

REVIEW ON THE MANUFACTURING PROCESSES OF ORGANO-MINERAL FERTILIZERS AND THEIR BENEFICIAL EFFECT ON SOIL-PLANT SYSTEMS

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ABSTRACT

Finding the ideal balance between production intensification and sustainability is one of agriculture's main goals. Innovative agricultural methods must be developed in order to guarantee food security because of the world's population expansion, climatic variability, and soil degradation. Organo-mineral fertilization has become a viable option in this situation. This strategy addresses soil fertility and health concerns at the same time by combining the advantages of organic and mineral resources in novel fertilizer formulations. The production of organo-mineral fertilizers is based on the co-processing of organic and mineral ingredients and is very flexible. Organo-mineral fertilizers are produced using extremely flexible methods based on the co-processing of mineral and organic elements. We also examine the positive impact of these products on the plant-soil system, focusing on their mechanisms of action. Furthermore, the review analyzes the innovation landscape of OMF based on patent submission trends over the last 20 years and outlines future research and development pathways to address the current challenges and limitations in the industry.

Keywords: Organo-mineral fertilizers, Manufacturing, Beneficial effect.

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INTRODUCTION

A growing world population and a lack of land and raw materials are major obstacles to agriculture's ability to meet food security objectives. Important technologies that enabled the creation of intense and extremely productive agriculture systems were introduced during the last Green Revolution. These productivity-driven methods, however, mostly relied on overfertilization

and monocropping, which resulted in problems with soil degradation like salinization, erosion, nutrient imbalances, and the loss of soil organic matter (SOM). SOM affects microbial activity, nutrient dynamics and cycling, and physical properties, making it an essential indicator of soil health [1]. Numerous agricultural practices have been proposed to enhance

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SOM levels and ensure the sustainable fertility of degraded soils. These practices include cover cropping, reduced or no-till farming, integrated nutrient management, and amending soil with stable organic matter. Organic farming is often regarded as an eco-efficient strategy for improving SOM. However, it is frequently perceived as a low-production system due to its reliance on variable ecosystem services, which are significantly affected by environmental changes. Researchers indicate that organically managed farms yield 10-20% less than conventional farms [2-5]. Nevertheless, the profit trend is reversed, attributed to lower operating costs, better plant stress resistance, premium prices for end products, and a simpler supply chain. In contrast, Kirchmann argues that current meta-analyses may overestimate organic farming production, as these assessments often stem from nature-related philosophical perspectives rather than rigorous biological science, and claims for the complete substitution of mineral fertilizers lack scientific validity. Furthermore, Swedish statistical data suggest that converting to organic farming without yield loss may require a 50% increase in arable land [6].

There are clear benefits and drawbacks to both conventional and organic farming. Combining organic and mineral inputs is a potential strategy because both resources are theoretically compatible. According to a number of studies, this combination might be the best way to maintain sustainable soil fertility and health while optimizing crop productivity and agronomic efficiency. Because of the growing interest in this idea, a new class of fertilizer products called organo-mineral fertilizers (OMF) has been developed. These fertilizers are produced by combining an organic matrix or soil improver with nutrient-rich inorganic fertilizers through a chemical process [7].

One of OMF's main advantages is that their production method is built on the value-adding of organic waste, which is in line with the circular economy's tenets. Furthermore, manufacturing procedures might involve technologies like solid-state fermentation, anaerobic digestion, and thermal conversion in addition to chemical processes. The added value of the finished products arising from particular chemical interactions—such as enhanced nutrient bioavailability, increased chemical reactivity, and slow-release properties—justifies co-processing mineral and organic resources rather than applying them separately. OMFs are frequently recognized for their several advantages to agrosystems, including improving plant physiological characteristics, biological functions, and soil physico-chemical qualities [8-10].

There are few reviews on OMF, most of which concentrate on the chemical co-processing of mineral fertilizers and sewage sludge. By offering a methodical examination of the idea of organo-mineral fertilization, this critical study seeks to supplement earlier studies. It goes into great detail about both traditional and cutting-edge technologies (beyond chemical processes) that are employed in the production of these goods. It also discusses, for the first time, the conversion of phosphate industry mineral byproducts into OMF. With a focus on their methods of action, the review also shows how these compounds affect plant agrophysiological characteristics, soil physico-chemical and biological characteristics, and agronomic production. Ultimately, it outlines the current market status, highlights significant limitations, and offers future perspectives for advancing this vital segment of the fertilizer industry.

