



Co-composting of organic waste with mineral additives: Process optimization, ecological and agronomic benefits

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Abstract

Organic waste management and soil fertility restoration in agriculture are among the most pressing environmental challenges globally. Although composting is a natural and effective method for recycling organic matter, the traditional process poses problems such as nitrogen loss (in the form of ammonia emissions), greenhouse gas emissions, and bioavailability of heavy metals. This article comprehensively analyzes the process of composting organic waste (agricultural residues, manure, food waste) with mineral additives such as zeolite, phosphorite, gypsum, and bentonite. Studies have shown that mineral additives improve the physicochemical properties of compost, significantly reduce nitrogen loss, passivate heavy metals, and stimulate microbiological activity. In particular, the synergistic application of mineral and organic (e.g., biochar) additives increases the agronomic value of compost, reduces the need for chemical fertilizers, and contributes to sustainable agriculture.

Keywords: Composting, mineral additives, zeolite, phosphorite, nitrogen loss, heavy metal passivation, soil fertility, circular economy

Introduction

Composting is the aerobic (oxygen-requiring) biological decomposition of organic materials by microorganisms. This process converts agricultural residues, animal manure and food waste into valuable humus-rich fertilizers that improve soil structure and health. Ideal composting requires a carbon to nitrogen ratio (C/N) of approximately 30:1, as well as optimal moisture content (50-60%) and aeration. However, the traditional composting process suffers from a number of drawbacks. These include the loss of nitrogen in the form of ammonia and nitrous oxide, greenhouse gas emissions and the risk of heavy metals in the raw materials being released into the environment.

Studies show that 79-94% of the total nitrogen loss during composting is due to NH₃ emissions. This not only reduces the nutritional value of the compost, but also causes serious odor and

causes air pollution. In order to solve these problems, the addition of various external additives to the composting process has been widely studied in recent years. Mineral additives play a crucial role in optimizing the process due to their high specific surface area, cation exchange capacity and porous structures. The aim of this article is to deeply analyze the mechanisms, ecological and agronomic benefits of co-composting mineral additives such as zeolite, phosphorite (rock phosphate), gypsum and bentonite with organic waste based on the existing scientific literature.

The Role of Mineral Additives in the Composting Process

1. Zeolite

Zeolites are naturally occurring crystalline aluminosilicates with a three-dimensional porous structure consisting of SiO₄ and AlO₄ tetrahedra. The negative charge in their

structure is balanced by alkali and alkaline earth metals, which gives them a high cation exchange capacity. The use of zeolite in the composting process has several positive effects.

First, zeolite dramatically reduces ammonia emissions. NH₄⁺ ions are trapped in the pores of the zeolite, preventing the emission of gaseous NH₃. A study by Bernal showed that adding zeolite at a rate of 53-82 g/kg to the compost material resulted in the retention of 80% of the nitrogen in the manure compost. Second, zeolite regulates the moisture content of the compost and reduces methane emissions by preventing the formation of anaerobic zones. Third, the addition of 5-15% natural zeolite during the composting of municipal solid waste significantly limited the uptake of heavy metals such as Pb, Cu, Mn, Zn, Ni and Cd by corn plants.

2. Phosphorite and Natural Phosphates

Although phosphorus (P) is a critical macronutrient for plant growth, most of the phosphorus in the soil is in a form that cannot be absorbed by plants. Particularly in regions such as Sub-Saharan Africa, low soil phosphorus levels limit agricultural productivity. Composting phosphorite with organic waste is an effective and cost-effective way to address this problem.

During composting, organic acids and enzymes secreted by microorganisms break down insoluble phosphates into a form that can be absorbed by plants. In a study by Sagnon *et al.*, composts prepared using sorghum straw, calcined Burkina phosphorite, and chicken manure were tested. The results showed that,

Calcined phosphorite and chicken manure-based compost increased the amount of available phosphorus in the soil and increased sorghum productivity to the highest level.

Table 1: Chemical properties of various phospho-compost mixtures

Compost Type	Raw materials Ingredients	General Carbon (g/kg)	Total Nitrogen (g/kg)	General Phosphorus (g/kg)	C/N Ratio
Comp-1	80% sorghum straw, 10% BPR (phosphorite), 10% rhizosphere land	326.0	10.9	9.37	29.92
Comp-3	80% sorghum straw, 10% BPR, 10% chicken manure	359.1	13.9	8.37	25.78
Comp-4	80% sorghum straw, 10% Calcination done BPR, 10% chicken manure	386.0	8.8	5.05	43.96

3. Gypsum and Phosphogypsum

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and its industrial by-product phosphogypsum act as both a source of sulfur and calcium in the composting process. One of the most important properties of gypsum is its ability to regulate the pH of the compost. A sharp increase in pH in the early stages of composting accelerates the conversion of NH_4^+ ions to NH_3 gas. Gypsum addition, by relatively lowering the pH and increasing the moisture content of the compost, limits the activity of ammonifying bacteria and reduces nitrogen loss. A study by Mouthier *et al.* on wheat straw and manure-based compost showed that the absence of gypsum led to an increase in pH to 9 and a gaseous ammonia level of 3.4 kg/m³.

