biomass

MDPI

Article

Synergies in the Co-Valorization of Sugar and Agroindustrial Byproducts: Physicochemical Screening and Exploratory Classification of Filter Mud-Based Amendments

Noé Aguilar-Rivera

Faculty of Biological and Agricultural Sciences, Universidad Veracruzana, Orizaba Córdoba Región, Calle Josefa Ortiz de Domínguez, camino Peñuela-Amatlán, s/n. Peñuela, Amatlán de los Reyes C.P. 94945, Veracruz, Mexico; naguilar@uv.mx

Abstract

The transition from conventional agro-industrial production toward circular bioeconomy models requires the comprehensive valorization of process by-products as resources ("Waste-to-Wealth"). This study presents an exploratory physicochemical characterization of four biotechnological pathways—composting, vermicomposting, accelerated Bokashi-type fermentation, and biol production—for transforming filter mud (cachaza), sugarcane trash, boiler ash, bagasse, vinasse, and other agro-industrial by-products into candidate soil amendment formulations. Based on analytical procedures established by official Mexican standards (NOM), pH, electrical conductivity (EC), organic matter (OM), macronutrients (N–P–K), and the carbon-to-nitrogen ratio (C/N) were characterized across 37 distinct, non-replicated formulations, revealing pronounced physicochemical heterogeneity and three preliminary functional profiles. Vermicompost-derived formulations exhibited relatively high OM and nutrient contents and C/N ratios within a range commonly associated with stabilized organic materials. In contrast, alkaline Bokashi formulations incorporating ash and agricultural lime produced highly alkaline matrices (pH > 10) with high calcium concentrations (up to 37% CaO), suggesting potential for use as acidity-correcting mineral–organic amendments. The liquid BIOL formulation exhibited a high K_2O concentration (27.35%), identifying it as a candidate potassium-rich liquid formulation; however, its suitability for fertigation or foliar application requires appropriate dilution, salinity and phytotoxicity assessment, and controlled agronomic validation. Exploratory multivariate screening differentiated the 37 formulations into distinct physicochemical profiles, indicating that filter mud-based amendments do not constitute a chemically uniform product class but rather encompass formulations with contrasting compositional characteristics and potential functional niches. These findings support a differentiated cascade-valorization framework for sugarcane agro-industrial by-products, while agronomic performance, phytotoxicity, sanitary safety, environmental impacts, economic feasibility, and reproducibility across production batches require independent validation before field-scale or commercial application.

Keywords: agroindustry's waste; circular economy; filter mud; tailored biofertilizers; biotechnological pathways

Check for updates

Academic Editor: Cristiano Varrone

Received: 30 June 2026
Revised: 1 September 2026
Accepted: 15 September 2026
Published: 1 October 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Sugarcane is one of humanity's oldest crops, producing one of the most widely consumed caloric sweeteners—table sugar, or sucrose—whose nutritional value is currently

being questioned due to potential risks to human health. However, both caloric and non-caloric substitutes also pose significant risks [1,2]. Beyond these nutritional concerns, the sugarcane sector itself faces mounting sustainability challenges: the global expansion of cultivated acreage to meet growing sugar demand is increasingly accompanied by declining agricultural yields and severe environmental impacts. Consequently, there is an urgent need to incorporate clean technologies that ensure food security and optimize material and energy balances. Addressing these challenges requires efficient management of natural resources and economic inputs, together with the elimination of pre-harvest burning to sustain agricultural productivity amid climate change. Furthermore, implementing green technologies is essential to valorize byproducts—such as crop trash, filter mud, bagasse, molasses, vinasse, ash, and wastewater. Transitioning toward flexible biorefineries and enhancing cogeneration efficiency within a water-energy-food nexus approach will ultimately drive the sector's sustainable development [3,4].

Filter Mud from the Sugar Industry

Filter mud—also referred to as press mud or filter cake, and known regionally in Latin America as "cachaza"—is a dark, moist, spongy, and insoluble solid generated in large quantities during sugarcane juice clarification. It decomposes slowly under natural conditions, a process accompanied by intense heat generation and a foul odor [5]. Its chemical and biological composition constitutes its greatest value within the circular bioeconomy, enabling its use as a biofuel, soil conditioner, organic amendment, biofertilizer, animal feed, and raw material for heavy-metal bioremediation, wax extraction, and concrete manufacturing. However, the composition of filter mud varies considerably depending on sugarcane variety, soil type, and other environmental factors. Technological barriers also pose a major challenge for researchers seeking to harness its potential across different industries [6,7]. Extensive research into the agricultural use of filter mud is therefore warranted, and such research is expected to support its widespread adoption by promoting a holistic approach to agricultural and environmental challenges. Nevertheless, the development of large-scale composting technologies remains limited in sugar-producing countries. From an agribusiness perspective, for a filter mud-based amendment to achieve commercial success, it must meet three criteria: it must address a real agronomic need (demand), rely on accessible inputs (low production cost), and offer an attractive profit margin [8–10] (Figure 1).



Figure 1. Filter mud spread on open fields and application in sugarcane fields.

The predominant disposal strategy for uncomposted filter mud has been to spread it directly across sugarcane fields near the mill, owing to its immediate availability and apparently low cost. Sugar mills often promote this practice among sugarcane growers and their union leaders by offering freight subsidies that reduce the cost burden on growers

who require a steady supply of this byproduct as an alternative soil amendment. However, filter mud is generated in very large volumes and exhibits a comparatively low nutrient concentration per unit weight, owing largely to its high moisture content (70–80%). This moisture content economically restricts its direct application to plots located near the mill (generally within 10–15 km). Moreover, the lack of accessible technological processing options—particularly composting infrastructure—leads to its accumulation at most sugar mills, where uncontrolled decomposition in open fields generates leachate and emissions of greenhouse gases such as methane (CH_4) [11].

Because it has not undergone thermal and microbial stabilization, fresh raw filter mud—rich in organic matter and residual bagasse—undergoes accelerated decomposition when applied directly to sugarcane fields. This process generates thermophilic hot spots (marked temperature increases) and releases organic acids capable of damaging newly planted shoots or buds; furthermore, its high carbon-to-nitrogen (C/N) ratio can immobilize soil nitrogen during early decomposition stages [12].

Filter mud is nonetheless an exceptional reservoir of phosphorus (P), nitrogen (N), calcium (Ca), and magnesium (Mg)—qualities that have earned it the informal designation "bio-earth"—and, when properly applied, it functions as a slow-release biofertilizer or amendment that reduces dependence on chemically synthesized inputs. For this reason, agricultural producers commonly purchase filter mud from sugar mills as a base ingredient for composting, vermicomposting, or the production of fermented (bokashi) and liquid (Biol) biofertilizers. These formulations often incorporate additional agro-industrial residues, such as manure, coffee pulp, rice husks, corn stover, alfalfa and soybean residues, distillery vinasse, molasses, boiler ash, and firewood. However, the physicochemical properties of these resulting liquid and solid biofertilizers have rarely been systematically evaluated, and their field application is often carried out without a sound technological basis—resulting in inconsistent agronomic performance and reduced profitability for agribusinesses [13,14].

Despite the global expansion of circular bioeconomy models within the sugarcane agroindustry, research on the technical valorization of process byproducts—particularly filter mud—for biofertilizer and organic amendment production remains largely empirical. Current literature frequently evaluates organic biofertilizers derived from these residues through isolated physicochemical parameters or limited treatment comparisons, implicitly promoting a monolithic, "one-size-fits-all" agronomic solution. Consequently, a significant knowledge gap persists regarding the functional segmentation of these organic matrices. Comprehensive studies utilizing advanced multivariate statistical frameworks to systematically categorize diverse filter mud-based treatments into specialized functional profiles (e.g., corrective soil amendments versus nutrient-dense fertilizers) are currently lacking. This absence of robust, comparative screening limits the strategic transition of traditional sugar mills into highly efficient facilities capable of producing tailored agricultural inputs.

Furthermore, the design of filter mud-based biofertilizers and amendments—including precision soil products tailored to address regional soil fertility constraints such as excess acidity or deficiencies in potassium and organic matter—could generate meaningful cross-sectoral synchronization along a shared production value chain linking the local sugar, coffee, rice, and livestock industries. This synergy would, in turn, help resolve environmental liabilities and reduce final disposal costs [15,16].

The exploratory and pioneering nature of this study—given the lack of direct methodological precedents regarding these specific byproducts in the region—entails limitations inherent in any initial statistical approach to a previously uncharacterized phenomenon. Far from constituting weaknesses that invalidate the findings, these limitations precisely

define a research agenda necessary for the consolidation of a regional amendment and biofertilizer industry based on filter mud.

This study was designed to determine the physicochemical properties of compost, vermicompost, and bokashi in the sugarcane-producing region of Córdoba, Gulf of Veracruz, Mexico, and to establish that the formulation of filter mud-based amendments or biofertilizers with other regional agro-industrial byproducts may yield higher nutrient content and a broader range of applications than raw filter mud, which remains widely used as a soil conditioner despite receiving no prior stabilization treatment.

This research represents a significant innovation by moving away from the traditional use of raw filter mud toward the development of a catalog of "tailored biofertilizers" through distinct biotechnological formulations, demonstrating that no universal organic matrix exists for soil treatment based on filter mud. Among its main scientific and technological contributions, the study categorizes these bioproducts into specific strategic niches: compost, vermicompost, bokashi-type alkaline matrices (enriched with lime and ash), and concentrated Biol with a physicochemical profile consistent with potential use for fertigation [17–19].

The hypothesis of this work is that the specific biotechnological stabilization pathway (e.g., vermicomposting, bokashi, or aerobic composting) exerts deterministic control over the physicochemical evolution of sugarcane filter mud, shifting its potential agronomic utility from a universal amendment or organic biofertilizer to a catalog of functionally segmented bioproducts—ranging from nutritional matrices to corrective amendments—that are essential for targeting the sustainable use of filter mud as a byproduct.

2. Materials and Methods

2.1. Study Area and Source of Biomass

The research was conducted at the facilities of the Facultad de Ciencias Biológicas y Agropecuarias (Faculty of Biological, Agricultural, and Livestock Sciences), Universidad Veracruzana, located in the locality of Peñuela, municipality of Amatlán de los Reyes, Veracruz, Mexico (18°53′ N, 96°55′ W). This location lies at the heart of the Córdoba–Gulf of Mexico production region, an area characterized by intensive monoculture of sugarcane (*Saccharum officinarum* L.). The main agroindustrial byproducts used as raw materials included fresh or raw filter mud, boiler ash, bagasse, bagacillo (fine bagasse pith), pachaquil (partially decomposed filter mud/bagasse residue from sugar mill yard), vinasse, and sugarcane trash, all collected directly from local sugar mills during the 2024–2025 harvest season. Various manures (cattle, horse, sheep, poultry, and rabbit), coffee husks, rice husks, soybean pulp, yard waste and pruning residues, yeast, non-centrifugal sugar (piloncillo), and diluted molasses were used as co-substrates or biological activators to balance the C/N ratio and inoculate microorganisms.

2.2. Experimental Design and Formulation of Treatments

A cascade recovery experiment was designed, establishing 37 different formulations (Treatments A–B11 as a single approach without independent biological replicates), categorized into four biotechnological pathways for organic matter stabilization:

1. Thermophilic aerobic composting: Mixtures of filter mud (50%) with varying proportions of mineral material, such as boiler ash or agricultural lime (10–15%) and lignocellulosic biomass or manure (35–40%), which were mechanically turned weekly to ensure aeration and irrigated weekly to maintain 60% moisture content for 90 days.
2. Vermicomposting: Pre-composts of filter mud (50%), manure (30%) and waste biomass (20%) for 30 days, before being inoculated with California red worms (*Eisenia fetida*), cultivated in the shade with humidity controlled at 70–80% for 60 days.

3. Accelerated solid fermentation—Bokashi-type: Mixtures of filter mud (50%), waste biomass (bagasse, sugarcane trash, coffee husk or green biomass) (40%), enriched with agricultural lime, ash, fresh yeast (*Saccharomyces cerevisiae*), and rapidly assimilated carbohydrates (molasses/non-centrifuged sugar), processed under semi-anaerobic conditions with daily turning for 14–21 days, starting with an initial moisture content of up to 60% [19].
4. Liquid fermentation—BIOL: Anaerobic digestion in sealed bioreactors to produce concentrated liquid biofertilizer containing at least 30% filter mud, manure, and green biomass for 45 days under tropical conditions at approximately 30 °C.

Temperature, as a factor in managing the time required to maintain moisture and determine compost maturity, was measured using a Dostmann TFA thermometer with a 40-cm probe (TFA Dostmann GmbH & Co. KG, Reicholzheim, Germany).

In addition, raw materials such as filter mud, pachaquil (cane yard trash), ash from the bagasse boiler, and earthworm leachates were characterized as reference control treatments. All solid formulations were processed using the standardized plastic container technique (pilot scale) over biological cycles ranging from 45 to 90 days, depending on the technological route, until the thermal maturation phase was reached.

2.3. Physicochemical Characterization

Once stabilized, a representative composite sample was collected from each treatment by five-point sampling method [20]. Laboratory analysis was conducted in accordance with the guidelines of the Official Mexican Standard NOM-021-RECNAT-2000 (soil fertility) [20] and NMX-FF-109-SCFI-2008 (earthworm humus) [21] in a laboratory certified by the Mexican government; therefore, the results regarding the physicochemical properties of the biofertilizers represent the average of the measurements taken in accordance with official standards.

2.4. Córdoba-Gulf Region

The Córdoba-Gulf region is one of the historical and productive epicenters of the sugar agroindustry in Mexico, with a long tradition and cultural identity linked to sugarcane cultivation, as well as established industrial infrastructure (multiple sugar mills located in proximity to one another). However, its conventional production model—based on the Green Revolution, intensive use of agrochemicals, uncomposted raw filter mud, and burned harvesting—led to diminishing yields and high ecological vulnerability for over a decade, where uninterrupted monoculture has favored the proliferation of endemic pests (such as sugarcane stem borer) and diseases, requiring ever-increasing doses of new-generation pesticides on degraded and compacted soils (low organic matter). The region comprises the sugarcane stalk supply zones for 11 sugar mills [22,23].

However, the region suffers from a critical loss of organic matter, with levels predominantly “Low” or “Very Low.” This is a result of the burning of sugarcane fields prior to harvest, which volatilizes carbon and nitrogen and destroys the surface microbiota. In addition, it is common practice to spread fresh filter mud (a byproduct of juice clarification) directly onto the fields. Since it is not composted, filter mud undergoes anaerobic fermentation in the soil, drastically raising the temperature, altering the pH, generating polluting leachates, and temporarily immobilizing nitrogen, which affects the sugarcane roots [24] (Figure 2).

Nevertheless, the socioeconomic challenges faced by most ejido farmers or smallholders on smallholdings hinder economies of scale and result in limited bargaining power with sugar mills. Their income depends on the KARBE (Kilogram of Recoverable Sugar, Standard Base) payment indicator for sugarcane stalks, which is diminished by the poor quality of the sugarcane resulting from poor soil, the rising cost of synthetic fertilizers

(mostly imported), which drastically reduces sugarcane farmers' profit margins, as well as risks to human health from chronic exposure to agrochemicals and the inhalation of smoke and ash during the burning season, which cause serious respiratory problems in local communities [25].