MANUFACTURING PROCESSES OF ORGANO-MINERAL FERTILIZERS

The manufacturing processes for converting organic and mineral wastes into organo-

mineral fertilizers are highly varied. Research has shown that chemical, thermochemical, and biological methods can all effectively produce fertilizers with desirable properties. The selection of the appropriate process primarily depends on the type of feedstock used and the intended market. This section systematically reviews the most notable chemical and biological methods employed in the development of organo-mineral fertilizers by valorizing organic and mineral waste, as well as low-grade phosphate.

OMF from Chemical Fertilizers and Organic Waste

Implementing a process to produce organo-mineral fertilizers largely depends on the properties of raw materials, typically comprising organic waste and a mineral fraction. Various formulations have been tested, as outlined in Table 1, with granular and pelletized forms being the most prevalent. Given the vast diversity of organic waste generated, the formulation possibilities are nearly limitless [11].

Transforming organic waste into OMF formulations has two primary objectives: producing a high-quality fertilizer and creating agronomic value from the organic waste. For instance, when processing sewage sludge, a key focus is the elimination of microbial pathogens, often achieved by adding alkali compounds such as lime, potassium hydroxide, and sodium hydroxide, or acidic compounds like phosphoric acid. Interestingly, these additives also enhance the nutritional value of the final product. To balance bio-waste-derived fertilizers, it is necessary to incorporate inorganic fertilizers or their precursors. The simplest approach involves mixing moistened organic raw materials with alkaline co-products like gypsum, cement, lime, and fly ash, followed by optimizing the NPK ratio by adding potash, phosphates, and liquid ammonia [12].

OMF from Organic Byproducts and Mineral

Theoretically, OMF technologies are especially useful for valorizing mineral waste, particularly phosphate industry leftovers, which are numerous and rich in fertilizing chemicals. Phosphate washing sludge and phosphogypsum are two important mineral wastes produced in the phosphate value chain. The main byproduct of the phosphate industry is PG, which is made by the wet process of phosphoric acid manufacture from rock phosphate using sulfuric acid. Global production is estimated to be between 200 and 250 million tons annually, of which only 15% is recycled. By 2025, the total discarded PG is projected to reach 8 billion tons. PG is a poorly water-soluble acidic powder composed of oxides of sulfur, calcium, silicon, aluminum, iron, phosphorus, fluorosilicate, fluorine aluminate, and fluoride phosphate [13].

Research on PG processing into OMF has produced encouraging results, albeit being primarily restricted to compost and biochar synthesis. For instance, a study examined the possibility of co-plasma processing banana peduncles with PG to produce a nutrient-rich and less hazardous biochar (in comparison to PG). Three distinct plasmagen gases—argon, ammonia, and oxygen—were used in an extended arc thermal plasma reactor for this experiment. In comparison to PG, the addition of argon produced biochar with greater potassium (12.7%) and sulfur (13.3–17.8%) contents, but ammonia decreased the biochar's leachable portion of fluoride and heavy metals.

Additionally, researchers addressed the by-products of kitchen waste composting, specifically greenhouse gas emissions, by incorporating PG (10%) as an additive. The results indicated that PG significantly reduced methane and ammonia emissions by

85.8% and 23.5%, respectively, without impacting compost maturity. This reduction was attributed to a lower pH, increased NH_4^+ concentration, and higher sulfate content in the PG treatment, which may suppress methanogens and enhance the compost's agronomic value [14-17].

Additionally, a study showed that co-composting PG and phosphate flotation waste with calf manure enhanced the composting process and raised the final product's nutritional value. In comparison to compost made entirely of manure, agronomic testing revealed that compost based on PG and phosphate flotation waste produced more biomass from chickpeas. These research show that OMF can be developed by processing complicated mineral matrices using simple, environmentally friendly processes like biochar and composting [18]. Additionally, a recently suggested procedure for the commercial conversion of PG into OMF is merely combining mineral NPK, PG (20–25%), and lignin waste sludge (75–80%). Due to limited strontium uptake by plant tissue, which is linked to calcium/strontium competition, agronomic experiments conducted under controlled settings showed that combining the soil with the OMF in similar amounts improved optimal plant growth and decreased PG toxicity.

