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Engineering Organomineral Composting Using Sugarcane Residues: Effects of Phosphate Sources and Phosphate-Solubilizing Bacteria on Nutrient Dynamics

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Abstract

The formulation of organomineral composts can be used to modulate nutrient dynamics and improve the quality of fertilizers produced from agro-industrial residues. This study evaluated the effects of compost formulation, phosphorus source, and inoculation with phosphate-solubilizing bacteria on nutrient dynamics during the composting of sugarcane filter cake. Six formulations combining filter cake, poultry litter, and agricultural gypsum were evaluated: organic compost (T1); compost enriched with reactive phosphate rock (T2); reactive phosphate rock + phosphate-solubilizing bacteria (T3); triple superphosphate (T4); triple superphosphate with a modified filter cake-to-poultry litter ratio (T5); and compost without gypsum (T6). The experiment was conducted in a completely randomized design with five replicates, and composts were evaluated at 45, 65, and 115 days. Data were subjected to analysis of variance considering formulation, composting time, and their interaction. A significant interaction between compost formulation and composting time was observed for organic matter, organic carbon, P, K, Ca, Mg, and pH, whereas N and S were independently affected by these factors. Organic matter and organic carbon contents decreased by 18% and 19%, respectively, at 115 days compared with the earlier composting periods. P-enriched formulations had 52% higher P content than non-enriched composts, while T2 and T5 showed comparable P content. Inoculation with phosphate-solubilizing bacteria temporarily increased P content during the composting phase, whereas gypsum did not improve N conservation. These findings demonstrate that formulating composts with reactive phosphate rock is a technically feasible strategy for producing P-enriched organomineral fertilizers while promoting nutrient recycling and the valorization of agro-industrial residues.

Keywords: filter cake; agro-industrial residues; nutrient management; tropical agriculture

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1. Introduction

The transition toward circular and low-input agricultural systems has increased the demand for technologies capable of converting agro-industrial residues into high-value agricultural inputs [1,2]. Rather than being treated as waste, organic by-products generated

by food and bioenergy industries are increasingly recognized as strategic raw materials for the production of engineered fertilizers capable of improving nutrient recycling, reducing environmental impacts, and decreasing dependence on synthetic mineral fertilizers [3,4].

Among the available technologies, composting has become one of the most effective biological processes for transforming organic residues into stabilized products suitable for agricultural use. Beyond organic matter stabilization, composting represents a controlled bioconversion process in which physical, chemical, and microbiological interactions determine nutrient conservation, mineral transformation, and fertilizer quality [5–8]. Consequently, compost formulation has become a critical engineering step, since the selection of raw materials and additives directly influences process efficiency and the agronomic value of the final product.

Sugarcane production generates large amounts of organic residues, particularly filter cake, which contains considerable concentrations of organic matter and plant nutrients. Although widely available, the direct agronomic use of filter cake remains limited by its variable chemical composition and the need for stabilization before field application [9,10]. Composting this residue with complementary organic substrates offers an opportunity to produce standardized organomineral fertilizers while simultaneously promoting waste valorization and nutrient recycling within sugarcane production systems [11–13].

Phosphorus management represents one of the greatest challenges during the development of compost-based fertilizers. Highly soluble phosphate fertilizers rapidly increase phosphorus availability but are associated with elevated production costs, dependence on finite phosphate reserves, and relatively low phosphorus use efficiency under tropical conditions due to intense phosphorus fixation by iron and aluminum oxides [14–16]. Consequently, alternative phosphorus sources such as reactive phosphate rock have attracted increasing attention because of their lower economic and environmental costs. However, their reduced solubility limits their direct agronomic effectiveness, requiring technological approaches capable of enhancing phosphorus release during composting [17,18].

One promising strategy consists of integrating low-solubility phosphate sources with phosphate-solubilizing bacteria (PSB). These microorganisms release organic acids, phosphatases, and chelating compounds that may accelerate phosphate dissolution while simultaneously participating in organic matter decomposition and nutrient cycling [19–21]. Nevertheless, the effectiveness of microbial inoculation during composting remains inconsistent because microbial activity is strongly affected by substrate composition, temperature, moisture, pH, and compost maturity [8,22,23]. Therefore, understanding the interaction between compost formulation, phosphorus source, and microbial inoculation is essential for designing efficient composting systems capable of producing fertilizers with greater nutrient availability.

Despite recent advances in compost-based fertilization, most studies have focused on the agronomic performance of the final compost after soil application. Comparatively less attention has been given to nutrient transformations during the composting process, particularly to how formulation composition and P sources affect the temporal dynamics of P and other nutrients throughout compost maturation. In addition, limited information is available on whether the effects of phosphate-solubilizing bacteria on P mobilization from reactive phosphate rock are maintained throughout compost maturation. This process-level information is essential for understanding how formulation strategies influence nutrient availability during composting and for optimizing organomineral compost production systems for large-scale agricultural use [1].

We hypothesized that engineering compost formulations by integrating sugarcane filter cake, alternative phosphorus sources, and phosphate-solubilizing bacteria would improve nutrient dynamics during composting. Specifically, we hypothesized that phosphate-

solubilizing bacteria could enhance P mobilization from reactive phosphate rock through mechanisms such as the production of organic acids and other compounds that promote phosphate mineral dissolution, thereby increasing P availability during compost maturation and allowing P availability from reactive phosphate rock to approach that obtained with soluble phosphate fertilizers.

Therefore, the objective of this study was to evaluate how compost formulation, phosphorus source, and phosphate-solubilizing bacteria influence nutrient dynamics throughout the composting process, providing engineering information for the development and optimization of phosphorus-enriched organomineral composts produced from sugarcane agro-industrial residues.