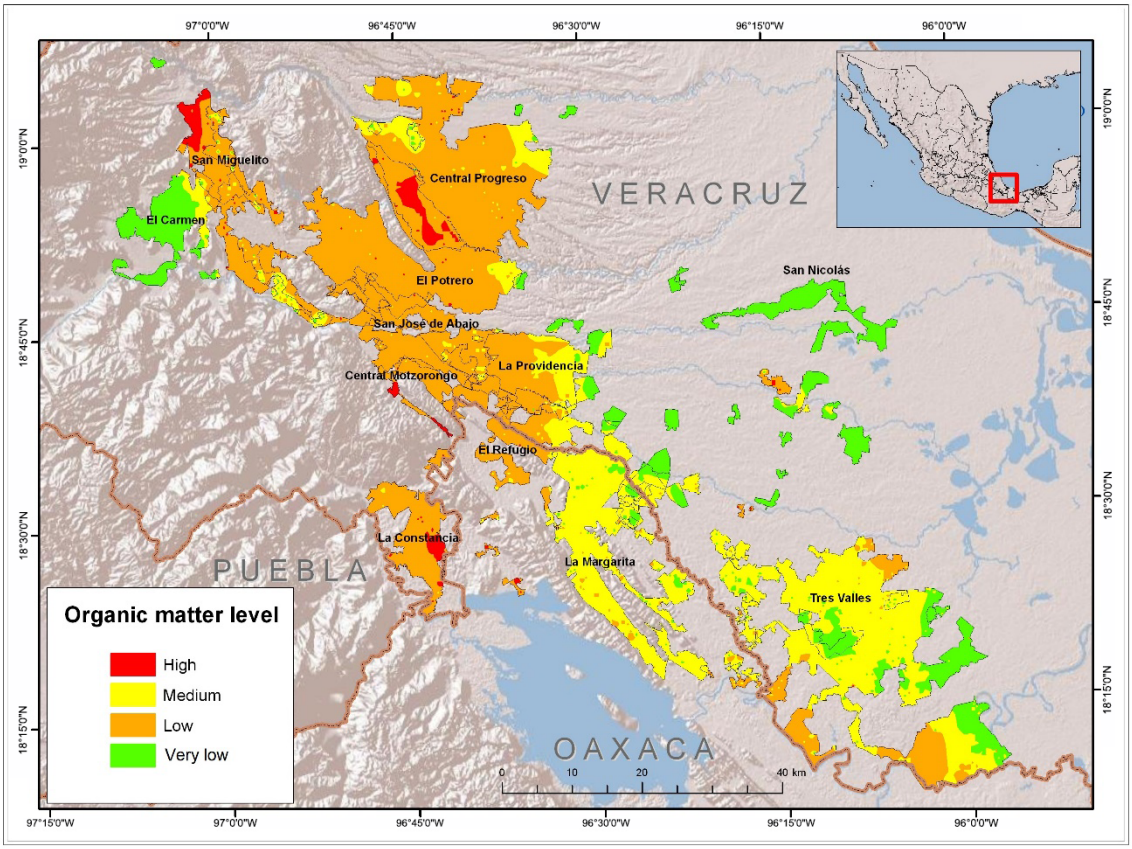


Figure 2. Organic matter levels in the Córdoba Gulf region and sugar mills (data from CONADESUCA 2026, URL https://www.gob.mx/conadesuca/acciones-y-programas/geoportal-del-comite-nacional-para-el-desarrollo-sustentable-de-la-cana-de-azucar) (accessed on 15 May 2026).

Consequently, to restore productivity in the Córdoba-Gulf region and mitigate its environmental impact, the byproducts of the sugar industry must be transformed into inputs of high agronomic value through Technical Composting of Byproducts, as strategic solutions toward productivity management.

In other words, the region's sugar mills generate thousands of metric tons of filter mud (Figure 3), boiler ash, bagasse pith, and vinasse, which are currently used in their raw form as "Cenichaza." The key is to establish large-scale aerobic composting facilities.

Furthermore, by combining filter mud (rich in nitrogen, phosphorus, calcium, and organic matter), ash (rich in potassium and silicon), and bagasse (cellulose and lignin), the phytotoxicity of raw filter mud can be eliminated, and weed seeds and pathogens destroyed, and a highly assimilable humified organic soil amendment is obtained, which will gradually enable the restoration of organic matter, and the productivity of the sugar cane crops (Net-Zero Path) through the replacement of synthetic fertilizers, nitrous oxide (N_2O) mitigation, and carbon sequestration. By increasing the organic matter content across hundreds of thousands of hectares, the Córdoba-Gulf region would cease to be a net source of carbon and instead become a carbon sink, capturing atmospheric CO_2 in the black, fertile soil. However, a fundamental and critical step in sustainable soil management—given the socioeconomic and environmental implications for this sugarcane-growing region—is the transition to green harvesting (zero burning), as green harvesting leaves a thick layer of

crop residue (sugarcane trash mulch) on the field. This cover protects the soil from water erosion, suppresses weed growth (reducing the use of herbicides), and, as it decomposes, adds even more organic carbon to the system, closing the cycle [26,27].

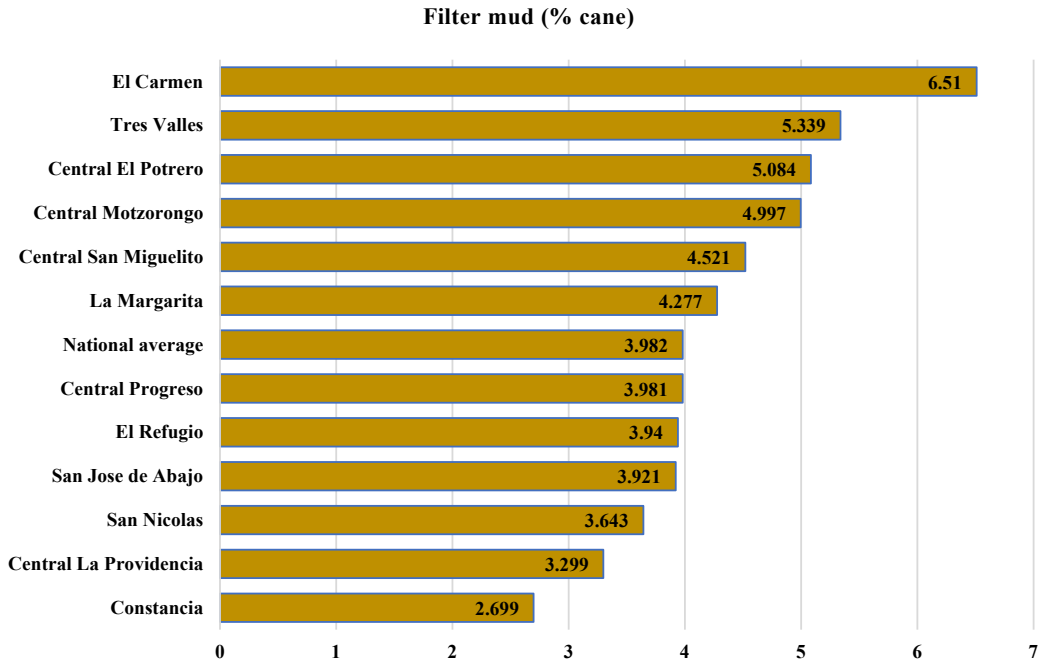


Figure 3. Filter mud production in the Córdoba-Gulf region.

2.5. Production of Filter Mud Biofertilizers

The following formulations and equipment were used to produce filter mud-based biofertilizers (Table 1 and Figures 4–7).

Table 1. Amendment or biofertilizer composition.

Code	Biofertilizer Composition	
A	Filter Mud	100% FM
B	Ashes from bagasse	100% Ashes
C	Filter Mud Compost	100% FM
D	Filter mud vermicompost	100% FM
E	Compost of filter mud, bagasse and ashes	60% FM, 30% SCB, 10% ash
F	Pachaquil	100% Pachaquil
G	Compost of Pachaquil	100% Pachaquil
H	Vermicompost of pachaquil	100% Pachaquil
I	Bokashi of pachaquil	70% Pachaquil,
J	Compost Filter mud and horse, cow and sheep manure	70% FM, 30% MA
K	Compost Filter mud and horse, cow and sheep manure, and gardening waste	60% FM, 30% MA, 10% GB
L	Compost Cenichaza (filter mud and ashes) and pith	50% FM, 25% MM, 25% Pith
M	Compost Cenichaza (filter mud and ashes)	50% FM, 50% MM
N	Compost Cenichaza (filter mud and ashes) and vinasse (irrigation)	75% FM, 25% MM
O	Compost Cenichaza (filter mud and ashes) and bagasse	50% FM, 25% MM, 25% SCB
P	Compost Cenichaza (filter mud and ashes) and cow manure	50% FM, 25% MM, 25% MA
Q	Bokashi filter mud, boiler ash, agricultural lime, sheep manure, coffee husks, non-centrifuged sugar, and yeast	50% FM, 15% MM, 15% MA, 20% WA

Table 1. *Cont.*

Code	Biofertilizer Composition	
R	Bokashi filter mud, boiler ash, agricultural lime, horse manure, coffee husks, non-centrifuged sugar, and yeast	50% FM, 15% MM, 15% MA, 20% WA
S	Bokashi filter mud, boiler ash, chicken manure, coffee husks, non-centrifuged sugar, and yeast	50% FM, 15% MM, 15% MA, 20% WA
T	Vermicompost of filter mud and bagasse	75% FM, 25% SCB
U	Vermicompost of filter mud, trash and pith	75% FM, 25% WB
V	Vermicompost of filter mud, rice hulls, and chicken manure	50% FM, 25% MA. 25% WB
W	Vermicompost of filter mud, rice hulls, and rabbit manure	50% FM, 25% MA. 25% WB
X	Vermicompost of filter mud, rice hulls, and sheep manure	50% FM, 25% MA. 25% WB
Y	Vermicompost of filter mud, rice hulls, and horse manure	50% FM, 25% MA. 25% WB
Z	Vermicompost of filter mud, sugarcane bagasse, cow manure, and coffee husks	50% FM, 15% SCB, 20% MA. 15% WB
B1	Bokashi Filter mud, horse manure, grey ash, sugarcane bagasse, agricultural lime, fresh yeast, diluted molasses, and urea.	40% FM, 30% MA, 10% MM, 20% SCB
B2	Bokashi Filter mud, horse manure, grey ash, sugarcane bagasse, agricultural lime, fresh yeast, diluted molasses, and soy pulp	40% FM, 30% MA, 10% MM, 10% SCB, 10% WB
B3	Bokashi Filter mud, chicken manure, grey ash, sugarcane bagasse, agricultural lime, fresh yeast, and diluted molasses	40% FM, 30% MA, 15% MM, 15% SCB
B4	Bokashi Filter mud, horse manure, grey ash, sugarcane bagasse, agricultural lime, fresh yeast, diluted molasses and alfalfa waste	40% FM, 30% MA, 10% MM, 10% SCB, 10% WB
B5	Bokashi filter mud, horse, cow and chicken manure, grey ash, sugarcane trash, pleurotus mushroom production waste, agricultural lime, fresh yeast and diluted molasses	40% FM, 30% MA, 10% MM, 20% WB
B6	Bokashi Filter mud, sheep manure, grey ash, coffee husks, agricultural lime, fresh yeast, and diluted molasses	40% FM, 30% MA, 10% MM, 20% WB
B7	Bokashi filter mud, rabbit manure, grey ash, orange peels, agricultural lime, fresh yeast, and diluted molasses	40% FM, 30% MA, 10% MM, 20% WB
B8	Bokashi Filter mud, rabbit, cow, horse and sheep manure, grey ash, orange peels, agricultural lime, fresh yeast, diluted molasses	40% FM, 30% MA, 10% MM, 20% WB
B9	Bokashi filter mud, cow manure, grey ash, sugarcane trash, agricultural lime, fresh yeast, diluted non-centrifuged sugar	40% FM, 30% MA, 10% MM, 20% WB
B10	Bokashi filter mud, boiler ash, vinasse, non-centrifuged sugar, fresh yeast, cow manure and agricultural lime	40% FM, 30% MA, 10% MM, 20% WB
B11	BIOL concentrated liquid biofertilizer (Filter mud, fresh green grass, milk, cow manure, coffee grounds, yeast, molasses, bagasse boiler ash) and water	15% FM, 15% MA, 5% MM, 10% GB, 5% WB, 50% Water

FM: Filter Mud; WB: Waste biomass; GB: Green biomass; MA: Manure; M: Molasses; NCS: Non-centrifuged sugar; MM: Mineral Material.



Figure 4. Composting of filter mud biofertilizers.



Figure 5. Vermicomposting of filter mud.



Figure 6. Bokashi production.



Figure 7. BIOL production.

2.6. Statistical Analysis

2.6.1. Study Material

A total of 37 treatments or formulations derived from filter mud and other sugar agro-industry by-products (bagasse boiler ash, bagasse, vinasse) were evaluated following

different biological transformation pathway: unprocessed raw material (n = 2), conventional aerobic composting (n = 11), vermicomposting (n = 8), short-term thermophilic bokashi fermentation with mineral amendments (n = 15), and a concentrated liquid biofertilizer obtained through anaerobic fermentation (BIOL, n = 1), as exploratory multivariate screening. Each treatment represents a distinct formulation defined by a specific combination of base materials (filter mud, ash, agricultural lime, bagasse, bovine, equine, ovine, caprine, rabbit and poultry manure, molasses, yeast, vinasse, coffee husk, orange peel, among others). Seventeen physicochemical variables were determined for each treatment: moisture (%), pH, electrical conductivity (EC, dS m^{-1}), ash content (%), organic matter (%), total carbon (%), total nitrogen (%), carbon-to-nitrogen ratio (C/N), calcium (% CaO), magnesium (% MgO), sodium (% Na_2O), potassium (% K_2O), phosphorus (% P_2O_5), iron (% Fe), copper (% Cu), zinc (% Zn), and manganese (% Mn) [28–31].

Therefore, given the heterogeneity of the treatments and their formulations, the following research question was addressed: Can diverse formulations of filter mud and agroindustrial by-products be physically and chemically differentiated and classified into functional amendment profiles to support a cascade valorization strategy using exploratory multivariate analysis? Each of the 37 treatments or formulations was considered a single, non-replicated experimental case. The analytical data were generated by a laboratory certified by the Mexican government in accordance with applicable official standards; therefore, the value reported for each variable represents the mean of the analytical measurements obtained for that formulation. Accordingly, the dataset was used to characterize and explore multivariate patterns among formulations rather than to infer statistically significant differences among replicated treatment means. Furthermore, the trials were not independent biological replicates of a common treatment; each formulation was evaluated only once as an experimental unit.

Therefore, the dataset should be interpreted as an exploratory physicochemical characterization of distinct formulations rather than as a replicated biological experiment.

A grouping variable was generated from hierarchical cluster analysis to facilitate the subsequent comparison and characterization of the resulting formulation groups. This cluster-derived variable was subsequently incorporated as a fixed factor in analysis-of-variance (ANOVA) and multivariate analysis-of-variance (MANOVA) procedures. A nominal $\alpha = 0.05$ threshold was retained for reporting purposes; statistical significance was interpreted cautiously and exclusively as exploratory evidence of cluster-level physicochemical separation.

Despite the sampling limitations inherent to this preliminary, non-replicated study, the analytical framework was considered appropriate for the exploratory characterization of formulations derived from sugarcane agroindustrial by-products, including filter mud, ash, bagasse, and vinasse, subjected to controlled biological transformation processes. To our knowledge, few studies have systematically integrated the physicochemical characterization of such residue-derived fertilizer formulations with multivariate approaches capable of identifying compositional patterns and functional profiles. In practice, the production and use of organic fertilizers and biofertilizers derived from sugarcane-processing residues have often relied on empirical practices, traditional knowledge, and producer experience, with limited standardization of formulations and, in some contexts, insufficiently defined physicochemical criteria for differentiating products according to their potential agronomic value. This lack of systematic characterization and standardization may constrain the reproducibility, quality assessment, and broader agricultural application of these residue-derived fertilizers. Therefore, the present analysis was designed primarily to identify physicochemical patterns and formulation profiles that can serve as a basis for subsequent validation through replicated experiments and agronomic trials.

2.6.2. Descriptive Statistics and Normality Test

For each physicochemical variable, descriptive statistics were calculated to characterize the central tendency, dispersion, and distributional shape of the 37 formulation-level observations. These statistics included the mean, median, standard deviation, minimum, maximum, coefficient of variation, skewness, and kurtosis. The Shapiro–Wilk test was used as an exploratory assessment of the distributional characteristics of each variable across the 37 formulations. Given the non-replicated formulation-level structure of the dataset, these distributional assessments were interpreted descriptively rather than as evidence of biological replication or as a basis for inferring treatment-level effects.