The application of gypsum significantly reduced these indicators.

4. Bentonite and Other Clay Minerals

Bentonite is a clay mineral, mainly composed of montmorillonite, with high water absorption and cation exchange capacity. It reduces nitrogen loss during composting and limits the bioavailability of heavy metals. In a study by Soda *et al.*, acidic waste bentonites from the vegetable oil industry were composted with rice husks and chicken manure. As a result of the process, the hydrophobicity of the bentonite was significantly reduced, and the pH and cation exchange capacity increased. The application of this compost to the soil significantly increased the production of maize biomass over two consecutive cropping seasons.

Synergistic Effect of Mineral and Organic Supplements

Recent studies have shown that the use of a single mineral additive is sometimes not enough to solve all the problems of composting. For example, although biochar is distinguished by its high porosity, it can sometimes increase ammonia emissions due to its alkaline nature. Therefore, the combined application of mineral additives with organic additives creates a synergistic effect.

In a study by Gu *et al.*, the combined application of biochar and gypsum shortened the composting time and simultaneously reduced both nitrogen and carbon losses. Gypsum neutralized the high alkalinity generated by biochar, preventing NH_3 emissions. In another study, the combined application of biochar and zeolite dramatically reduced the bioavailability of heavy metals in multi-metal contaminated soils. While biochar alone could mobilize anions such as As and W, the combination with zeolite eliminated this risk and reduced the total bioavailability toxicity by 57.3%.

1. Ecological and Microbiological Effects

Composting with mineral additives has a profound effect on the microbiological ecology of the soil. The composting process itself is characterized by microbiological succession. Mineral additives create a favorable microenvironment for microorganisms and regulate enzymatic activity.

During phospho-composting, the activity of genes such as alkaline phosphatase is of particular importance. Sagnon *et al.* found that compost

(Comp-4) supplemented with calcined phosphorite and chicken manure

significantly increased the abundance of the gene and total bacteria. These genes are directly involved in the mineralization of organic phosphates and the solubilization of inorganic phosphorus.

In addition, the combined application of biochar and compost at high doses (e.g., 8% biochar + 7.5% compost) increases the stability of the microbial network in urban soils. According to a study by Wang *et al.*, this combination balances the carbon-nitrogen-phosphorus cycle and activates carbon fixation pathways by supporting the development of oligotrophic bacteria such as.

2. Agronomic Benefits and Economic Efficiency

The application of composts enriched with mineral additives in agriculture improves the physical and chemical properties of the soil and increases productivity. The EPA notes that compost increases soil porosity, improves water retention capacity, and prevents erosion. Mineral additives further enhance these effects.

For example, for plants that require high levels of potassium and phosphorus, such as tomatoes, composts based on animal manure are ideal. According to a report from Clemson University, composts based on cow manure were able to fully meet the pre-plant nitrogen needs of tomatoes and provided 59% of the required phosphorus. At the same time, in a study by Sagnon *et al.*, grain yield and economic profitability of sorghum plants in fields where phosphocompost was applied were comparable to those in fields where traditional chemical fertilizers were applied, and in some cases even higher.

In addition, mineral-enriched composts promote carbon sequestration in the soil. The combined application of biochar and compost increases soil organic carbon stocks, while compensating for the rapid mineralization losses of compost through the stable carbon structure of biochar.

Conclusion

Composting organic waste with mineral additives is an innovative and multifaceted approach for both waste management and sustainable agricultural development. The scientific literature analyzed proves that mineral additives significantly reduce nitrogen loss and greenhouse gas emissions, which are the biggest problems of the composting process.

At the same time, these additives ensure food safety by passivating heavy metals.

In particular, the synergistic application of mineral and organic additives maximizes the agronomic value of compost. Such enriched composts increase the microbiological biodiversity of the soil, facilitate plant access to nutrients, and increase productivity. Future research should be focused on studying the long-term effects of specific mineral-organic combinations in different climatic and soil conditions and on the cost-effective application of these technologies on an industrial scale. This approach will make a significant contribution to the implementation of circular economy principles on a global scale and reducing dependence on chemical fertilizers.

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