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was conducted at the composting facility of the Santa Helena sugar and ethanol mill, located at Santa Helena Farm (MS-134 Highway, km 25; 21°59′54.5″ S, 53°25′35.8″ W), Mato Grosso do Sul, Brazil. According to the Köppen–Geiger classification, the region has a tropical climate, with a mean annual rainfall of approximately 1650 mm, concentrated mainly during the summer months.

The experiment followed a completely randomized design with six compost formulations and five replicates. Each replicate consisted of a 2-m section within the windrow, while the outer 1 m at both ends was excluded from sampling to minimize edge effects. Chemical analyses were performed at 45, 65, and 115 days after composting initiation on the same experimental units, characterizing a repeated-measures design in which composting time was considered a fixed factor in the statistical analysis.

2.2. Raw Materials and Compost Formulations

The composts were prepared using sugarcane filter cake, chicken litter, and agricultural gypsum, all of which are widely available agro-industrial by-products commonly used in fertilizer production. Before composting, the raw materials were chemically characterized to determine their physicochemical properties and to establish the compost formulations.

Sugarcane filter cake had an acidic pH (4.9), organic matter content of 65.8% (38.2% organic carbon), 1.9% N, 1.3% P_2O_5, 0.2% K_2O, 1.3% Ca, 0.4% Mg, 0.1% S, and approximately 64% moisture. Chicken litter showed a near-neutral pH (6.9), organic matter content of 57.5% (33.3% organic carbon), 2.1% N, 1.6% P_2O_5, 4.4% K_2O, 3.8% Ca, 1.7% Mg, 0.5% S, and 22.1% moisture.

Reactive natural phosphate was used as an alternative phosphorus source. The material contained 30.0% total P_2O_5, including 2.9% soluble in neutral ammonium citrate and 8.7% soluble in 2% citric acid, as well as 33.0% total Ca. Triple superphosphate was used as the conventional soluble phosphorus source.

Compost formulations were established based on the chemical composition of the raw materials and the phosphorus fertilizer recommendation for sugarcane establishment (150 kg ha^{-1} P_2O_5), following the guidelines proposed by Sousa and Lobato (2004) [24] for Cerrado soils. The formulations were designed to compare conventional and alternative P sources, as well as to evaluate the effects of phosphate-solubilizing bacteria inoculation and agricultural gypsum addition on the chemical evolution of the compost during the composting process. Agricultural gypsum was included primarily as a source of Ca and S to enrich the final product, while its potential effects on nutrient dynamics during composting were also evaluated.

The six compost formulations were designated as T1–T6. T1 consisted of the base compost without an additional phosphorus source; T2 received reactive natural phosphate;

T3 received reactive natural phosphate combined with phosphate-solubilizing bacteria; T4 received triple superphosphate; T5 received triple superphosphate with a modified filter cake-to-chicken litter ratio; and T6 consisted of the base compost without agricultural gypsum. The composition of the six compost formulations is presented in Table 1.

Table 1. Composition of the compost formulations evaluated in the experiment. Values represent the amounts of raw materials used to prepare each compost windrow.

Treatment	Filter Cake (t)	Chicken Litter (t)	Gypsum (t)	P Source	PSB * Inoculation
T1	5.5	4.0	0.5	None	No
T2	5.5	4.0	0.5	Reactive natural phosphate	No
T3	5.5	4.0	0.5	Reactive natural phosphate	Yes
T4	5.5	4.0	0.5	Triple superphosphate	No
T5	7.0	2.5	0.5	Triple superphosphate	No
T6	6.0	4.0	0	None	No

* PSB: phosphate-solubilizing bacteria.

2.3. Composting Process

Each compost formulation was prepared as an independent windrow measuring 12 m in length, approximately 3.5 m wide at the base, 1.0 m wide at the top, and 1.1 m in height, resulting in an estimated volume of 29.7 m^3 per windrow. Each windrow was divided into five 2 m sections, which were considered experimental units, while 1 m at each end of the windrow was excluded from sampling to minimize edge effects (Figure 1).