2.6.3. Hierarchical Cluster Analysis

The 17 physicochemical variables were standardized using z-scores. Agglomerative hierarchical clustering was performed using Ward's method and Euclidean distance. The optimal number of clusters was selected by maximizing the average silhouette coefficient across two- to six-cluster solutions and was corroborated by visual inspection of the dendrogram.

Cluster membership was used solely to describe exploratory physicochemical profiles among the 37 distinct formulations. Cluster membership does not represent an experimental treatment factor, biological replication, or an independently randomized grouping.

2.6.4. Comparison of Means Among Clusters

Homogeneity of variances across the clusters, interpreted as exploratory physicochemical profiles, was assessed for each of the 17 variables using Levene's test based on deviations from the group mean. Differences in cluster-level means were examined using one-way analysis of variance (ANOVA), with cluster membership treated as a three-level grouping variable for exploratory comparison. The Kruskal–Wallis H test was additionally applied as a non-parametric robustness check when the assumptions underlying ANOVA were not adequately met. For variables exhibiting a significant omnibus ANOVA result, Tukey's honestly significant difference (HSD) test based on the studentized range distribution was used for pairwise comparisons.

Because the clusters were derived from the same physicochemical variables subsequently subjected to between-cluster comparisons, and because each underlying formulation represented a single non-replicated case, these analyses were interpreted exclusively as exploratory assessments of physicochemical differentiation among the identified clusters. Accordingly, *p*-values from ANOVA, Kruskal–Wallis tests, and post-hoc pairwise comparisons were not interpreted as confirmatory evidence of treatment effects, causal relationships, or the efficacy of any specific biological transformation pathway or formulation.

2.6.5. Correlation and Linear Regression

Pearson correlation coefficients were calculated among the 17 physicochemical variables, together with their corresponding two-tailed significance tests, to characterize the strength and direction of linear associations within the observed formulation set. In addition, an exploratory multiple linear regression model was fitted using ordinary least squares (OLS) to examine the association of total nitrogen with organic matter and phosphorus content. These predictors were selected based on their observed associations with total nitrogen and the absence of severe multicollinearity, as assessed using the variance inflation factor (VIF < 5). The analysis included unstandardized and standardized regression coefficients, standard errors, t-statistics, associated significance levels, the coefficient of determination (R^2), adjusted R^2, the overall model F-test, and the Durbin–Watson statistic as an indicator of potential residual autocorrelation. Given the non-replicated formulation-level structure

of the dataset and the exploratory nature of the analysis, the regression results were interpreted as describing empirical relationships within the observed set of formulations rather than as externally validated predictive models or evidence of causal relationships.

2.6.6. Principal Component Analysis

Principal component analysis (PCA) was performed on the correlation matrix of the 17 standardized physicochemical variables as an exploratory dimensionality-reduction approach to identify the major axes of variation and characterize relationships among the 37 distinct formulations. The suitability of the correlation structure for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. The number of components to retain was determined primarily through inspection of the scree plot and supported by the Kaiser criterion (eigenvalue > 1). Varimax orthogonal rotation with Kaiser normalization was applied to facilitate the interpretation of component loadings. Component scores for each formulation were subsequently estimated using the regression method. Given the formulation-level, non-replicated structure of the dataset, PCA was interpreted as an exploratory description of multivariate physicochemical patterns rather than as an inferential assessment of population-level structure or treatment effects.

2.6.7. Multivariate Analysis of Variance (MANOVA)

The multivariate differences among the three clusters were examined using a one-way multivariate analysis of variance (MANOVA), with the four retained principal component scores as dependent variables and cluster membership as a three-level fixed factor. MANOVA was used exclusively as an exploratory quantitative description of the multivariate separation among clusters identified from the same dataset and was not intended to test replicated treatment effects. Multivariate significance was evaluated using the four standard test statistics—Pillai's trace, Wilks' lambda, the Hotelling–Lawley trace, and Roy's largest root—with Rao's F approximation used for Wilks' lambda. Follow-up univariate Type III analyses of variance (ANOVA) were conducted for each principal component to characterize the contribution of individual components to the observed multivariate separation. These univariate analyses were likewise interpreted as exploratory measures of cluster differentiation rather than as confirmatory tests of treatment effects. A nominal significance level of $\alpha = 0.05$ was retained for reporting purposes; however, *p*-values were interpreted cautiously given the non-replicated formulation-level design, the data-driven formation of the clusters, and the reuse of the same physicochemical variables for cluster generation and subsequent between-cluster comparison.

2.6.8. Data Processing

All analyses were performed using custom routines developed in Python 3 (NumPy, SciPy, and scikit-learn libraries), implementing the same procedures, decision criteria, and output format conventionally used by the commercial statistical software SPSS v31 GradPack Standard For Students (IBM Corp, Armonk, NY, USA). Figures were designed following the visual conventions typical of SigmaPlot-style scientific graphics (framed axes, inward tick marks, monochrome palette), generated using Python (Matplotlib 3.10.0).

3. Results

3.1. Production of Biofertilizers from Filter Mud

The results of the physicochemical analyses of the resulting fertilizers, based on the processing described in Table 1, were obtained in accordance with official Mexican standards (Table 2).

Table 2. Physicochemical Composition of Treatments.

Manure	Moisture	pH	Electrical Conductivity	Ashes	Orgánic Materia	Total Carbon	Total Nitrogen	C/N	Calcium (CaO)	Magnesium (MgO)	Sodium (Na_2O)	Potassium (K_2O)	Phosphorus (P_2O_5)	Iron (Fe)	Copper (Cu)	Zinc (Zn)	Manganese (Mn)
A	51.143	7.419	2.200	32.670	53.564	35.581	1.156	31.291	7.059	0.702	0.158	1.195	3.433	0.587	0.008	32.873	0.231
B	40.245	10.245	6.690	64.770	35.230	20.435	0.320	65.060	1.659	1.075	0.065	5.639	1.611	0.116	0.010	0.024	0.045
C	46.909	6.128	1.880	34.386	64.368	38.181	1.839	20.773	5.679	0.744	0.040	0.657	5.718	0.692	0.020	0.045	0.197
D	55.905	6.730	1.813	33.510	66.490	38.567	1.020	37.800	37.810	3.698	0.341	0.327	0.288	2.696	0.616	0.003	0.014
E	48.120	7.000	2.340	43.840	56.160	32.575	1.030	31.630	6.172	0.853	0.066	0.572	5.726	0.248	0.014	0.022	0.063
F	8.750	6.190	0.505	76.540	23.460	13.608	0.690	19.720	0.404	0.064	0.152	0.064	0.102	0.042	0.001	0.002	0.030
G	17.230	7.750	0.443	74.770	25.230	14.635	0.430	34.040	3.562	0.117	0.404	0.175	0.231	0.159	0.001	0.003	0.032
H	10.570	7.710	0.814	73.180	26.820	15.557	0.240	64.820	7.036	0.219	0.446	0.219	0.278	0.049	0.001	0.004	0.004
I	4.640	7.320	0.306	88.860	11.140	6.462	0.290	22.280	1.782	0.089	0.385	0.027	0.001	0.027	0.001	0.006	0.003
J	39.680	8.420	4.120	39.990	60.010	34.810	1.450	24.010	12.740	1.805	0.359	2.367	4.760	0.394	0.016	0.051	0.137
K	45.420	8.440	3.040	31.160	68.840	39.930	1.570	25.430	8.600	1.262	0.300	2.098	3.800	0.189	0.010	0.029	0.102
L	34.025	6.145	2.374	45.850	29.575	22.905	1.440	15.345	2.068	0.265	0.030	0.675	1.698	1.048	0.008	0.023	0.201
M	38.510	8.550	0.630	96.330	3.670	2.129	0.260	8.190	4.245	0.552	0.172	1.388	0.877	0.349	0.006	0.008	0.082
N	43.310	8.670	1.329	95.140	4.860	2.819	0.170	16.580	3.973	0.646	0.195	1.589	0.879	0.448	0.006	0.006	0.080
O	53.390	9.140	0.458	94.460	5.540	3.213	0.170	18.900	3.223	0.599	0.182	1.478	0.921	0.498	0.005	0.007	0.085
P	53.850	7.640	0.960	85.240	14.760	8.560	0.420	20.380	4.684	0.893	0.157	1.324	2.068	0.313	0.007	0.021	0.097
Q	16.470	10.780	8.290	85.040	14.960	8.677	0.260	33.370	22.216	0.785	0.110	1.493	0.198	0.051	0.001	0.007	0.030
R	24.800	10.750	8.680	83.930	16.070	9.321	0.340	27.410	22.260	1.240	0.115	1.759	0.556	0.192	0.002	0.001	0.339
S	14.360	10.710	10.650	87.680	12.320	7.146	0.250	28.580	19.687	0.758	0.138	1.720	0.282	0.071	0.002	0.001	0.033
T	45.670	6.010	2.090	31.830	68.170	39.540	1.020	38.760	2.550	0.251	0.334	0.229	2.165	0.475	0.003	0.013	0.550
U	60.10	5.43	1.745	62.62	37.38	21.682	0.72	30.11	1.616	0.439	0.048	0.269	0.749	0.4959	0.0029	0.0176	0.1180
V	65.620	7.950	4.240	47.400	52.600	30.510	1.160	26.300	8.859	1.291	0.181	1.208	5.516	0.582	0.008	0.048	0.200
W	67.150	7.980	2.750	43.280	56.720	32.900	1.430	23.010	8.080	1.270	0.143	1.387	5.365	0.629	0.009	0.028	0.248
X	67.390	7.910	6.150	46.050	53.950	31.294	1.610	19.440	8.526	1.414	0.113	1.998	5.214	0.472	0.009	0.025	0.220
Y	69.530	7.780	3.180	48.820	51.180	29.687	1.460	20.330	8.030	1.053	0.125	1.066	5.327	0.636	0.009	0.024	0.246
Z	50.800	6.820	1.300	32.430	67.570	39.194	1.520	25.790	3.975	0.522	0.068	0.651	3.332	1.220	0.006	0.023	0.140
B1	40.600	8.570	3.170	73.450	26.550	15.400	0.540	28.520	27.054	0.478	0.050	0.468	0.242	0.078	0.001	0.003	0.020
B2	45.080	11.240	5.370	60.510	39.490	11.906	0.910	25.170	20.186	0.386	0.042	0.642	0.557	0.061	0.002	0.004	0.014
B3	48.310	12.820	6.540	67.020	32.980	19.130	0.540	35.430	26.211	0.496	0.060	0.573	0.711	0.060	0.002	0.008	0.026
B4	45.380	12.870	7.930	69.400	30.600	17.749	0.570	31.140	27.010	0.491	0.060	0.575	0.463	0.049	0.001	0.004	0.018
B5	48.980	8.950	4.440	45.710	54.290	31.491	0.670	47.000	23.447	0.734	0.452	1.394	2.197	0.219	0.003	0.011	0.071
B6	16.470	10.780	8.290	85.040	14.960	8.677	0.260	33.370	22.216	0.785	0.110	1.493	0.198	0.051	0.001	0.007	0.030
B7	31.640	8.240	6.130	65.160	34.840	20.209	1.020	19.810	9.125	0.746	0.153	1.178	1.893	0.261	0.007	0.014	0.065
B8	27.600	8.370	6.890	63.960	36.040	20.905	1.040	20.100	13.476	0.746	0.174	1.283	1.358	0.252	0.004	0.008	0.060
B9	61.020	8.280	1.806	62.120	37.880	21.976	1.530	14.360	18.279	0.726	0.042	0.322	2.839	0.598	0.005	0.028	0.020
B10	57.170	12.200	2.133	62.720	37.280	21.624	0.690	31.340	31.299	0.968	0.058	0.475	1.444	0.086	0.005	0.028	0.019
B11	97.560	7.730	17.100	54.850	45.150	26.190	0.140	187.000	3.600	4.133	1.266	27.360	0.538	0.071	0.005	0.027	0.034

3.2. Biofertilizer Properties

A detailed analysis of this matrix of physicochemical parameters of filter mud-based fertilizers provides a fundamental technical basis for closing cycles in the sugar agroindustry.

The stabilization of organic matter is at the core of the agronomic value of these fertilizers. Filter mud contains a high proportion of organic matter (53.56%) and has a C/N ratio of 31.29, providing a thermodynamically ideal starting point for composting on its own or as a component (50%) in formulations (Figures 8–18).

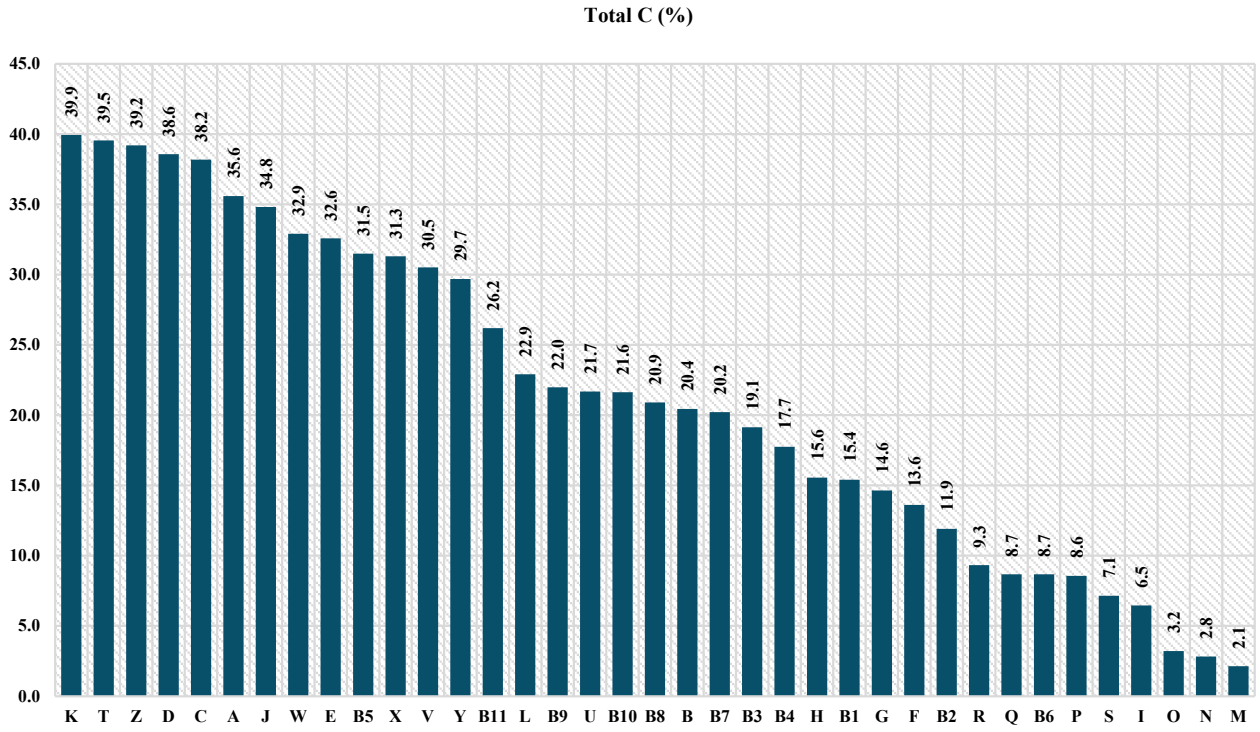


Figure 8. Total carbon (%) in the treatments.

