to form phosphate fertilizer.	[83]
	Phosphogypsum conversion with sodium carbonate	Conversion of phosphogypsum into monocalcium phosphate and nitrogen-phosphorus fertilizer.	[84]
Alternative phosphorus sources	Recycling of phosphorus-containing sludge	Phosphate sludge mixed with organic materials and ammonium sulfate.	[85]-[87]
	Recycling of phosphate waste	Recycling of industrial phosphate waste into fertilizers.	[88][89]
Phosphorus recovery from industrial waste	Decomposition of cottrel dust with sulfuric acid	Acidic decomposition of cottrel dust to extract phosphorus.	[90]
	Ammoniation of cottrel dust	Cottrel dust mixed with ammonium sulfate and humic acids to enhance phosphorus availability.	[91]
Cottrel dust processing	Cottrel dust processing with magnetized ammonium nitrate	Cottrel dust treated with magnetized ammonium nitrate and phosphogypsum.	[92]
	Cottrel dust-based fertilizer production	Chemical treatment of cottrel dust to produce a high-phosphorus fertilizer.	[93]

significant amounts of valuable components, which makes it potentially useful for recycling and use as a secondary raw material. There are developments that offer to process cottrel dust into fertilizer products. For example, Ismailov et al. [91] sulfuric acid was used to decompose it and thus obtained a phosphorus-containing fertilizer. According to this study, the mineral part of cottrel dust is characterized by an abundant amount of phosphorus (about 30%).

According to the development of Nazarbek et al. [92] the method uses a mixture of phosphorus-containing sludge and cottrel dust in a ratio of 2/1, which is treated with 30% ammonium sulfate and humic acid in a ratio of 1:1.5–1:3.0 at 60 °C. The mixture is stirred for 45–60 min, then filtered, ammoniated with 25% ammonia water to pH 6.0 and dried until complete crystallization at 100 °C. The resulting fertilizers have a high content of digestible phosphoric anhydride and nitrogen. This method is effective both for the production of fertilizers and for the disposal of phosphorus production waste.

Another method of processing cottrel dust is its treatment with a magnetized solution of ammonium nitrate, subsequent coating of the mixture with phosphogypsum and chemical treatment for 12 h [93]. The resulting fertilizer at a humidity of less than 5% is packaged and sent to the consumer, and at a humidity of more than 5% it is dried first. One of the main disadvantages of phosphogypsum and cottrel dust processing methods is the complexity of processing these materials due to their toxicity and the presence of heavy metals, radionuclides and other harmful impurities. This requires specialized technologies and equipment to ensure safety and compliance with environmental standards, which increases the cost of the process. In addition, the need for strict quality control of the final product may limit the use of the obtained materials. At the same time, this sector has significant development prospects, since the intensification of research in the field of industrial waste disposal in order to minimize their impact on the environment and the creation of new economically profitable products is an urgent task. The development of innovative, efficient and environmentally friendly technologies for the processing of these wastes can lead to a significant reduction in the environmental burden and open up new opportunities for the industrial use of recycled materials. While the various approaches discussed in this section—such as polyaminoacid salt fertilizers, sugar-enhanced phosphorus fertilizers, and phosphogypsum recycling technologies—demonstrate promising advancements in phosphorus fertilizer innovation, they differ significantly in terms of cost-efficiency, environmental footprint, nutrient availability, and scalability. Conventional superphosphates remain dominant due to established infrastructure, yet waste-derived fertilizers and bio-based formulations offer clear sustainability benefits. Further comparative studies are needed to evaluate these innovations across diverse agro-ecological contexts and assess their potential integration into mainstream agricultural practice.

5. CONCLUSION

Considering the current state and innovative trends in the production of nitrogen, potash and phosphorus fertilizers, the focus was not only on technological advances, but also on the importance of a sustainable environmental approach in this area. Promising areas in the production of nitrogen fertilizers include the development of methods to reduce emissions of nitrogen oxides and ammonia, as well as the use of alternative nitrogen sources such as bioazote. In the field of potash fertilizers, the emphasis is on optimizing the extraction and processing of potash minerals, as well as on developing technologies for the effective use of potassium contained in various waste and by-products. Phosphorus fertilizers are being developed thanks to technologies capable of utilizing phosphorus from waste and wastewater, which reduces dependence on traditional sources of phosphate ores and promotes a closed cycle of resource use. Considerable attention is paid not only to innovations in the field of fertilizer production, but also to the development of sustainable environmental approaches. This includes the use of renewable energy sources, minimizing waste and pollution, as well as improving the efficiency of fertilizer use to reduce their environmental impact and prevent eutrophication of aquatic ecosystems. Thus, the future of the production of complex mineral fertilizers is associated with the integration of technological innovations and the principles of sustainable development, which will meet the growing needs of agriculture while maintaining an ecological balance and ensuring a sustainable future.

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Conceptualization, P. A. and Y. R.; Methodology, Writing—Original Draft Preparation, Y. R.; Software, Visualization, Writing—Review and Editing, P. A.; Validation, S. Y., U. N. and P. A.; Investigation, Data Curation, S. Y.; Resources, Supervision, Funding Acquisition, Project Administration, U. N. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI

Not applicable.

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