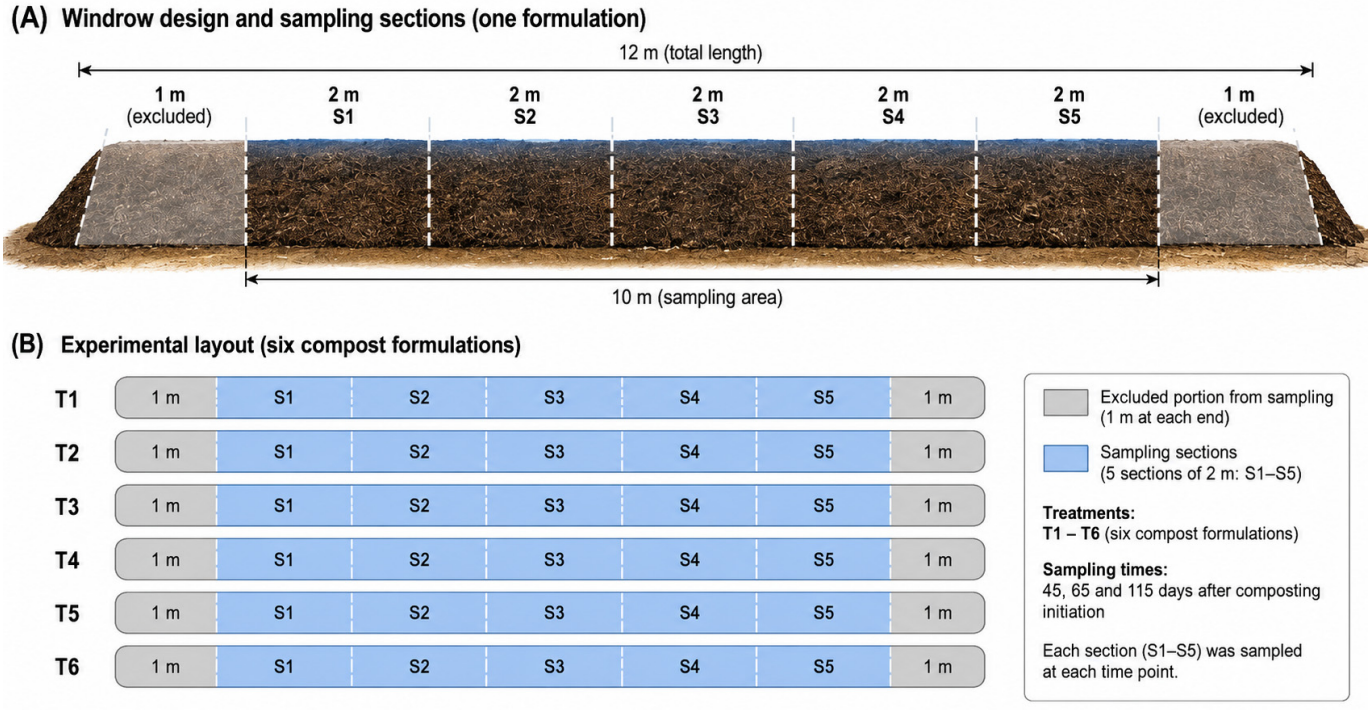

Figure 1. Schematic representation of the experimental design and the division of each compost windrow.

Filter cake, chicken litter, and agricultural gypsum were distributed according to the mass proportions described in Section 2.2 and Table 1 using a front loader. Phosphorus enrichment was performed on the first day of composting by applying either reactive phosphate rock at 51.72 kg m^{-1} of windrow or triple superphosphate at 32.6 kg m^{-1} of

windrow, according to the respective treatment. The phosphate sources were manually distributed over the composting material and subsequently homogenized using a tractor-mounted compost turner.

For treatments inoculated with phosphate-solubilizing bacteria, a commercial inoculant containing *Bacillus megaterium* and *Bacillus subtilis* (2×10^9 CFU mL^{-1} each) was applied at a rate of 10 mL m^{-3} of compost. The inoculant was diluted in 20 L of water and applied on days 1 and 30 of composting, followed by mechanical turning to promote uniform incorporation. The survival and population dynamics of the inoculated *B. megaterium* and *B. subtilis* strains were not monitored during the composting process. Therefore, the microbial treatment represents the effect of inoculant application rather than a direct assessment of bacterial establishment or persistence within the compost matrix.

During the first month of composting, the windrows were mechanically turned two to three times per week using a tractor-mounted compost turner to maintain adequate aeration and promote homogenization of the composting material. Thereafter, turning was performed as required according to the operational conditions of the composting process, particularly following water addition for moisture adjustment.

2.4. Compost Monitoring and Chemical Analyses

The total composting period was 115 days, corresponding to the operational composting cycle routinely adopted by the sugar and ethanol mill before field application. Temperature and moisture were monitored at 10-day intervals throughout the composting period as operational indicators of process conditions. Temperature was maintained below approximately 60 °C, while moisture was managed at approximately 40% (Table S1). Whenever moisture decreased below the target level, water was applied using a water truck, followed by mechanical turning to promote homogeneous water distribution and restore aeration within the windrow. During the first month, when microbial activity and oxygen demand were expected to be greatest, the windrows were mechanically turned two to three times per week.

Aeration was managed operationally through mechanical turning rather than by direct measurement of oxygen concentration or airflow. Therefore, aeration was considered an operational management condition rather than a quantitatively measured process variable.

Temperature was measured using five thermometers per experimental unit, inserted 50 cm deep, with readings taken after a stabilization period of 10 min. Temperature data are presented as mean ± standard deviation (SD) of the measurements obtained at each monitoring time. Moisture was determined gravimetrically from samples dried in an oven (Table S1).

Composite samples were collected from each experimental unit at 45, 65, and 115 days after composting initiation. Each composite sample consisted of five subsamples collected from different points of the windrow and thoroughly homogenized before chemical analysis. These sampling times were selected to represent the initial, intermediate, and final stages of the operational composting cycle. Chemical analyses were performed following the official analytical procedures established by the Brazilian Ministry of Agriculture and Livestock [25]. Organic carbon was determined by oxidation with potassium dichromate in an acidic medium, followed by quantification of the oxidized carbon. Organic matter was estimated from organic carbon. Total N was determined by digestion followed by distillation and titration. P was extracted using the prescribed extraction procedure and quantified by spectrophotometry. K was extracted and determined by flame photometry, whereas Ca and Mg were extracted and quantified by atomic absorption spectrometry. S was determined gravimetrically as barium sulfate. Compost pH was determined potentiometrically in an aqueous suspension, and moisture content was determined gravimetrically

after oven drying. Analytical quality control included duplicate analyses, reagent blanks, and calibration standards.

2.5. Statistical Analysis

Data were analyzed using a two-way repeated-measures analysis of variance (ANOVA), with compost formulation and composting time as fixed effects and their interaction. Experimental units were considered the subjects for repeated measurements over time. When significant effects or interactions were detected, means were compared using Tukey's test at $p \leq 0.05$. The assumptions of normality and homogeneity of variances were assessed before the analysis. All statistical analyses were performed using SISVAR software, version 5.6.