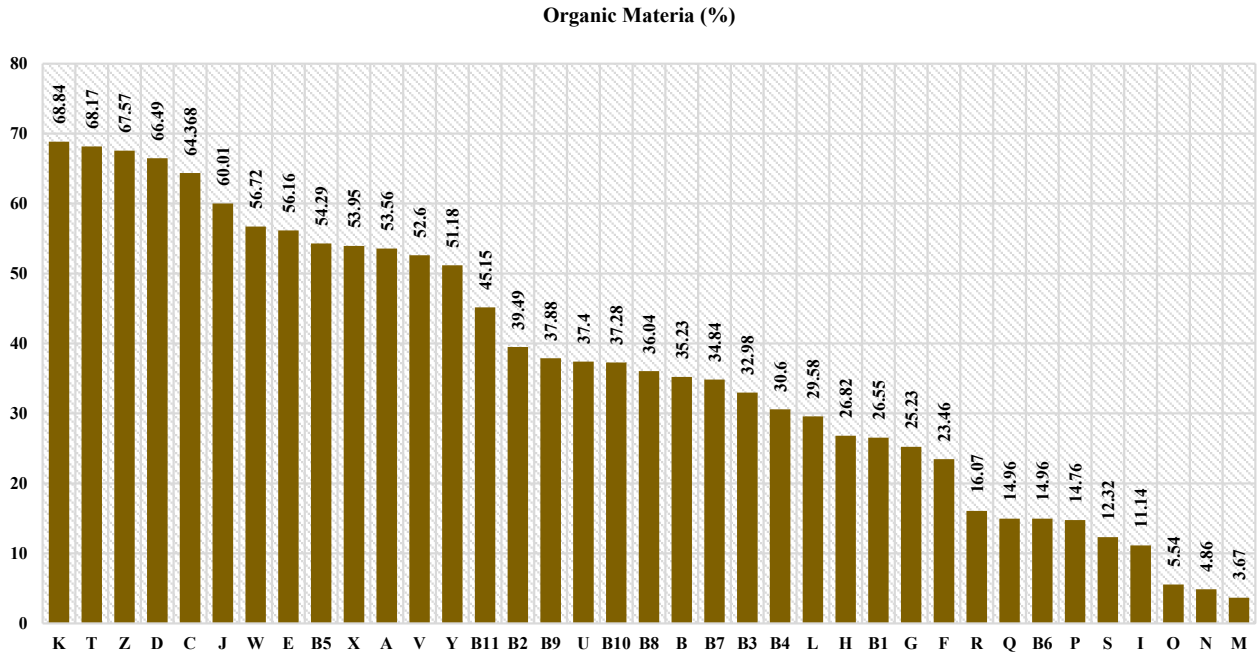


Figure 9. Organic matter (%) in the treatments.

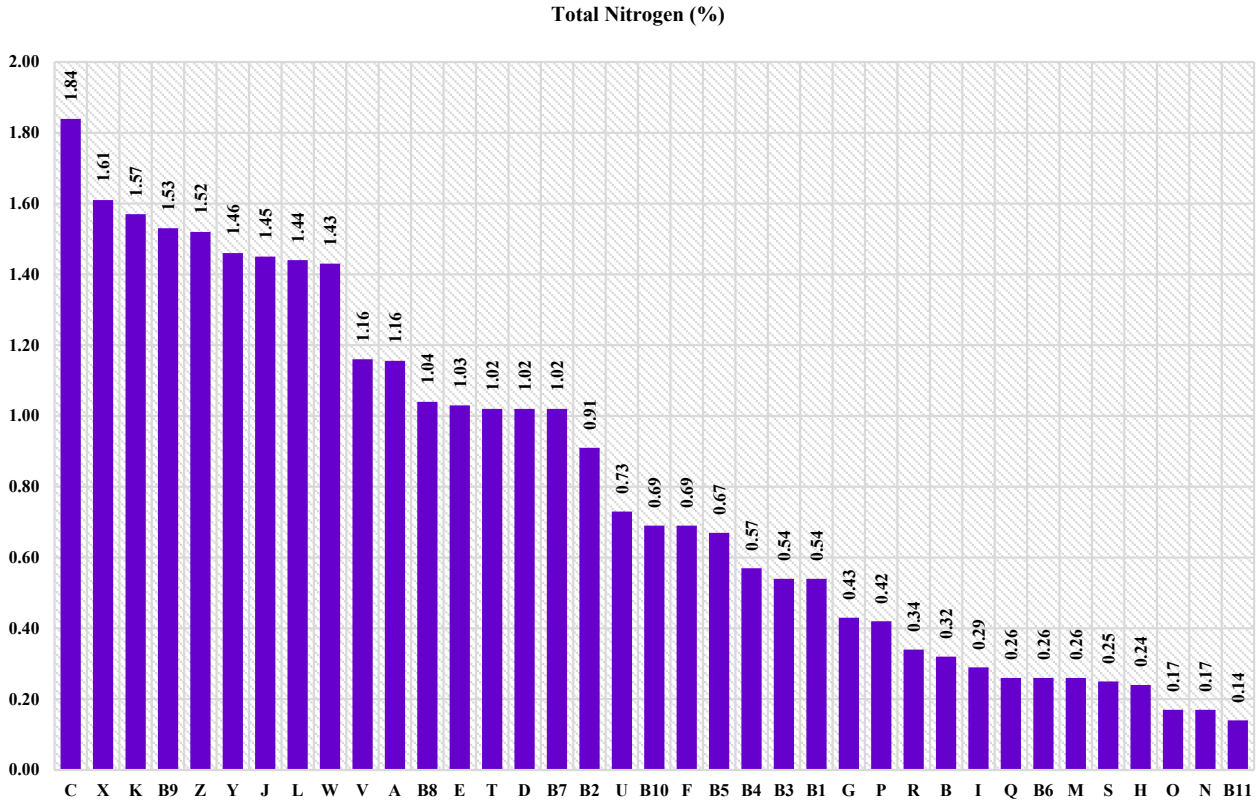


Figure 10. Total nitrogen (%) in the treatments.

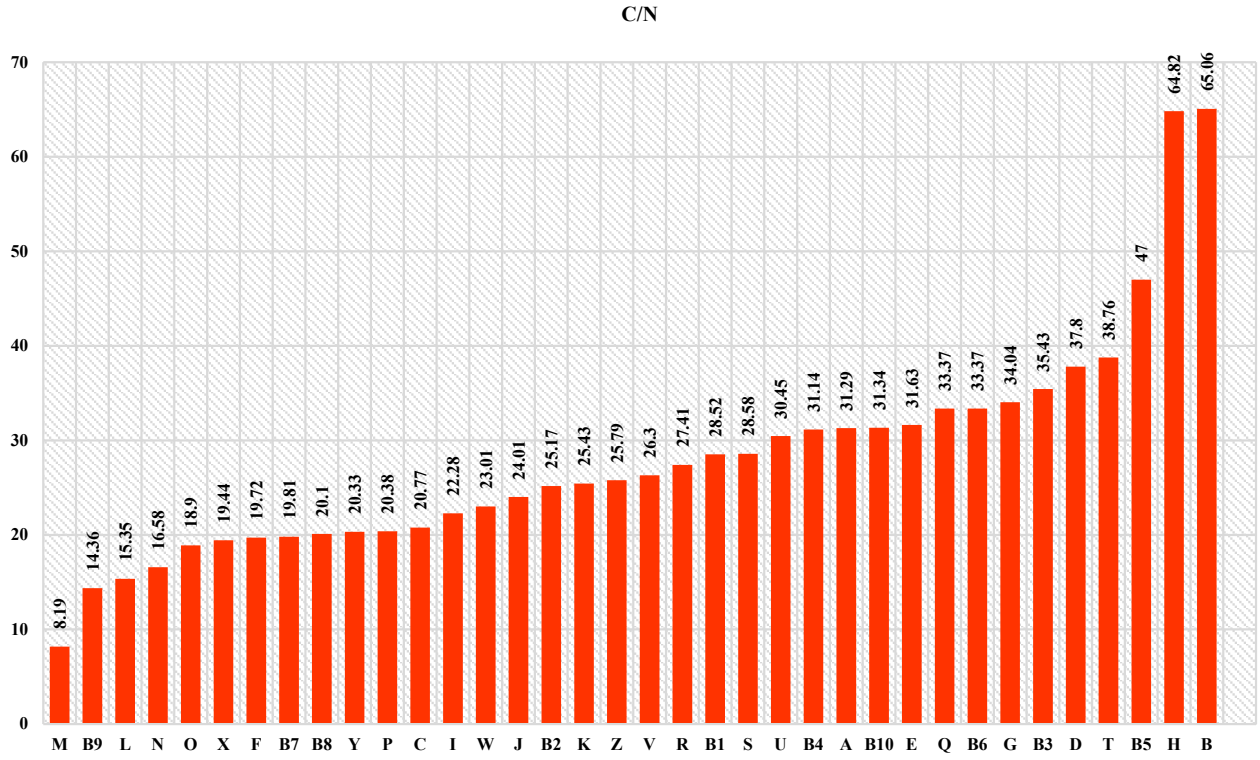


Figure 11. C/N Ratio of the Treatments.

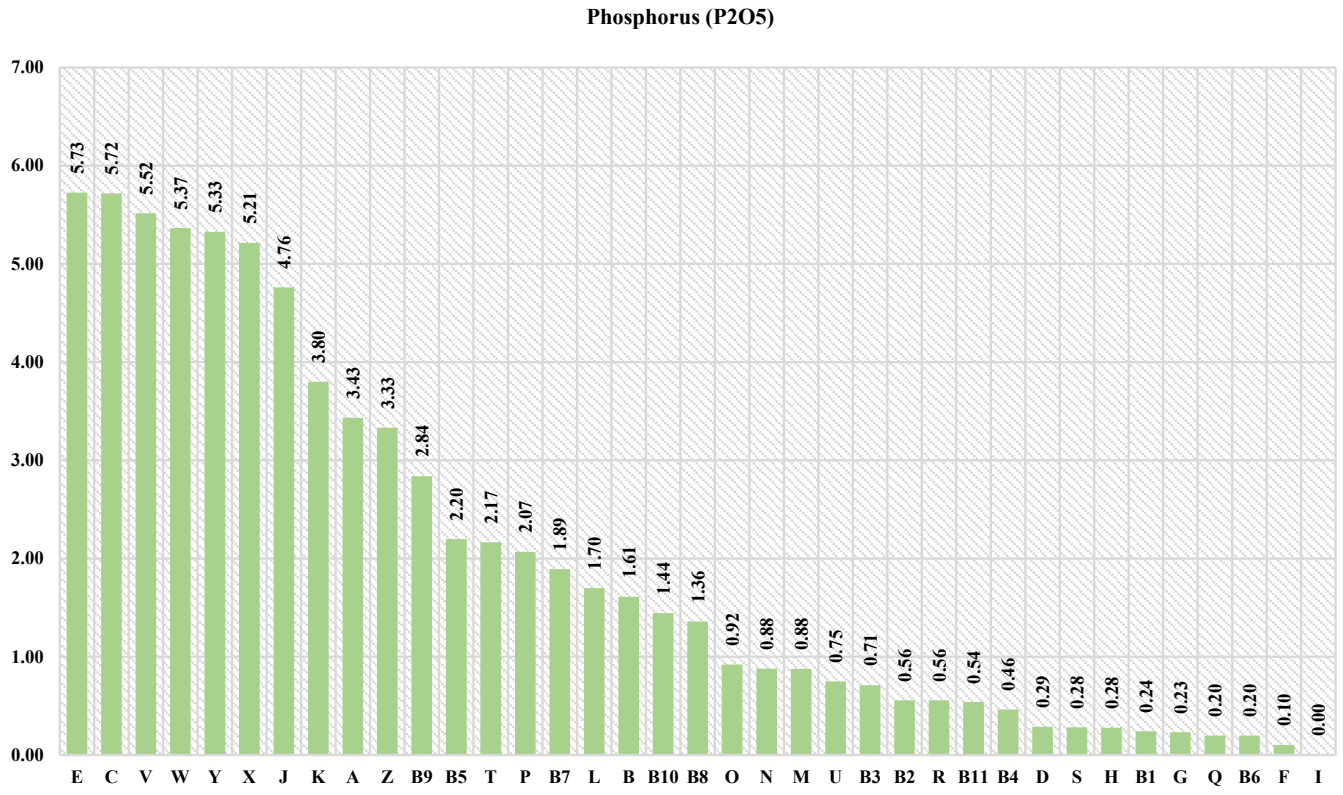


Figure 12. Phosphorus (%) in the treatments.

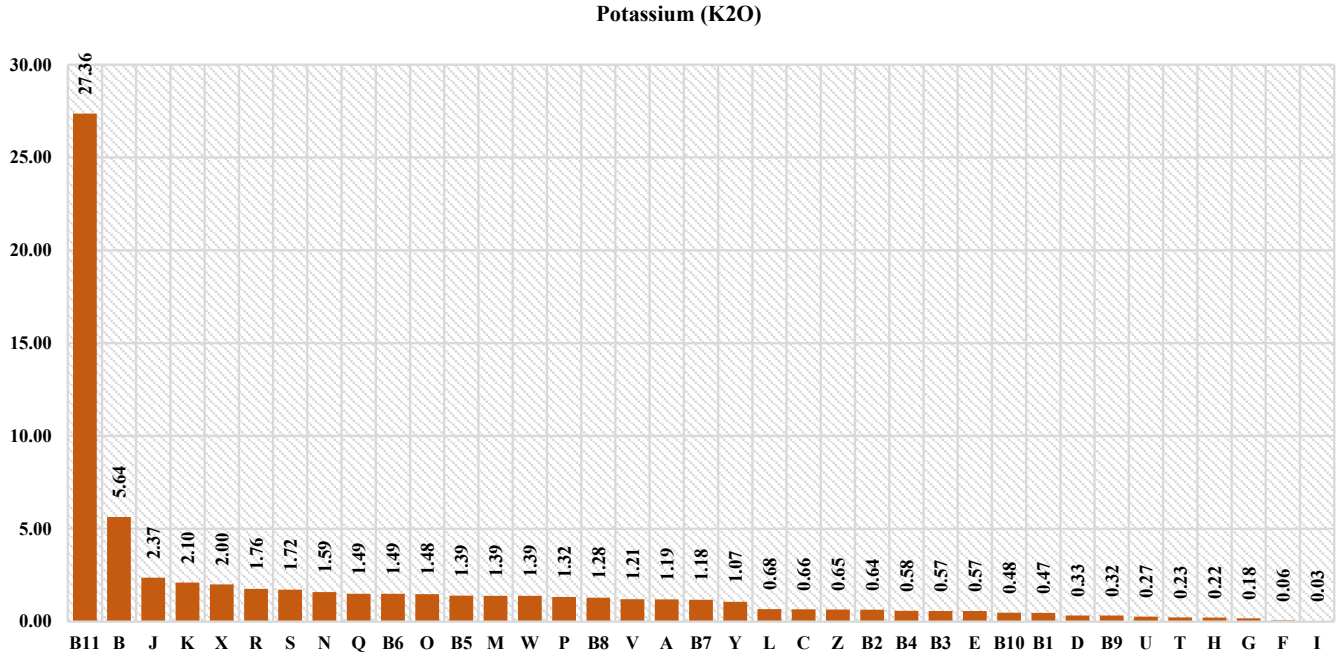


Figure 13. Potassium (%) in the treatments.