PWS is a significant environmental issue for the phosphate industry, with an estimated 28 tons produced annually in Morocco alone. Unfortunately, PWS is typically disposed of in decantation basins without prior treatment. Despite the potential value of this mineral waste, little effort has been made to convert it into agricultural inputs. Research has explored the co-composting of PWS with olive mill waste sludge, green waste, and sugar lime sludge. When PWS was used at a rate of 20%, the resulting compost showed improved quality in terms of hygienic properties, humification, and nutrient content

compared to using only sugar lime sludge. While these findings are promising, additional studies are necessary to determine the technical feasibility of producing organo-mineral fertilizers from PWS, as it may exhibit significant physico-chemical variability due to differences in rock phosphate (RP) properties and the environmental impact of decantation basins [19-22].

OMF from Valuable Ore

Low-grade RP is gaining traction in the organic farming market as a source of plant nutrients. Although it is appealing, RP primarily contains phosphorus in an unavailable form, and its effectiveness relies on rock reactivity and soil pH [23].

The market for goods appropriate for organically labeled crops can grow and RP's agronomic efficiency can be improved by using biological techniques in OMF production. Co-composting organic wastes with RP in reactor systems or composting windrows is the standard procedure for developing RP-based OMF, which frequently calls for the addition of microbial inoculum to improve rock solubilization and aid in the breakdown of refractory organic compounds. According to research, the OMF product can contain up to 2.32 mg g⁻¹ of accessible phosphorus when RP and phosphorus-solubilizing microbes are added to an organic matrix of poultry manure. Co-composting with RP was found to dramatically boost phosphorus solubilization rates using a variety of organic wastes, including urban garbage and plant residues. Similarly, adding phosphate-solubilizing microorganisms such *Trichoderma harzianum*, *Aspergillus niger*, and *Aspergillus flavus* to waste treatment increased phosphorus availability to around 8.19% without slowing down the pace of decomposition.

Additionally, vermicomposting has the potential to improve phosphorus solubilization. *Eisenia fetida* earthworms were shown to

dramatically increase resin-extractable phosphorus, improve humification, and decrease heavy metal contamination when RP was co-composted with a manure-paper mixture. Mechanistically, increased phosphorus solubilization is attributed to microbial enzymes such as phosphatase and dehydrogenase. Furthermore, stable organic matter ligands compete with phosphorus during cation adsorption, increasing phosphorus availability in the soil [24-27].

IMPACT OF OMF ON SOIL-PLANT SYSTEMS

Research on the impact of organic-mineral fertilizers on soil physico-chemical properties is limited. However, their anticipated effects are expected to parallel those observed in studies involving the co-application of stable organic matter and mineral fertilizers, the primary components of OMF. For instance, the combination of SOM—such as vermicompost, compost, and biochar—with mineral fertilizers has been shown to enhance soil health indicators like pH, soil organic carbon, total nitrogen, and cation exchange capacity. The soil's response to these amendments is highly dependent on the quality of the raw materials used. The organic component of OMF may enhance the bioavailability of soil nutrients by modifying soil pH; for example, in acidic soils, compost-based OMF can effectively reduce acidity, similar to lime. Another commonly noted benefit of OMF application is the stabilization of initial CEC values, attributed to their high buffering capacity. It has been demonstrated that amending sandy loam soil with OMF derived from municipal biosolids or wood biochar effectively corrected soil salinity. Additionally, the co-application of OMF based on green waste/biosolid compost and biochar in saline-sodic soil resulted in a 79% reduction in electrical conductivity compared to unamended soil. These organic matrices also improve bulk density while

enhancing soil nutrient and SOM content [28-31].

High soil CEC is primarily influenced by the soil's physico-chemical properties and its ability to store cations. The retention capacity of soil can be significantly improved with the application of stable organic matter, such as humic substances and biochar. When these materials interact with soil oxygen and water over time, they undergo greater oxidation, resulting in increased negative charges and CEC. The aggregation of soil organic matter is closely linked to these negative charges. Biochar and humic substances feature reactive surfaces due to functional groups such as $-C-H$, $-C-O$, $C=O$, $-COOH$, and $-NH$, making them valuable for OMF formulation. Temperature and moisture conditions directly affect the polymerization and composition of humic acids, leading to significant variability. In cooler temperatures with adequate humidity (e.g., tundra landscapes), only 20–45% of soil-extractable humic acids can withstand acid hydrolysis. However, this percentage rises to 64–75% under standard temperature and moisture conditions (e.g., steppe landscapes). Furthermore, these environmental factors influence HA composition. Research indicates that lower carbon-to-nitrogen ratios enhance biodegradation resistance and prolong persistence. Similar findings suggest that soil humic fractions are more resistant to degradation and turnover, lasting up to thousands of years, due to their association with soil mineral colloids. Greater stability correlates with increased aromatic cores and enhanced interactions with mineral surfaces, directly contributing to higher soil CEC [32].