3. Results

The composting process progressed throughout the 115-day operational cycle. The temperature profile is presented in Table S1. Compost temperature increased during the initial phase, reaching the highest values during the first month, and subsequently declined as composting progressed. Throughout the monitoring period, the mean temperature remained below 60 °C. The decline in temperature during the later stages coincided with the reduction in readily decomposable organic substrates and the progression toward compost stabilization. The reduction in organic matter (OM) and organic carbon (OC) contents further reflected the progression of the composting process (Figure 2), and compost formulation significantly influenced these changes (Table 2).

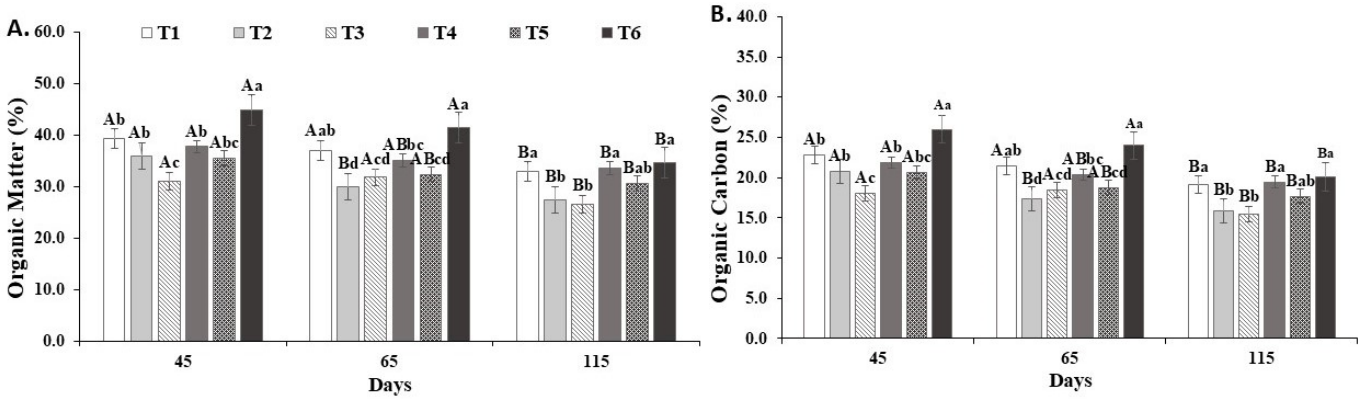

Figure 2. Organic matter (%) (**A**) and organic carbon (%) (**B**) contents during the composting process at 45, 65, and 115 days under open-air conditions. Different lowercase letters indicate significant differences among compost formulations within the same composting time, whereas different uppercase letters indicate significant differences among composting times within the same formulation, according to Tukey's test ($p \leq 0.05$). Treatments: T1, organic compost (5.5 t filter cake + 4.0 t chicken litter + 0.5 t gypsum); T2, compost + phosphate rock; T3, compost + phosphate rock + phosphate-solubilizing bacteria; T4, compost + triple superphosphate; T5, compost (7.0 t filter cake + 2.5 t chicken litter + 0.5 t gypsum) + triple superphosphate; T6, compost (6.0 t filter cake + 4.0 t chicken litter).

A significant interaction between compost formulation and composting time was observed for OM and OC (Table 2). In general, higher OM and OC contents were recorded at 45 and 65 days of composting, followed by a reduction at 115 days, indicating advancement toward compost stabilization.

Table 2. Summary of the analysis of variance for the evaluated characteristics considering compost formulation, composting time, and their interaction.

Parameter	Df	MS	F-Value	Pr > F	CV (%)
OM	10	12.36251	2.31	0.0405 *	7.17
OC	10	4.155178	2.23	0.0400 *	7.15
N	10	0.040044	1.40	0.2078 NS	11.63
P_2O_5	10	1.299378	3.86	0.0007 *	11.73
K_2O	10	0.5494	4.11	0.0004 *	15.68
Ca	10	4.398244	3.86	0.0007 *	12.71
Mg	10	0.016978	2.59	0.0135 *	7.27
S	10	0.390778	2.02	0.0513 NS	19.18
pH	10	0.189378	7.10	0.0000 *	2.11

OM = organic matter; OC = organic carbon; Df = degrees of freedom; MS = mean square; CV = coefficient of variation; Pr > F = probability associated with the F test; NS = not significant; * significant at $p \leq 0.05$.

Across all composting periods, treatment T6 consistently showed the highest OM and OC contents, whereas treatments T2 and T3 presented the lowest values (Figure 2A,B). The reduction observed at 115 days reflects the mineralization of labile organic fractions and the predominance of more stable organic compounds at later composting stages.

Nitrogen content was not affected by the interaction between compost formulation and composting time (Table 2). When compost formulations were analyzed independently, treatments T4 and T6 showed the highest N contents, while treatments T2 and T3 exhibited the lowest values. The presence of gypsum in the compost did not reduce nitrogen losses. Treatment T6, which did not receive gypsum, consistently showed high N contents (Figure 3A).