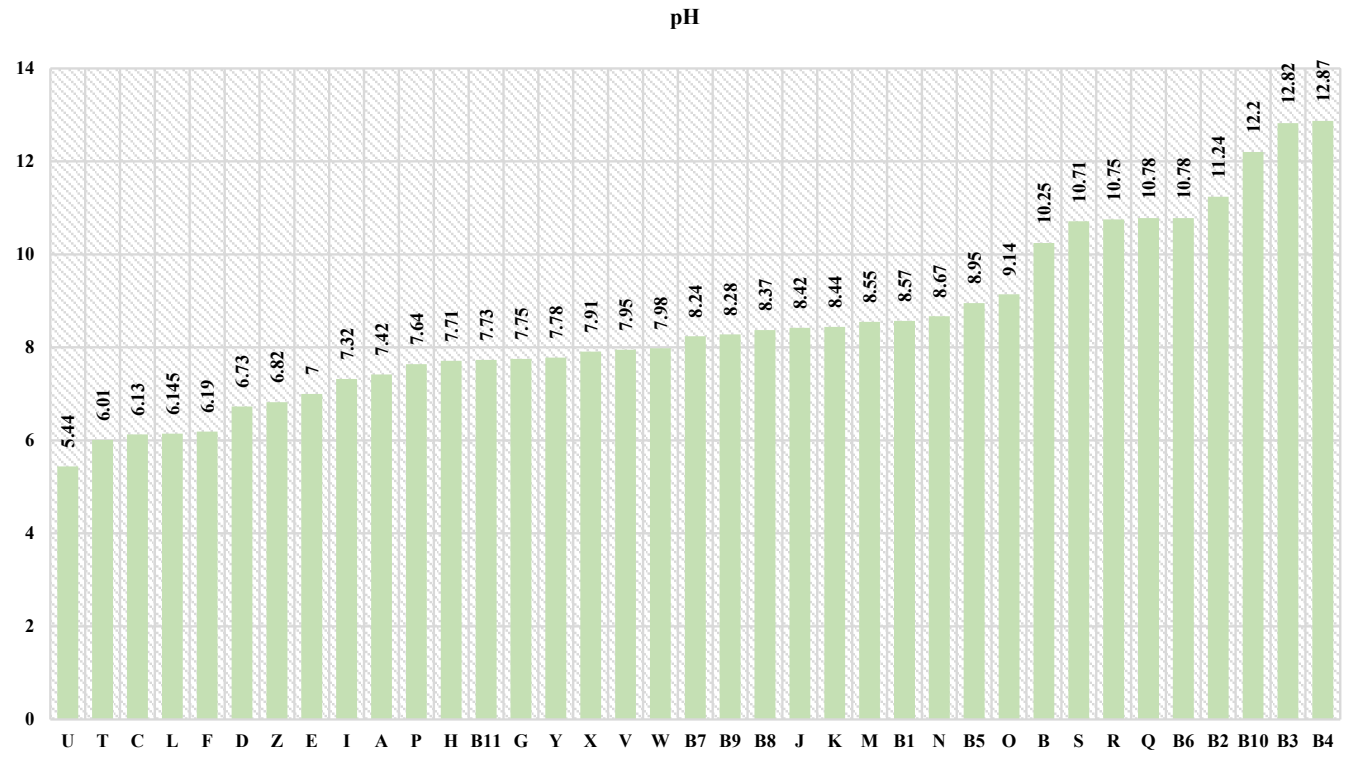


Figure 14. pH of the treatments.

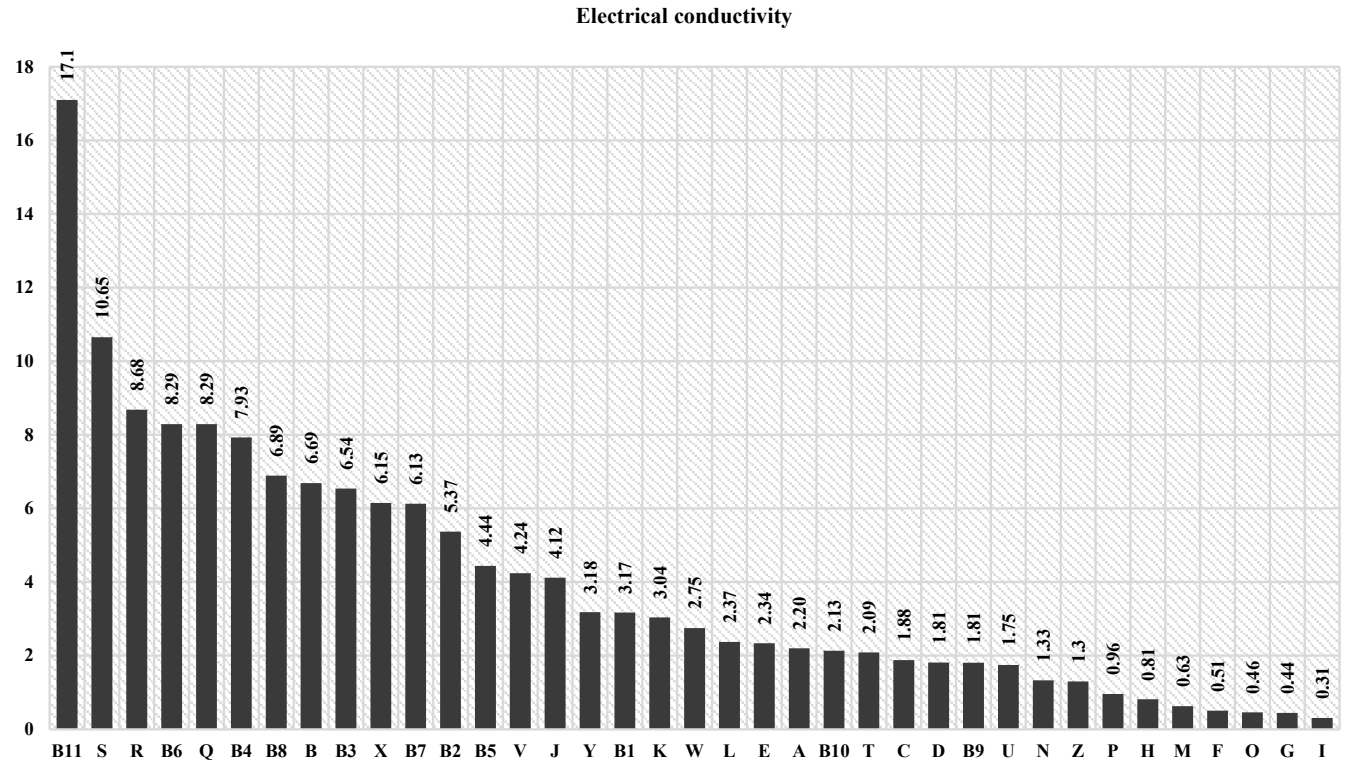


Figure 15. Electrical conductivity (dS/m) of the treatments.

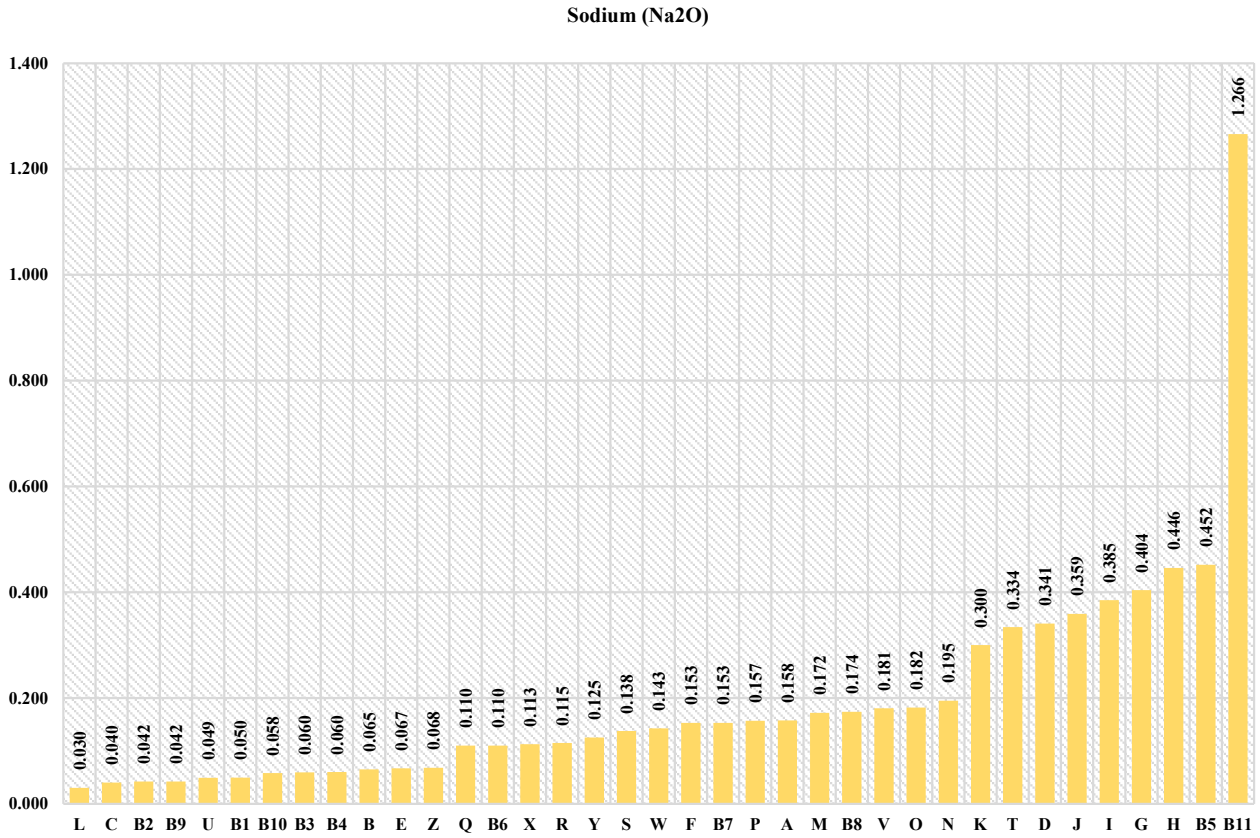


Figure 16. Sodium (%) in the treatments.

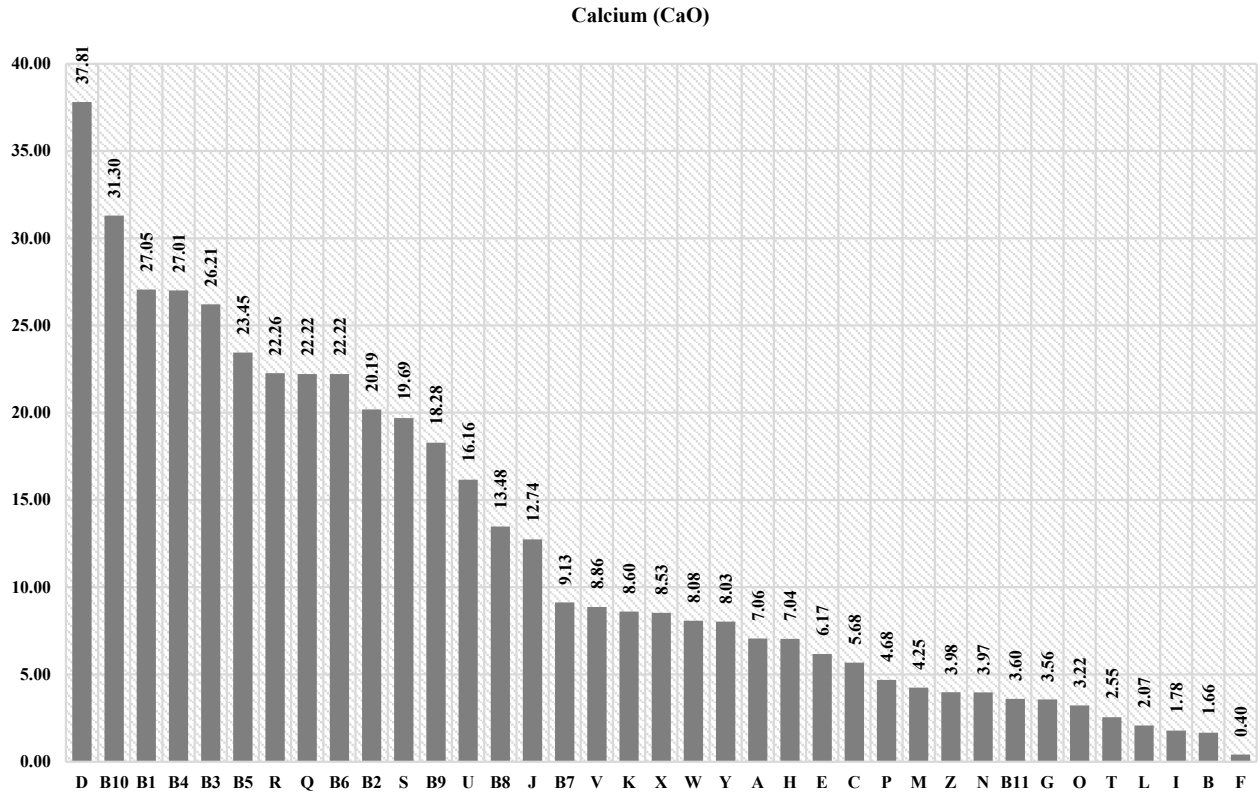


Figure 17. Calcium (%) in the treatments.

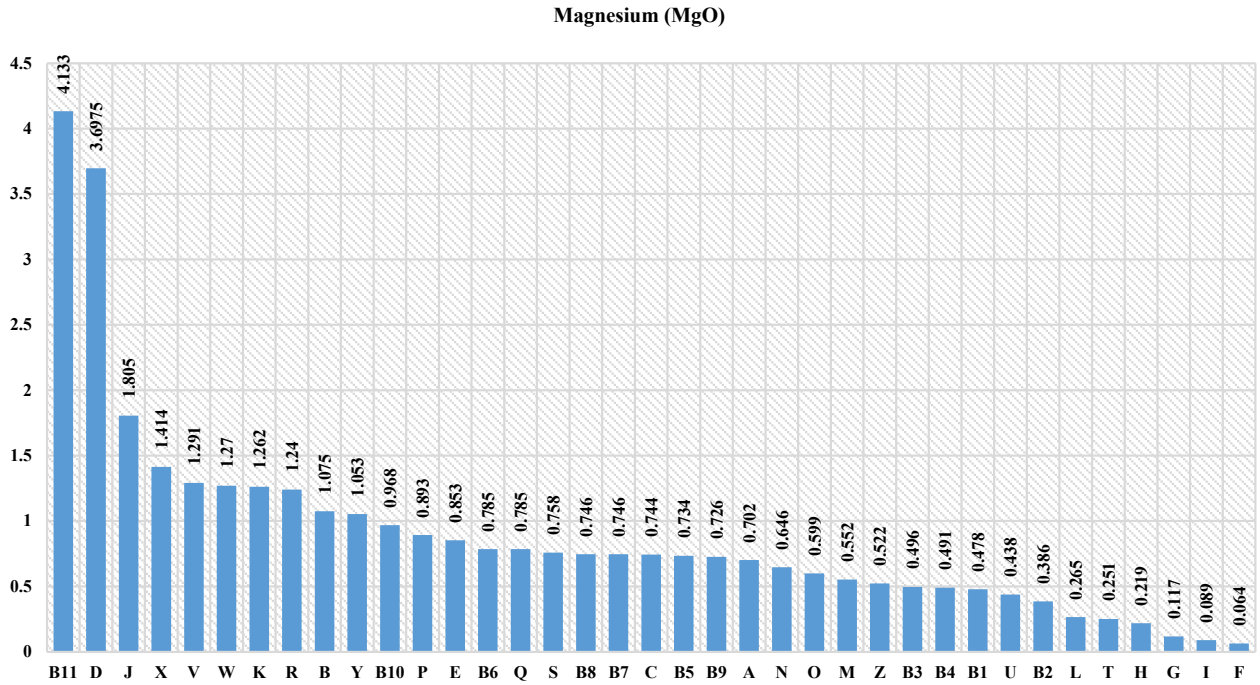


Figure 18. Magnesium (%) in the treatments.

4. Discussion

The 37 formulations exhibited marked physicochemical heterogeneity that could be organized into three exploratory functional profiles: organic nutrient-rich amendments, alkaline mineral–organic amendments, and a potassium-rich liquid formulation. Vermicompost-derived formulations generally exhibited higher organic matter and phosphorus concentrations, whereas ash- and lime-rich formulations were strongly alkaline, indicating a physicochemical profile potentially suitable for applications requiring acidity correction. The BIOL formulation represented a distinct multivariate outlier, characterized by high K_2O content and electrical conductivity. These findings support the concept of tailoring valorization pathways for sugarcane filter mud and associated agroindustrial by-products according to their physicochemical profiles. However, the agronomic suitability of candidate formulations requires independent validation, including assessment of phytotoxicity, sanitary safety, nutrient-release dynamics, crop responses, and techno-economic feasibility, before field-scale or commercial claims can be substantiated. As throughout this manuscript, these functional profiles were derived from 37 distinct, non-replicated formulations, and the statistical contrasts presented below characterize exploratory differences among formulations rather than replicated treatment effects. Analysis of the physicochemical composition of the 37 formulations revealed several distinct trends:

4.1. pH and Electrical Conductivity (EC)

Treatments based on filter mud and manure (e.g., C, D, and J, as well as the vermicompost series V–Z) exhibited pH values ranging from 6.1 to 8.4, which fall within the generally acceptable range reported for organic amendments. This pH profile is consistent with effective stabilization of organic acids during the biotransformation process, although this interpretation should be confirmed through direct monitoring of organic acid dynamics and process maturity.