Impact of OMF on Soil Nature

Soils are complex mediums that undergo permanent changes influenced by various factors, including edaphic, pedoclimatic, fertilization, and land use elements. These factors directly impact the diversity, distribution, and functionality of indigenous

microorganisms. The addition of soil organic matter significantly influences both soil biota and its microbial components.

Variations in soil characteristics arise from the relative stability and quality of available carbon in these formulations. The positive effect of organic matter fertilizers on soil microbial activity is linked to improved soil porosity, which enhances substrate availability and enzymatic activity near organic particles [33, 32].

Several studies have demonstrated that, depending on the characteristics of the soil and plants, the feedstock, and the production process, OMF combined with phosphate-solubilizing microorganisms can greatly increase microbial phosphorus solubilization. However, microbial biomass and variety may be adversely affected by the use of raw materials such as wood, sewage sludge, and industrial waste during OMF development. Some low-molecular-weight organic chemicals and inorganic nutrients can be naturally absorbed by the SOM portion in OMF formulations. The steady release of nutrients and carbon sources into the soil is made possible by this delayed breakdown. As a result, depending on the physicochemical characteristics of the soil and the porosity of SOM, various microbial populations (actinobacteria, bacteria, and fungus) react differently [33].

Compared to using only mineral fertilizers, research has demonstrated that OMF made from compost and mineral fertilizers (such as rice straw and pig manure) improves sugar content and yield characteristics in sugarcane [34]. The enhanced SOM fractions' greater microbial diversity and functionality are principally responsible for this enhancement. According to the study, there was a strong correlation between the dynamics of soil nutrients and increased energy metabolism and the abundance of particular species, such as Acidobacteria, Proteobacteria, Chloroflexi, and Gemmatimonadetes, in

OMF treatments. Similarly, tomato output and quality were enhanced by applying vermicompost extract containing bacterial species as *Bacillus megaterium*, *Frateruria aurantia*, and *Azotobacter vinelandii* [35-39].

Impact of OMF on Crop Yields

The application of organic mineral fertilizers is often linked to enhanced crop yields, primarily due to improved nutrient availability in the soil. Research indicates that the beneficial effects of OMF, compared to chemical fertilizers, can be directly attributed to their organic components. For instance, applying an OMF composed of straw, rice composts, and mineral NPK significantly improved the nutrient content in the shoots and roots, as well as the overall biomass of maize, compared to the exclusive use of mineral fertilizers [40-43].

Furthermore, some minerals produced during biodegradation may actively contribute to the precipitation of essential elements. Several studies have shown that using untreated organic matter—such as poultry manure, organic waste, or other natural products—in OMF formulation can yield similar positive effects on plant nutrients as treated soil organic matter. It was reported that an OMF derived from untreated manure and mineral fertilizer increased tomato yields by 600% compared to unfertilized treatments. Additionally, OMF application positively influenced soil macro and micronutrients and the nutrient content of tomato shoots.

CONCLUSION

According to the present literature analysis, the idea of OMF has a lot of potential. As it tackles important issues in agribusiness, especially food production and waste management, this cutting-edge area of the fertilizer industry is likely to receive more attention, supporting the ideas of a circular economy. However, further study is required to address important business and technical issues. For instance, the humification and polymerization processes may be impacted

by the makeup of the raw materials utilized in the manufacturing of OMF. Selecting the appropriate combinations with inorganic fertilizers to improve their interactions and prolong their efficacy requires an understanding of these substrates' basic roles. The final product's uniformity and quality may be impacted by a number of complicated and unpredictable interactions that take place during the OMF production process. Thus, modeling the intricate processes of valorization for turning waste into OMF and simulating these interactions are crucial for process optimization.

There is still much to learn about the formation of OMF through the co-processing of phosphate mineral by-products and organic waste. Given the potential consequences for the phosphate value chain, more research in this area is necessary.

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