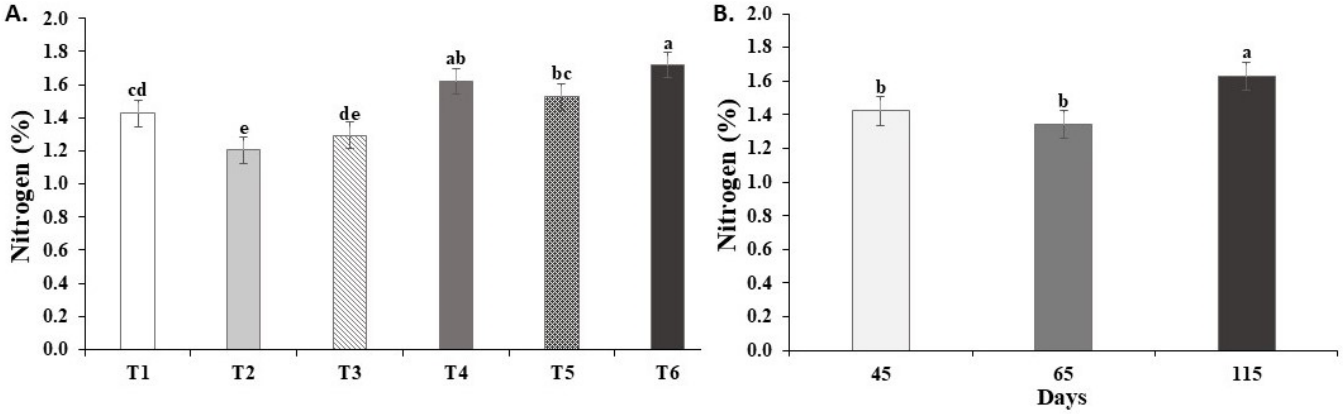

Figure 3. Nitrogen (%) content during the composting process under open-air conditions, considering compost formulation (**A**) and composting time at 45, 65, and 115 days (**B**). Means with the same letter do not differ significantly ($p < 0.05$). Treatments: T1, organic compost (5.5 t filter cake + 4.0 t chicken litter + 0.5 t gypsum); T2, compost + phosphate rock; T3, compost + phosphate rock + phosphate-solubilizing bacteria; T4, compost + triple superphosphate; T5, compost (7.0 t filter cake + 2.5 t chicken litter + 0.5 t gypsum) + triple superphosphate; T6, compost (6.0 t filter cake + 4.0 t chicken litter).

Regarding composting time, N contents were lower at 45 and 65 days and increased at 115 days (Figure 3B).

Different phosphorus enrichment strategies markedly influenced phosphorus dynamics during composting. Both reactive phosphate rock and triple superphosphate successfully increased phosphorus availability relative to non-enriched composts, demonstrating

the effectiveness of phosphorus incorporation during compost formulation. Phosphorus availability, expressed as P_2O_5, was significantly influenced by the interaction between compost formulation and composting time (Table 2). Treatments enriched with phosphate rock (T2 and T3) and triple superphosphate (T4 and T5) exhibited higher P_2O_5 contents than treatments without mineral phosphorus addition (T1 and T6) throughout the composting process (Figure 4A).

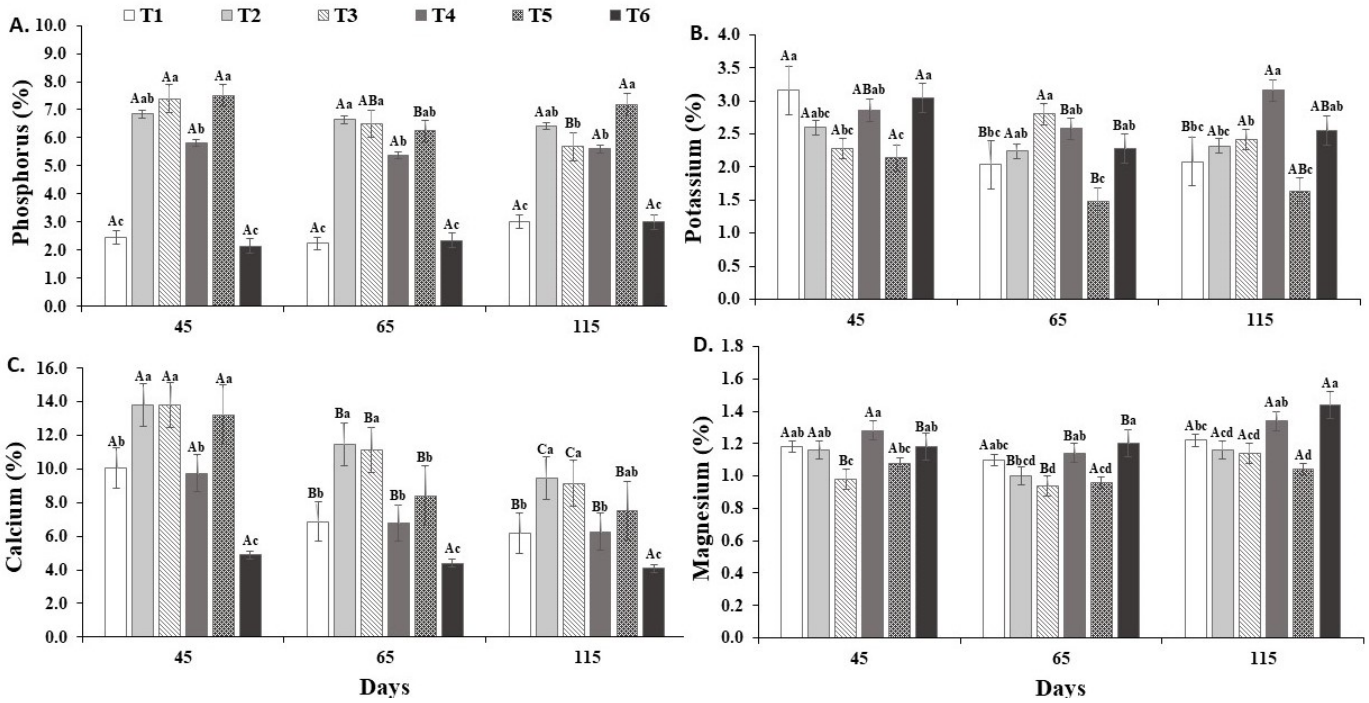

Figure 4. Phosphorus (%) (**A**), potassium (%) (**B**), calcium (%) (**C**), and magnesium (%) (**D**) contents during the composting process at 45, 65, and 115 days under open-air conditions. Different lowercase letters indicate significant differences among compost formulations within the same composting time, whereas different uppercase letters indicate significant differences among composting times within the same formulation, according to Tukey's test ($p \leq 0.05$). Treatments: T1, organic compost (5.5 t filter cake + 4.0 t chicken litter + 0.5 t gypsum); T2, compost + phosphate rock; T3, compost + phosphate rock + phosphate-solubilizing bacteria; T4, compost + triple superphosphate; T5, compost (7.0 t filter cake + 2.5 t chicken litter + 0.5 t gypsum) + triple superphosphate; T6, compost (6.0 t filter cake + 4.0 t chicken litter).