Some formulations also exhibited physicochemical profiles potentially suitable for applications involving soil-acidity correction. In particular, the highly alkaline amendments in the Bokashi category, which incorporated agricultural lime and ash (Q, R, S, and

B2–B4 and B6), exhibited markedly alkaline pH values ranging from 10.7 to 12.8. Such formulations may have potential as liming amendments for strongly acidic soils; however, their direct agronomic application should be evaluated on the basis of soil buffering capacity, application rate, electrical conductivity, crop sensitivity, and nutrient balance. Their potential use as alternatives or complements to conventional liming materials therefore requires independent agronomic validation, particularly under tropical soil conditions.

Regarding electrical conductivity (EC), which provides an indirect indication of the concentration of soluble ions and salts, the vermicompost formulations exhibited EC values below 4 dS m^{-1}, whereas formulations such as S (Bokashi) and the liquid formulation B11 (BIOL) exhibited substantially higher values of 10.7 and 17.1 dS m^{-1}, respectively. The elevated EC of B11 indicates a high soluble-solute load and suggests that dilution and application-rate optimization may be necessary before foliar application or fertigation, depending on crop sensitivity and the final application concentration. Other formulations, including Q, R, X, BA, B4, and B6, also warrant caution because of their relatively high EC values. The remaining formulations exhibited EC values within the range considered appropriate for organic amendments according to the reference criteria used in this study [32].

4.2. Organic Matter (OM), Total Carbon, and the C/N Ratio

The stabilization of organic matter is a primary objective of composting and vermicomposting. In the present dataset, vermicompost formulations (e.g., U, V, X, and Y) and traditional composts (C, D, and K) exhibited relatively high organic matter (OM) contents, ranging from 50% to 68% [31]. In contrast, "Cenichaza"-type formulations (M, N, O, and P) exhibited substantially lower OM contents (3.6–14.7%) and very high ash contents (>85%). These ash-rich materials, which are widely used in sugarcane-growing regions, should therefore be regarded primarily as sources of inorganic mineral constituents rather than as organic matter–building amendments.

Regarding the carbon-to-nitrogen (C/N) ratio, vermicompost and filter mud compost formulations containing manure exhibited C/N ratios ranging from approximately 15 to 25 (e.g., C = 20.7, L = 15.3, V = 26.3, and X = 19.4). These values are generally consistent with organic materials undergoing substantial decomposition and nutrient mineralization; however, C/N alone cannot establish the absence of nitrogen immobilization or N losses following soil application. In contrast, bagasse boiler ash (B) and Pachaquil compost (H) exhibited markedly higher C/N ratios (>64), indicating a strong imbalance between carbon and nitrogen availability and suggesting a greater potential for slower decomposition and/or transient nitrogen immobilization. The B11 formulation, with a particularly high C/N ratio of 187 and a total nitrogen content of only 0.14%, was characterized by a pronounced carbon-to-nitrogen imbalance, consistent with a formulation containing a high proportion of soluble carbon relative to total nitrogen. Consequently, its agronomic potential, including the appropriate dilution and application rate, requires independent evaluation.

Overall, the C/N ratios observed in several vermicompost and compost formulations were consistent with physicochemical profiles commonly associated with relatively stabilized organic materials. Nevertheless, C/N ratio and pH should not be used as standalone indicators of compost maturity or agronomic safety. Confirmation of maturity and the absence of phytotoxic effects requires complementary assessment using established indicators, such as germination and seedling-growth assays, together with other maturity parameters where appropriate.

4.3. Macronutrient Profile (N, P, K, Ca, Mg)

Nitrogen (N). Formulations combining filter mud with manure, particularly sheep and cattle manure (e.g., C: 1.84%, K: 1.57%, and X: 1.61% N), exhibited among the highest total N concentrations and therefore represent promising sources of organic N within the formulation set. The formulations subjected to thermophilic processing followed by vermicomposting (T–Y) generally exhibited higher total N concentrations than most Bokashi formulations (B1a–B10), although exceptions were observed for B7–B9. These differences are consistent with the potential contribution of manure and biological processing to N retention; however, confirmation of N retention efficiency would require mass-balance data accounting for initial N inputs and potential gaseous and leaching losses.

Phosphorus (P_2O_5). A marked difference in total P_2O_5 concentration was observed among the formulations. Formulations C (5.72%), E (5.73%), and the vermicompost formulations V–Y (>5.2%), produced from filter mud and rice husks, exhibited substantially higher total P_2O_5 concentrations than the Bokashi formulations (<1%). These results indicate a greater concentration of total P in the vermicompost-derived formulations; however, they should not be interpreted as direct evidence of increased P bioavailability without measurements of plant-available or extractable P. The observed differences are consistent with previous reports on the transformation and recovery of P during the biological processing of agroindustrial residues [33–35].

Potassium (K_2O) and calcium (CaO). The highest total K_2O concentration was recorded in the BIOL formulation B11 (27.36%), consistent with its formulation and the potential solubilization of mineral constituents from ash in the liquid matrix. Raw bagasse boiler ash (B) also exhibited a relatively high K_2O concentration (5.64%). Thus, the physicochemical composition of B11 identifies it as a K-rich liquid formulation rather than providing direct evidence of its suitability for fertigation. Any potential fertigation application would require determination of an appropriate dilution range, assessment of crop- and soil-specific salinity tolerance, characterization of nutrient release and ionic composition, and controlled agronomic validation.

Calcium was particularly concentrated in formulations containing agricultural lime and/or boiler ash. Treatment D exhibited a high CaO concentration (37.81%), while the Bokashi formulations B1–B6 contained approximately 20–27% CaO. These compositions indicate a potentially relevant liming value for strongly acidic soils; however, their effectiveness as soil-acidity amendments should be confirmed through soil-incubation and agronomic trials that account for soil buffering capacity, application rate, and potential effects on nutrient availability.

4.4. Micronutrients and Trace Metals (Fe, Cu, Zn, Mn)

Despite the differences observed among formulations, several micronutrients were present at concentrations that fall within ranges commonly reported for organic amendments. Notable concentrations included Fe in the filter mud vermicompost formulation D (2.70%) and Mn in the bagasse-derived formulation T (0.550%). However, the present dataset does not allow these concentrations to be classified as agronomically safe or beneficial because crop-specific requirements, potential toxicity thresholds, and nutrient bioavailability were not experimentally assessed.

The measured concentrations of Fe, Cu, Zn, and Mn provide useful information on the micronutrient composition of the formulations; however, the study did not quantify potentially toxic elements (PTEs) of regulatory concern, including As, Cd, Cr, Hg, Ni, Pb, and other elements subject to applicable regulatory limits. Consequently, no conclusions regarding the overall heavy-metal or trace-element safety of the formulations can be drawn from the present dataset. Given the potential for long-term accumulation of potentially

toxic elements following repeated application of organic amendments, comprehensive elemental characterization should be considered a prerequisite for field application and commercialization of the formulations, in accordance with applicable regulatory requirements [36,37].

Overall, the physicochemical characterization of the 37 formulations revealed compositional patterns that are broadly consistent with those reported in the literature for sugar-industry by-products and their biologically transformed derivatives. The neutral-to-alkaline pH and electrical conductivity observed in the vermicompost formulations are generally comparable with ranges reported for filter mud-based organic amendments [38]. Similarly, the relatively high total P_2O_5 concentrations observed in several filter mud-derived formulations are consistent with previous reports showing that composting filter mud with manure can increase the N, P, K, and Ca content of amended sugarcane soils [39]. Previous studies have also identified phosphorus as a distinctive chemical characteristic of mill mud relative to bagasse and degraded soils [40]. In addition, the strongly alkaline composition of the Bokashi formulations suggests a potential acidity-correcting function, consistent with the use of mineral-rich organic amendments in the management of nutrient-depleted and degraded soils [41,42]. Nevertheless, these physicochemical characteristics should be interpreted as indicators of potential agronomic functionality rather than as direct evidence of fertilizer efficacy, soil restoration, or crop benefits, which require independent validation under controlled and field conditions.

4.5. Statistical Analysis of Biofertilizers Based on Filter Mud

As indicated in Section 2.6.1, each of the 37 formulations represents a single, non-replicated formulation-level case. Accordingly, the statistical analyses presented below—including descriptive statistics, ANOVA, Kruskal–Wallis, and MANOVA—are used as exploratory tools to characterize physicochemical differences and multivariate separation among the identified formulation profiles. The resulting contrasts are therefore interpreted descriptively and should not be taken as evidence of replicated treatment effects or causal relationships.

4.5.1. Descriptive Statistics and Distribution of Variables

The 37 formulations exhibited substantial physicochemical variability (Table 3). Mean moisture content was 43.1 $\pm$ 19.9%, while mean pH was slightly alkaline (8.53 $\pm$ 1.90). Across the pooled set of formulations, ash content (61.9 $\pm$ 20.5%) substantially exceeded organic matter content (37.0 $\pm$ 19.8%). The C/N ratio averaged 32.5 and exhibited pronounced positive skewness (g_1 = 4.64), largely attributable to extreme values associated with the BIOL formulation. Trace and micronutrient elements, together with mineral constituents such as K_2O and Na_2O, exhibited the highest coefficients of variation in the dataset (CV > 90%), with Zn showing the greatest relative variability (CV = 597.4%).

The Shapiro–Wilk test indicated that normality was not rejected for only four of the 17 variables (moisture, ash content, organic matter, and total carbon; $p > 0.05$), whereas the remaining 13 variables showed significant departures from normality (Table 4). These results, together with the formulation-level structure and non-replicated nature of the dataset, supported the complementary use of non-parametric procedures in the between-cluster comparisons. These procedures were applied as exploratory tools to characterize the observed physicochemical structure and differences among the formulation profiles rather than to provide confirmatory evidence of treatment effects.

Table 3. Descriptive statistics of the 17 physicochemical variables evaluated across the 37 treatments.

Variable	N	Mean	Median	S.D.	Min.	Max.	Skew.	Kurt.	CV (%)
Moisture	37	43.065	45.42	19.893	4.64	97.56	0.066	0.409	46.194
pH	37	8.532	8.24	1.9	5.43	12.87	0.736	−0.009	22.27
Electrical conductivity	37	4.021	2.75	3.568	0.306	17.1	1.631	3.621	88.739
Ashes	37	61.884	62.72	20.468	31.16	96.33	0.052	−1.194	33.075
Organic Matter	37	37.046	36.04	19.842	3.67	68.84	0.006	−1.115	53.562
Total Carbon	37	21.491	20.905	11.757	2.129	39.93	0.037	−1.198	54.706
Total Nitrogen	37	0.816	0.69	0.514	0.14	1.839	0.337	−1.242	62.985
C/N	37	32.502	26.3	28.636	8.19	187.0	4.639	24.692	88.105
Calcium (CaO)	37	11.849	8.08	10.005	0.404	37.81	0.887	−0.293	84.442
Magnesium (MgO)	37	0.9	0.744	0.831	0.064	4.133	2.753	8.693	92.307
Sodium (Na_2O)	37	0.197	0.142	0.219	0.03	1.266	3.465	15.63	111.117
Potassium (K_2O)	37	1.82	1.178	4.426	0.027	27.36	5.644	33.149	243.201
Phosphorus (P_2O_5)	37	1.987	1.358	1.929	0.001	5.726	0.893	−0.646	97.062
Iron (Fe)	37	0.391	0.252	0.484	0.027	2.696	3.282	14.116	123.798
Copper (Cu)	37	0.022	0.005	0.101	0.001	0.616	6.064	36.842	456.222
Zinc (Zn)	37	0.904	0.013	5.402	0.001	32.873	6.083	37.0	597.414
Manganese (Mn)	37	0.105	0.065	0.114	0.003	0.55	2.028	5.319	108.209

Note: S.D. = standard deviation; Skew. = skewness; Kurt. = kurtosis; CV = coefficient of variation.

Table 4. Shapiro–Wilk normality test for the 17 physicochemical variables (n = 37).

Variable	W	df	Sig.
Moisture	0.964	37	0.270
pH	0.931	37	0.024
Electrical conductivity	0.847	37	<0.001
Ashes	0.941	37	0.050
Organic Matter	0.951	37	0.100
Total Carbon	0.945	37	0.066
Total Nitrogen	0.915	37	0.008
C/N	0.491	37	<0.001
Calcium (CaO)	0.875	37	<0.001
Magnesium (MgO)	0.692	37	<0.001
Sodium (Na_2O)	0.636	37	<0.001
Potassium (K_2O)	0.306	37	<0.001
Phosphorus (P_2O_5)	0.832	37	<0.001
Iron (Fe)	0.659	37	<0.001
Copper (Cu)	0.185	37	<0.001
Zinc (Zn)	0.157	37	<0.001
Manganese (Mn)	0.782	37	<0.001

4.5.2. Exploratory Treatment Typology: Cluster Analysis

The average silhouette coefficient was maximal for a three-cluster solution (k = 3; silhouette = 0.331), which was selected as the final solution. Ward's hierarchical clustering (Figure 19) partitioned the 37 treatments into three groups of unequal size: Cluster 1 (n = 24), Cluster 2 (n = 12), and Cluster 3 (n = 1).

The clusters were interpreted as exploratory physicochemical profiles rather than as confirmatory treatment groups, and cluster membership was not considered equivalent to biological replication. Cluster 1 was characterized by the highest ash content and the lowest organic matter, total carbon, and total nitrogen contents. In contrast, Cluster 2 exhibited higher organic matter, nitrogen, and phosphorus contents, defining a comparatively nutrient- and organic-matter-rich profile. Cluster 3 comprised a single formulation and was

distinguished by extreme moisture content (97.6%), the highest C/N ratio (187), and the highest K_2O concentration (27.4%) observed across the entire formulation dataset (Table 5).

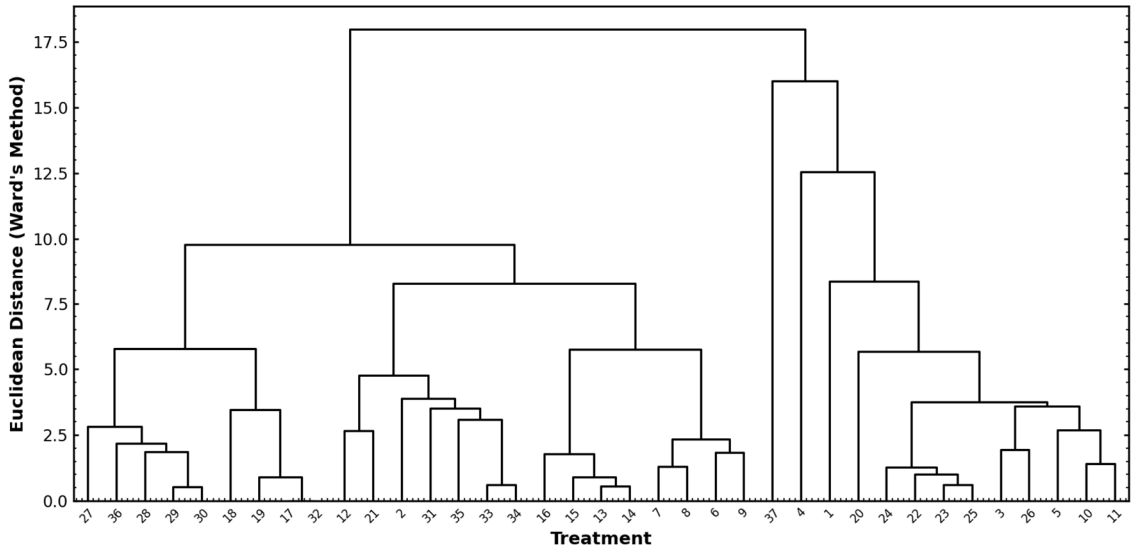


Figure 19. Hierarchical clustering dendrogram (Ward's method, Euclidean distance) of the 37 treatments based on 17 standardized physicochemical variables.

Table 5. Physicochemical profile (mean ± standard deviation) of the 17 variables by cluster.

Variable	Cluster 1 (n = 24)	Cluster 2 (n = 12)	Cluster 3 (n = 1)
Moisture	35.104 ± 17.472	54.445 ± 10.362	97.560 ± nan
pH	9.140 ± 2.053	7.382 ± 0.834	7.730 ± nan
Electrical conductivity	4.024 ± 3.314	2.925 ± 1.355	17.100 ± nan
Ashes	73.729 ± 14.376	38.781 ± 6.785	54.850 ± nan
Organic Matter	25.247 ± 13.125	59.969 ± 6.738	45.150 ± nan
Total Carbon	14.426 ± 7.614	35.231 ± 3.784	26.190 ± nan
Total Nitrogen	0.574 ± 0.381	1.355 ± 0.271	0.140 ± nan
C/N	28.793 ± 13.987	27.047 ± 6.498	187.000 ± nan
Calcium (CaO)	13.197 ± 10.460	9.840 ± 9.182	3.600 ± nan
Magnesium (MgO)	0.596 ± 0.308	1.239 ± 0.885	4.133 ± nan
Sodium (Na_2O)	0.158 ± 0.131	0.186 ± 0.117	1.266 ± nan
Potassium (K_2O)	1.093 ± 1.128	1.146 ± 0.708	27.360 ± nan
Phosphorus (P_2O_5)	0.931 ± 0.780	4.220 ± 1.686	0.538 ± nan
Iron (Fe)	0.232 ± 0.244	0.735 ± 0.670	0.071 ± nan
Copper (Cu)	0.003 ± 0.003	0.061 ± 0.175	0.004 ± nan
Zinc (Zn)	0.010 ± 0.009	2.765 ± 9.482	0.027 ± nan
Manganese (Mn)	0.063 ± 0.074	0.196 ± 0.134	0.034 ± nan

These patterns indicate pronounced physicochemical differentiation among the 37 formulations and provide a basis for exploratory classification according to their compositional profiles. The separation among the three clusters was particularly evident for four variables that capture major differences in organic matter content, mineral fraction, and carbon-to-nitrogen balance (Figure 20). Total nitrogen and organic matter exhibited distinct cluster-level patterns. Total nitrogen was highest in Cluster 2 (1.36 ± 0.08% N), intermediate in Cluster 1 (0.57 ± 0.08% N), and lowest in Cluster 3 (0.14% N). Organic matter was highest in Cluster 2 (60.0 ± 1.9%), intermediate in Cluster 3 (45.2%), and lowest in Cluster 1 (25.2 ± 2.7%). Ash content showed the opposite pattern, with the highest value in Cluster 1 (74.1 ± 3.0%) and the lowest in Cluster 2 (38.8 ± 1.9%), highlighting the contrasting mineral–organic composition of these two profiles. The C/N ratio was similar

between Clusters 1 and 2 (28.8 ± 2.9 and 27.0 ± 1.9, respectively) but was markedly higher in Cluster 3 (187.0). This extreme C/N ratio, together with its high moisture content and K_2O concentration, reflects the distinctive physicochemical composition of the single BIOL formulation relative to the predominantly solid formulations comprising Clusters 1 and 2.

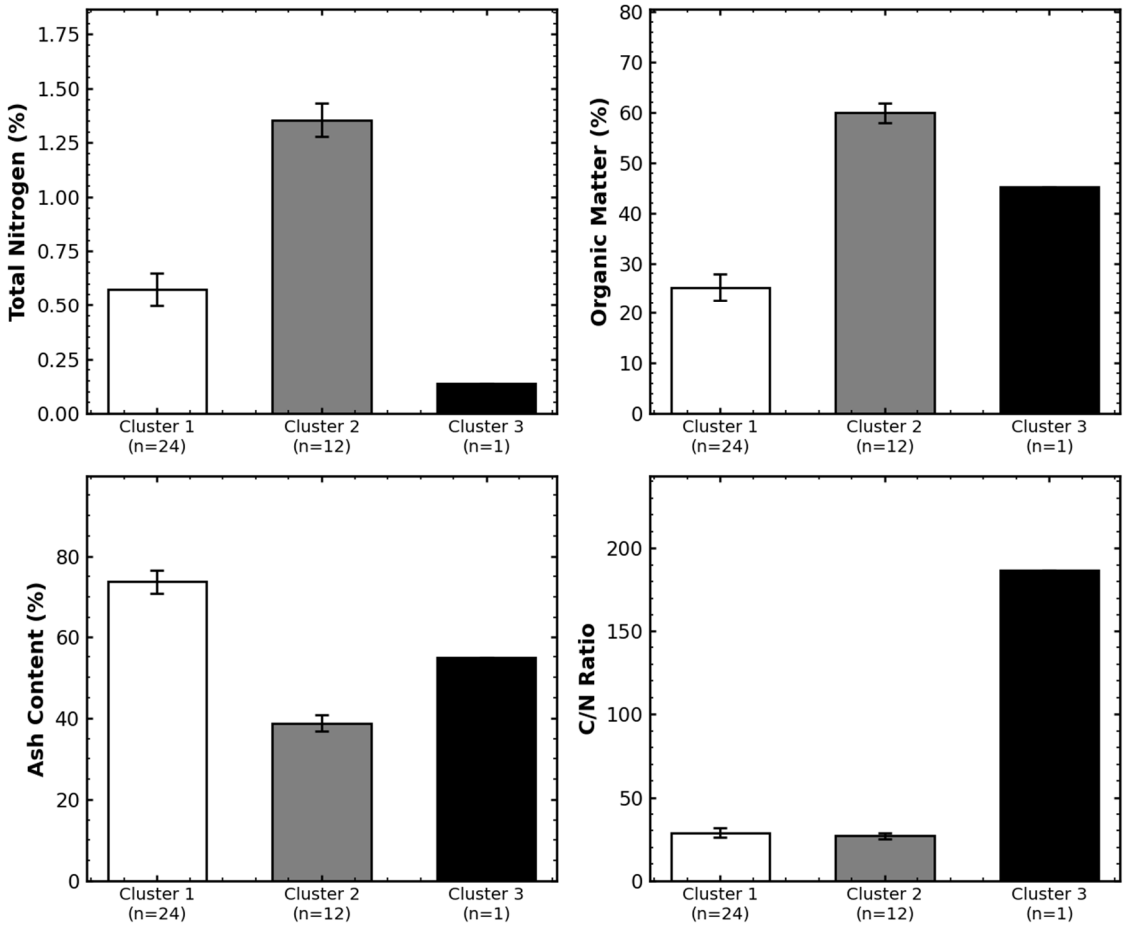


Figure 20. Variation in key physicochemical quality indicators among treatment clusters.

4.5.3. Exploratory Comparison of Cluster Profiles

Levene's test indicated significant heterogeneity of variances ($p < 0.05$) across the clusters for 10 of the 17 variables. One-way ANOVA identified nominally significant exploratory differences among clusters for 14 of the 17 variables (Table 6), while the Kruskal–Wallis test provided complementary non-parametric evidence of differences in cluster distributions. Only calcium (CaO), copper (Cu), and zinc (Zn) showed no statistically significant differences among clusters in the corresponding analyses. Given the data-driven formation of the clusters, the non-replicated formulation-level design, and the reuse of the physicochemical variables for both cluster generation and subsequent comparisons, these results are interpreted as descriptive evidence of cluster differentiation rather than as confirmatory evidence of treatment effects.

The strongest numerical separation was observed for ash content, organic matter, total carbon, total nitrogen, phosphorus, magnesium, sodium, potassium, and C/N ratio. The Kruskal–Wallis results provided complementary descriptive information regarding the relative ordering of the formulation clusters.

These ANOVA and Kruskal–Wallis results should be interpreted as quantitative descriptions of the degree of separation among data-driven physicochemical clusters, not as evidence of replicated treatment effects. Because the 37 formulations were each represented

by a single non-replicated case and the clusters were generated from the same physicochemical variables, the reported *p*-values do not establish causal effects of composting, vermicomposting, Bokashi fermentation, or any formulation.

Table 6. One-way ANOVA (factor: cluster) and Kruskal–Wallis test results for the 17 physicochemical variables.

Variable	F	df1,df2	ANOVA Sig.	H (K-W)	K-W Sig.
Moisture	12.53	2,34	<0.001	11.68	0.003
pH	4.12	2,34	0.025	7.67	0.022
Electrical conductivity	11.55	2,34	<0.001	2.88	0.237
Ashes	31.74	2,34	<0.001	22.68	<0.001
Organic Matter	37.01	2,34	<0.001	23.49	<0.001
Total Carbon	39.75	2,34	<0.001	23.80	<0.001
Total Nitrogen	21.99	2,34	<0.001	19.54	<0.001
C/N	84.10	2,34	<0.001	2.88	0.237
Calcium (CaO)	0.79	2,34	0.462	0.93	0.627
Magnesium (MgO)	22.15	2,34	<0.001	10.37	0.006
Sodium (Na_2O)	36.75	2,34	<0.001	3.51	0.173
Potassium (K_2O)	327.78	2,34	<0.001	3.19	0.203
Phosphorus (P_2O_5)	33.31	2,34	<0.001	18.13	<0.001
Iron (Fe)	5.73	2,34	0.007	13.02	0.001
Copper (Cu)	1.33	2,34	0.277	17.64	<0.001
Zinc (Zn)	1.06	2,34	0.358	13.41	0.001
Manganese (Mn)	7.64	2,34	0.002	11.17	0.004

Tukey's HSD post-hoc comparisons indicated that the predominant pairwise differences occurred between Clusters 1 and 2 for most variables exhibiting a significant omnibus ANOVA result. Cluster 3, which comprised a single formulation, showed marked differences from Clusters 1 and 2 for variables related to nitrogen, C/N ratio, and potassium. Because Cluster 3 contained only one observation, within-cluster variance and corresponding standard errors could not be estimated for this cluster using conventional methods. Accordingly, pairwise contrasts involving Cluster 3 were interpreted cautiously as exploratory indications of compositional distinctiveness rather than as statistically validated treatment differences (Figure 21).

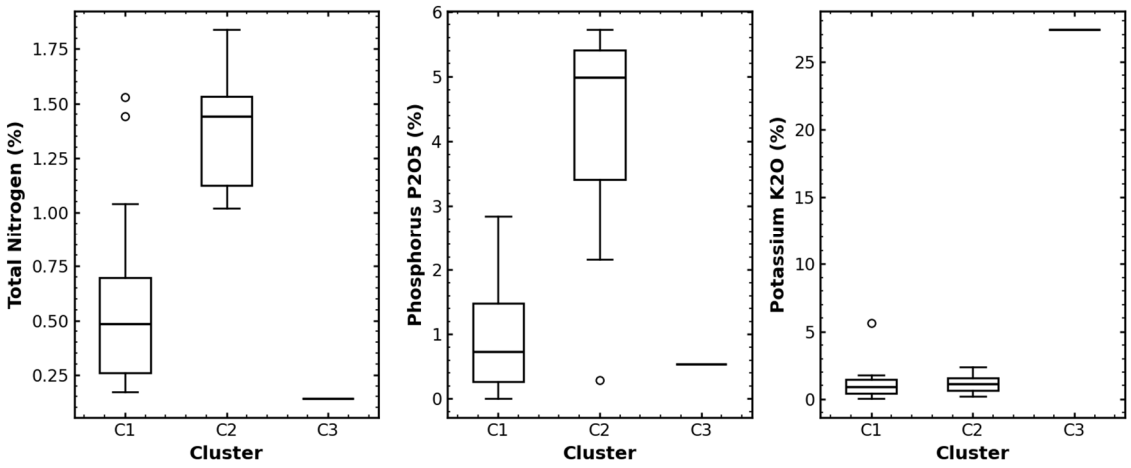


Figure 21. Distribution (box plots) of Total Nitrogen, Phosphorus (P_2O_5), and Potassium (K_2O).

Because cluster membership was derived from grouping the same 37 non-replicated formulations that were subsequently compared, the ANOVA and Kruskal–Wallis results reported above characterize exploratory physicochemical separation among clusters of

distinct formulations and should not be interpreted as evidence of replicated treatment effects. This caveat applies with particular force to Cluster 3 (n = 1): its marked descriptive separation from Clusters 1 and 2 does not allow for the estimation of within-group variance, and contrasts involving it should be interpreted as descriptive differences, not as classical statistical inference.

4.5.4. Relationships Among Variables: Correlation and Linear Regression

The Pearson correlation matrix (17 × 17 variables) revealed three prominent patterns of association among the physicochemical variables: a structural pattern involving organic matter, total carbon, and ash content; a salinity–mineral nutrient pattern involving the C/N ratio, potassium, and sodium; and a micronutrient pattern characterized primarily by the association between iron and copper (Table 7; Figure 22).

Table 7. Highest Pearson correlation coefficients (| r |) among pairs of physicochemical variables.

Variable A	Variable B	r	Sig.
Organic Matter	Total Carbon	0.982	<0.001
Ashes	Total Carbon	−0.981	<0.001
Ashes	Organic Matter	−0.975	<0.001
C/N	Potassium (K_2O)	0.914	<0.001
C/N	Sodium (Na_2O)	0.828	<0.001
Iron (Fe)	Copper (Cu)	0.817	<0.001
Ashes	Total Nitrogen	−0.814	<0.001
Sodium (Na_2O)	Potassium (K_2O)	0.793	<0.001

The multiple linear regression model for total nitrogen, as a function of organic matter and phosphorus, was statistically significant ($F(2,34) = 46.88$, $p < 0.001$) and explained 73.4% of the variance in total nitrogen (adjusted $R^2 = 71.8\%$) (Table 8). Both predictors contributed significantly and independently (VIF = 1.85 in both cases, indicating no evidence of severe collinearity; Durbin-Watson statistic = 1.710).

Table 8. Coefficients of the multiple linear regression model (dependent variable: Total Nitrogen).

Predictor	B	S.E.	Beta	t	Sig.
(Constant)	0.1240	0.0971		1.277	0.210
Organic Matter	0.0118	0.0031	0.458	3.801	<0.001
Phosphorus (P_2O_5)	0.1271	0.0321	0.477	3.964	<0.001

A significant positive linear association was observed between organic matter (OM) content and total nitrogen (N) across the 37 formulations (Figure 23). The fitted ordinary least-squares regression model was Total N = 0.0202 × OM + 0.0660 and was statistically significant ($p < 0.001$), explaining 61.1% of the observed variation in total N ($R^2 = 0.611$). The positive slope indicates that, within the observed formulation dataset, each one-percentage-point increase in OM was associated, on average, with a 0.020-percentage-point increase in total N. The dispersion of formulations around the fitted regression line was greater at intermediate OM contents (approximately 30–40%), where formulations with total N concentrations both above and below the model-predicted values were observed. This pattern suggests that, within this range, additional formulation-specific factors contribute to variation in total N that is not explained by OM alone. Given the non-replicated formulation-level design, this regression should be interpreted as an exploratory description of the observed association rather than as evidence of a causal relationship or as an externally validated predictive model.