Treatments T2 and T5 showed the highest P_2O_5 contents across all evaluation periods, with no significant differences between them. Treatment T3 presented higher P_2O_5 levels at 45 and 65 days, followed by a reduction at 115 days. In contrast, treatments T1 and T6 maintained consistently lower P_2O_5 contents throughout the composting period (Figure 4A).

A significant interaction between compost formulation and composting time was observed for potassium content (Table 2). Different compost formulations generated distinct nutrient profiles in the mature compost. Potassium concentrations were primarily associated with chicken litter proportion, whereas calcium reflected the phosphorus source used during compost formulation. Magnesium showed smaller variations among formulations, indicating greater stability throughout the composting process. Treatments T6 and T4 consistently showed the highest K_2O contents across all composting periods, whereas treatment T5 exhibited the lowest values (Figure 4B). The reduced potassium content observed in T5 is associated with the lower proportion of chicken litter in this

formulation. Potassium levels remained relatively stable over time in treatments T2, T3, and T4, indicating limited temporal influence for these composts (Figure 4B).

Calcium and magnesium contents were significantly influenced by the interaction between compost formulation and composting time (Table 2). Treatments containing phosphate rock (T2 and T3) showed the highest Ca contents throughout the composting process, whereas treatment T6 consistently exhibited the lowest Ca levels (Figure 4C).

For magnesium, treatments T4 and T6 presented the highest contents across all evaluation periods, while treatments T3 and T5 showed lower Mg contents (Figure 4D). Composting time had limited influence on Ca and Mg levels in most treatments, except for slight variations observed in treatments T1 and T5.

Sulfur content was not affected by the interaction between compost formulation and composting time (Table 2). Treatment T5 exhibited the highest sulfur contents, whereas treatment T6, which did not receive gypsum, showed the lowest values across all composting periods (Figure 5A). Regarding composting time, sulfur contents were lower at 45 days and increased at 65 and 115 days, with no significant difference between these latter periods (Figure 5B). These results indicate independent effects of compost formulation and composting time on sulfur dynamics.

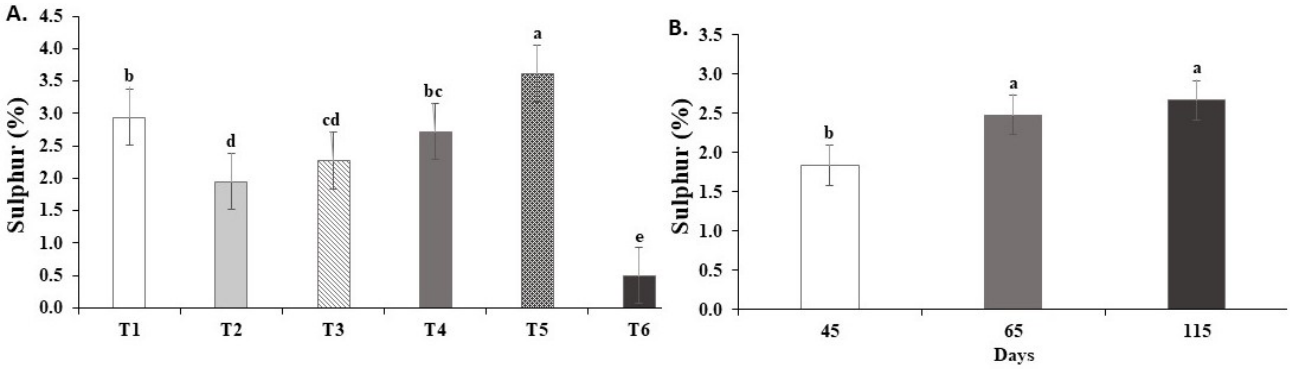

Figure 5. Sulfur content (%) during the composting process under open-air conditions, considering compost formulation (**A**) and composting time at 45, 65, and 115 days (**B**). Means with the same letter do not differ significantly ($p < 0.05$). Treatments: T1, organic compost (5.5 t filter cake + 4.0 t chicken litter + 0.5 t gypsum); T2, compost + phosphate rock; T3, compost + phosphate rock + phosphate-solubilizing bacteria; T4, compost + triple superphosphate; T5, compost (7.0 t filter cake + 2.5 t chicken litter + 0.5 t gypsum) + triple superphosphate; T6, compost (6.0 t filter cake + 4.0 t chicken litter).

The interaction between compost formulation and composting time significantly influenced pH values (Table 2). However, pH remained relatively stable over time within each treatment. Treatment T6 showed the highest pH values throughout the composting period, while treatment T5 consistently exhibited the lowest pH values (Figure 6). All composts maintained pH values above 6.0 during the composting process, although treatments receiving mineral phosphorus sources showed slightly lower pH values compared to composts without mineral fertilization (Figure 6).

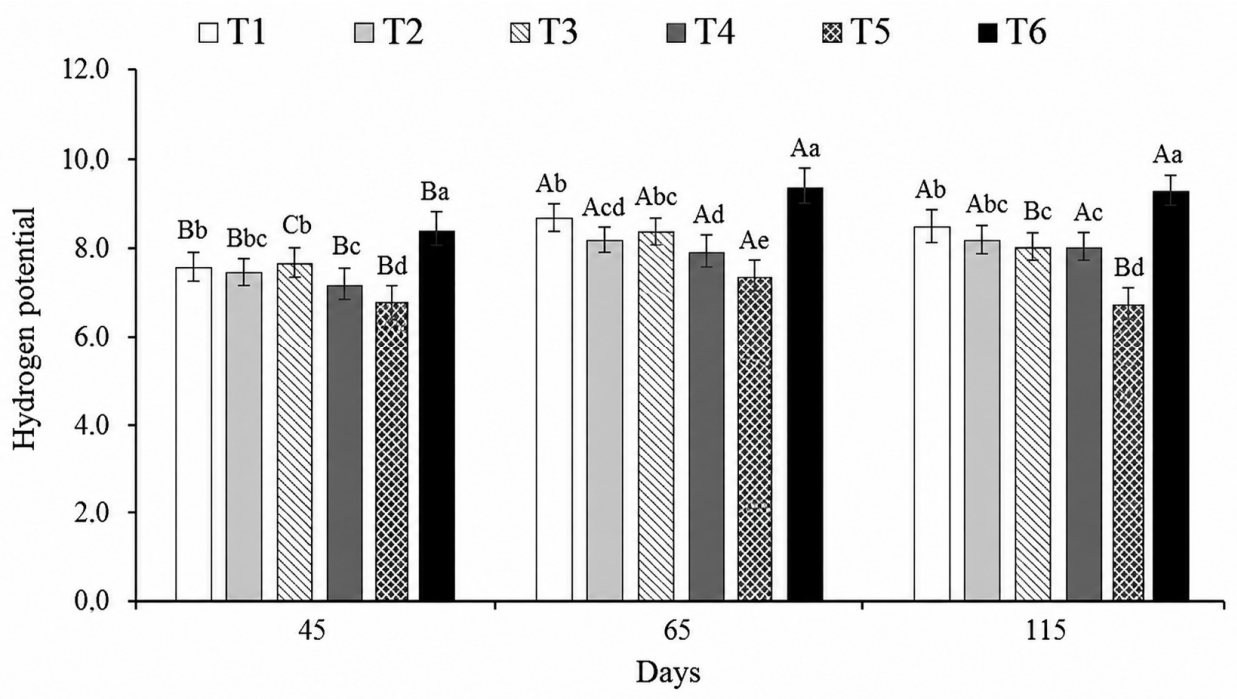

Figure 6. Variation in pH values during the composting process at 45, 65, and 115 days under open-air conditions. Different lowercase letters indicate significant differences among compost formulations within the same composting time, whereas different uppercase letters indicate significant differences among composting times within the same formulation, according to Tukey's test ($p \leq 0.05$). Treatments: T1, organic compost (5.5 t filter cake + 4.0 t chicken litter + 0.5 t gypsum); T2, compost + phosphate rock; T3, compost + phosphate rock + phosphate-solubilizing bacteria; T4, compost + triple superphosphate; T5, compost (7.0 t filter cake + 2.5 t chicken litter + 0.5 t gypsum) + triple superphosphate; T6, compost (6.0 t filter cake + 4.0 t chicken litter).

4. Discussion

The present study demonstrates that nutrient dynamics during filter cake composting are governed by the interaction between compost formulation, mineral amendments, and the progression of the composting process. Rather than acting independently, these factors collectively determine process performance and the quality of the final organomineral fertilizer. From an engineering perspective, compost formulation should therefore be considered a key design parameter for controlling nutrient conservation, phosphorus enrichment, and product stabilization during compost production.

The progressive reduction in organic matter (OM) and organic carbon (OC) observed throughout the composting period confirms the normal progression of the stabilization process, reflecting the mineralization of labile organic compounds and the accumulation of more recalcitrant organic fractions [6,26]. Similar behavior has been consistently reported for composts produced from sugarcane filter cake, in which carbon losses primarily result from microbial respiration, while the remaining carbon becomes incorporated into more stable humified fractions [27–29]. From the standpoint of compost engineering, these changes indicate that the adopted operational conditions were adequate to promote organic matter transformation and produce a stabilized material suitable for agricultural application. The production of stable composts is particularly important in tropical environments because they contribute to improved soil aggregation, greater carbon persistence, and long-term soil quality after field application [9,30].

Differences among formulations also demonstrate that raw material selection directly influences composting performance. Treatment T6, composed exclusively of organic residues, consistently retained higher OM and OC contents throughout the process, indicat-

ing slower decomposition compared with formulations enriched with mineral phosphorus sources. Mineral fertilizers may stimulate microbial metabolism and accelerate organic matter degradation, explaining the lower carbon retention observed in treatments containing reactive phosphate rock or triple superphosphate [10]. From an engineering perspective, these results demonstrate that compost formulation can be manipulated to regulate the balance between rapid stabilization and carbon preservation according to the intended agricultural application. Composts with greater stabilized carbon contents may provide longer residual effects in soils subjected to intensive sugarcane cultivation, where organic matter turnover is naturally high [31–33].

Nitrogen dynamics were mainly determined by compost formulation and composting time. The gradual increase in N concentration during the final stages of maturation indicates greater stabilization of organic N forms and lower microbial immobilization as decomposition progressed [34]. Nitrogen conservation is relevant to composting efficiency because excessive N losses reduce fertilizer quality and may increase N emissions. Under the evaluated conditions, agricultural gypsum did not increase N conservation, despite being included in some formulations. This result may be related to the amount of gypsum applied, the timing of its incorporation, or its effect on the chemical conditions involved in N transformations during composting. Because gypsum has little effect on pH, its addition may not have altered the conditions related to N retention. In addition, because different gypsum rates and application timings were not evaluated, the contribution of these factors to the observed result cannot be determined. Thus, under the conditions of this study, N dynamics were more closely related to substrate composition and composting time than to gypsum addition [35].

Among all evaluated nutrients, phosphorus showed the strongest interaction between compost formulation and composting time. Composts enriched with reactive phosphate rock showed P availability comparable to that of triple superphosphate-based treatments at different stages of compost maturation, demonstrating that low-solubility phosphate sources can be incorporated into filter cake-based compost production systems. Organic matter decomposition favors the production of organic acids and chelating compounds capable of increasing P solubilization while reducing P fixation by iron and aluminum oxides, thereby maintaining greater P availability within the compost matrix [36,37]. These findings are particularly relevant for compost engineering because they demonstrate that alternative P sources can provide P availability comparable to that obtained with highly soluble fertilizers under the conditions evaluated, contributing to more sustainable fertilizer production systems.

The P availability observed in the present study is comparable to that reported in previous studies evaluating the use of phosphate rock during composting. Biswas and Narayanasamy (2006) [38] observed that Olsen-extractable P in phosphate rock-enriched composts was initially lower than that in the diammonium phosphate treatment but increased with compost maturation, indicating greater P mobilization throughout the process. Similarly, Bustamante et al. (2016) [39] found that co-composting green waste with phosphate rock increased P mobilization, showing that composting can increase the availability of this relatively sparingly soluble P source. The results obtained in the present study follow a similar trend, with treatments containing reactive phosphate rock showing P availability similar to that of triple superphosphate treatments at different stages of composting. However, it is not possible to determine whether this availability will be maintained after compost application to the soil. Reactive phosphate rock may continue to dissolve in the soil after application, whereas P from more soluble sources may be released more rapidly and subsequently retained by soil minerals. Therefore, studies evaluating

residual P availability and plant P uptake after compost application are needed to assess the behavior of these P sources in the soil.

The temporary increase in P availability observed in the treatment inoculated with phosphate-solubilizing bacteria during the intermediate stages of composting may be related to P mobilization during the phase of highest biological activity. However, because the survival and population dynamics of *B. megaterium* and *B. subtilis* were not monitored, it is not possible to determine whether the reduction in this effect over the course of composting was related to changes in bacterial survival, abundance, or activity within the compost. Therefore, the observed response is associated with inoculant application but does not confirm bacterial establishment or persistence during maturation. The reduced effect in mature compost may also be related to changes in substrate availability as compost maturation progressed [40]. Future studies combining bacterial population monitoring with P dynamics may help clarify the relationship between microbial persistence and P transformation during composting.

The dynamics of K, Ca, and Mg further highlight the importance of formulation engineering for determining the nutritional profile of the mature compost. K availability was predominantly associated with poultry litter proportion, confirming its role as one of the principal K sources in organic fertilization systems [41]. Consequently, K concentrations can be adjusted through appropriate selection and balancing of organic residues, providing flexibility in the production of fertilizers designed for crops with high K demand, such as sugarcane [42]. Ca concentrations reflected the incorporation of reactive phosphate rock, whereas Mg availability was mainly determined by the chemical composition of the organic substrates, demonstrating that formulation design directly influences the final nutrient composition of organomineral composts.

Sulfur behavior was predominantly determined by agricultural gypsum incorporation, since this amendment represented the principal S source in the evaluated formulations. The progressive increase in sulfur concentration during composting reflects the stability and high solubility of sulfate, whose availability depends primarily on its direct incorporation rather than microbial mineralization. Unlike N and P, S remained largely independent of biological transformations occurring during compost maturation, explaining the limited influence of gypsum on the dynamics of the remaining nutrients [43]. These results indicate that gypsum can effectively enrich composts with sulfur without substantially modifying the overall composting process.

Throughout compost maturation, pH remained above 6.0, indicating favorable conditions for microbial activity and nutrient transformation. Minor reductions observed in formulations containing mineral P sources did not interfere with compost stabilization, probably because of the buffering capacity provided by the organic matrix [10]. The consistently higher pH values observed in treatments containing larger proportions of organic residues further demonstrate the importance of substrate composition in maintaining chemical stability during compost production, an important quality attribute for storage, transport, and agricultural application.

Overall, the results demonstrate that compost formulation represents a fundamental engineering strategy for controlling nutrient dynamics and determining the quality of filter cake-based organomineral fertilizers. The successful incorporation of reactive phosphate rock, either alone or combined with phosphate-solubilizing bacteria, produced composts with phosphorus availability comparable to those obtained using highly soluble mineral fertilizers. These findings indicate that engineering compost formulations through the integration of agro-industrial residues, alternative phosphorus sources, and biological amendments provides a technically feasible approach for producing phosphorus-enriched fertilizers while reducing dependence on conventional soluble phosphate fertilizers. Such

strategies contribute simultaneously to nutrient recycling, the valorization of sugarcane processing residues, and the development of more sustainable compost production systems.

5. Conclusions and Future Research Directions

Compost formulation influenced nutrient dynamics during filter cake composting. Reactive phosphate rock resulted in phosphorus availability comparable to that of triple superphosphate, showing its potential as an alternative phosphorus source for organomineral compost production. Phosphate-solubilizing bacteria increased phosphorus availability during the active composting phase, but this effect was not maintained in the mature compost. Agricultural gypsum did not improve nitrogen conservation. Further research should evaluate the agronomic performance of the resulting organomineral fertilizers, as well as their economic and environmental aspects under field conditions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriengineering8090359/s1. Table S1. Temperature, moisture content, and operational management of the compost windrows during the 115-day composting period.

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