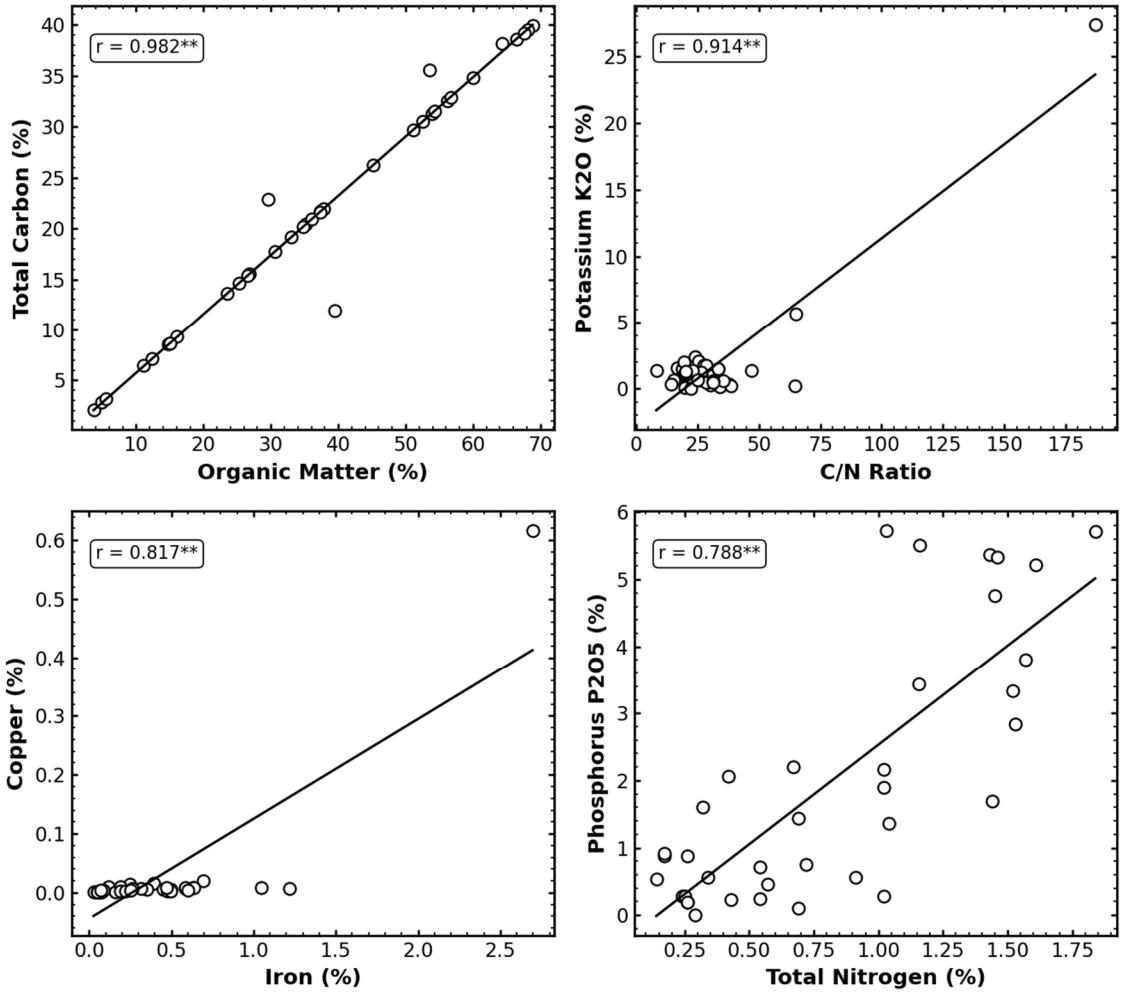


Figure 22. Scatter plots with simple linear regression lines for the variable pairs showing the highest correlations. ** $p < 0.01$.

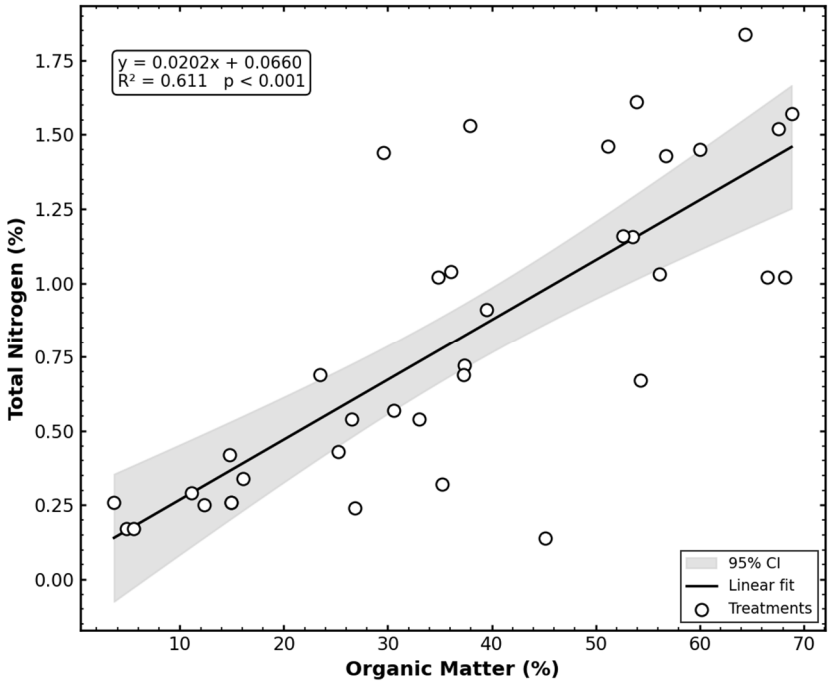


Figure 23. Simple linear regression between Organic Matter and Total Nitrogen with 95% confidence interval.

4.5.5. Multivariate Differentiation of Filter Mud-Based Formulations

The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.669, indicating a moderate level of common variance among the variables, while Bartlett's test of sphericity was significant ($\chi^2(136) = 755.9$, $p < 0.001$), indicating that the correlation matrix differed significantly from an identity matrix. Together, these results supported the use of PCA as an exploratory dimensionality-reduction approach for the observed formulation dataset. Four principal components with eigenvalues > 1 were retained according to the Kaiser criterion, jointly accounting for 79.6% of the total variance (Table 9; Figure 24). The retained solution was therefore used to summarize the major dimensions of physicochemical variation among the 37 formulations.

Table 9. Total variance explained by the principal components (initial eigenvalues and rotation sums of squared loadings after Varimax rotation).

Component	Eigenvalue	% Variance	Cumulative %
1	5.630	33.12	33.12
2	4.033	23.72	56.84
3	2.232	13.13	69.97
4	1.637	9.63	79.60
5	0.984	5.79	85.39
6	0.738	4.34	89.73
7	0.645	3.79	93.52
8	0.382	2.24	95.77
9	0.263	1.55	97.31
10	0.162	0.95	98.26
11	0.118	0.69	98.95
12	0.067	0.39	99.35
13	0.054	0.32	99.67
14	0.026	0.15	99.82
15	0.012	0.07	99.89
16	0.010	0.06	99.95
17	0.009	0.05	100.00

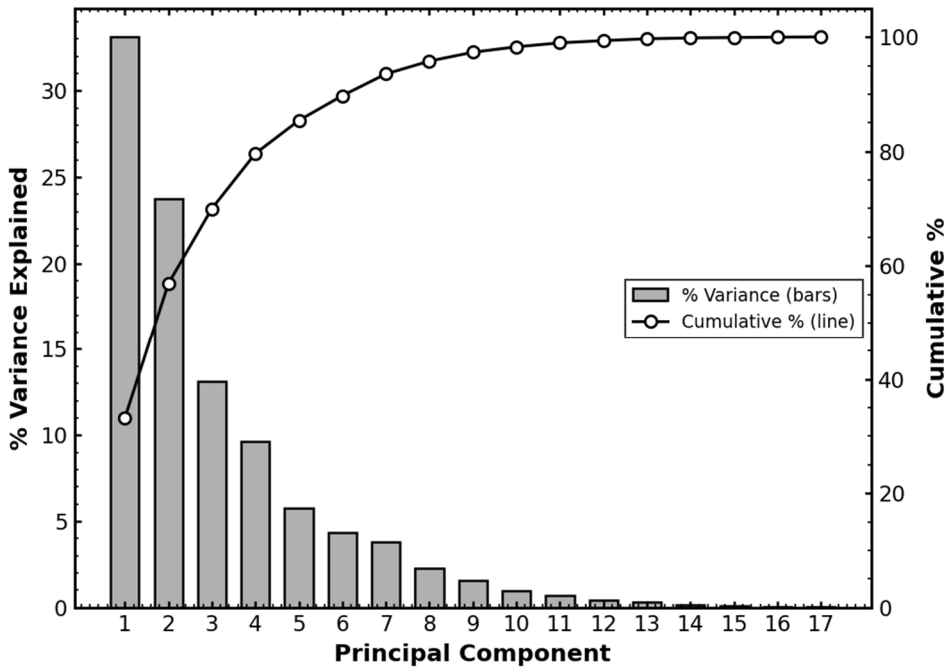


Figure 24. Scree plot (bars: % variance per component; line: cumulative %).

Following Varimax rotation, Component 1 (PC1; 29.8% of the total variance) was characterized by a strong positive loading for ash content and strong negative loadings for organic matter, total carbon, total nitrogen, and phosphorus. Component 2 (PC2; 23.3%) was primarily associated with potassium, C/N ratio, sodium, magnesium, and electrical conductivity. Component 3 (PC3; 14.2%) was characterized predominantly by copper and iron, whereas Component 4 (PC4; 12.3%) was primarily associated with calcium and pH (Table 10). Collectively, the four components accounted for 79.6% of the total variance and captured distinct dimensions of the physicochemical composition of the 37 formulations.

Table 10. Rotated component matrix (Varimax rotation with Kaiser normalization). Factor loadings of each variable on the four retained components.

Variable	1	2	3	4
Moisture	−0.593	0.441	0.094	0.048
pH	0.296	−0.012	−0.267	0.865
Electrical conductivity	0.031	0.673	−0.235	0.537
Ashes	0.927	−0.083	−0.207	0.083
Organic Matter	−0.919	0.115	0.211	−0.031
Total Carbon	−0.924	0.110	0.216	−0.089
Total Nitrogen	−0.876	−0.277	0.090	−0.107
C/N	0.032	0.956	−0.021	0.010
Calcium (CaO)	0.041	−0.082	0.366	0.872
Magnesium (MgO)	−0.258	0.735	0.503	0.181
Sodium (Na_2O)	0.077	0.872	0.101	−0.236
Potassium (K_2O)	−0.004	0.974	−0.097	−0.023
Phosphorus (P_2O_5)	−0.849	−0.124	−0.161	−0.158
Iron (Fe)	−0.364	−0.101	0.850	−0.164
Copper (Cu)	−0.070	0.052	0.971	0.106
Zinc (Zn)	−0.228	−0.036	−0.075	−0.121
Manganese (Mn)	−0.556	−0.100	−0.181	−0.316

The projection of the 37 formulations onto the first two principal components showed a clear spatial separation that was broadly consistent with the cluster structure obtained through hierarchical cluster analysis (Figure 25). Cluster 2 (gray squares) was relatively compact and was primarily located in the negative region of Component 1, with scores ranging from approximately −1.6 to −1.0, consistent with its relatively high organic matter, total nitrogen, and phosphorus contents. Cluster 1 (white circles) predominantly occupied the positive region of Component 1, with scores ranging from approximately −0.6 to 1.7, and was associated with higher ash content and a lower organic fraction. The greater dispersion of Cluster 1 compared with Cluster 2 suggests greater physicochemical heterogeneity within this formulation profile. Both clusters were centered near zero along Component 2, indicating limited differentiation between them along this axis.

In contrast, Cluster 3, represented by the single BIOL formulation (treatment 37; black triangle), was markedly separated from the remaining formulations along Component 2, with a score of approximately 5.7 compared with values ranging from −0.7 to 0.7 for the other formulations. This pronounced separation is consistent with the distinctive position of BIOL along the mineral-nutrient/salinity dimension represented by Component 2, particularly its high K_2O, Na, C/N, and electrical conductivity values. Thus, the PCA provided convergent exploratory evidence of the compositional distinctiveness of BIOL and of the contrasting organic–mineral profiles represented by Clusters 1 and 2.

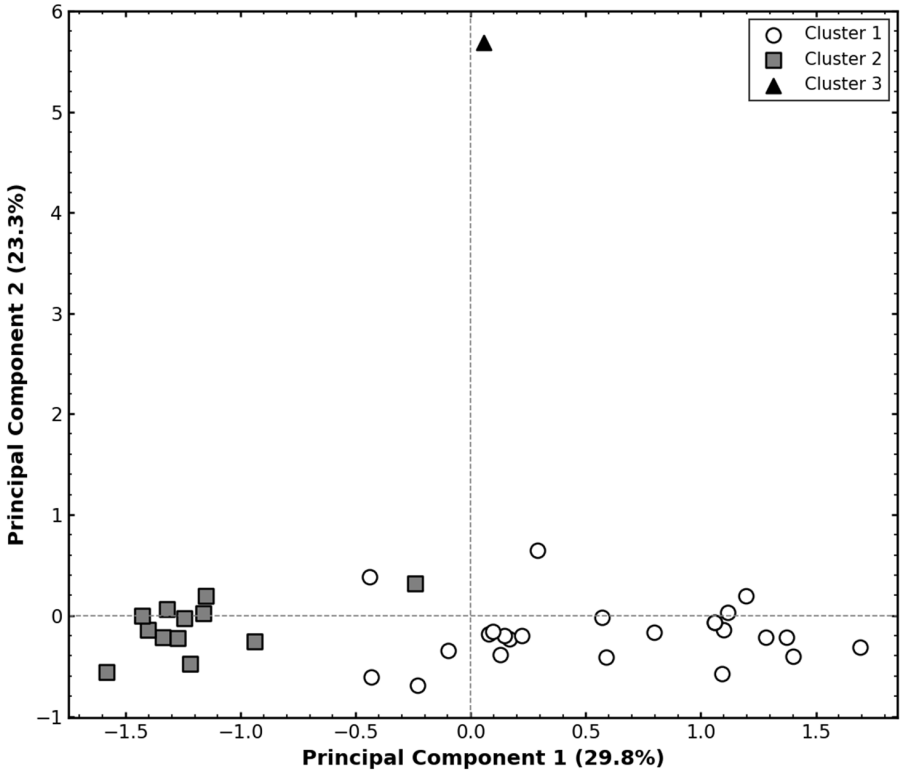


Figure 25. Scatter plot of the 37 treatments in the space of the first two principal components, differentiated by cluster (○ Cluster 1; ■ Cluster 2; ▲ Cluster 3).

4.5.6. Exploratory Statistical Validation of Multivariate Separation Among Formulation Clusters

The cluster-level MANOVA indicated statistically significant multivariate differences among the three exploratory formulation profiles based on the four retained principal component scores, according to all four multivariate test statistics evaluated (Table 11): Wilks' lambda = 0.0145 (F = 56.60, $p < 0.001$), Pillai's trace = 1.7156 (F = 48.25, $p < 0.001$), Hotelling–Lawley trace = 17.6091 (F = 66.03, $p < 0.001$), and Roy's largest root = 14.0192 (F = 112.15, $p < 0.001$). These results provide exploratory evidence of multivariate separation among the formulation profiles; however, because the clusters were derived from the same physicochemical dataset and the formulations were non-replicated, the MANOVA results should not be interpreted as confirmatory evidence of treatment effects or causal differences.

Table 11. Multivariate tests of the cluster effect on the scores of the four principal components (dependent variables).

Statistic	Value	F	Hypothesis df	Error df	Sig.
Pillai's Trace	1.7156	48.249	8.0	64.0	<0.001
Wilks' Lambda	0.0145	56.597	8	62.0	<0.001
Hotelling-Lawley Trace	17.6091	66.034	8.0	60.0	<0.001
Roy's Largest Root	14.0192	112.154	4	32	<0.001

Follow-up univariate analyses (Table 12) indicated statistically significant differences among the three exploratory clusters for Component 1 and Component 2 ($p < 0.001$ for both), whereas no statistically significant differences were detected for Component 3 ($p = 0.501$) or Component 4 ($p = 0.473$). These results suggest that the primary multivariate separation among the formulation profiles was driven predominantly by the dimensions represented by Components 1 and 2, while Components 3 and 4 contributed comparatively less to the differentiation among clusters. Given the data-driven formation of the clusters and

the non-replicated formulation-level design, these univariate results are interpreted as exploratory measures of cluster separation rather than as confirmatory treatment effects.

Table 12. Follow-up univariate effects (Type III ANOVA) of cluster membership on each principal component.

Dependent Variable	SS	df	MS	F	Sig.
CP1	25.546	2	12.773	41.541	<0.001
CP2	33.229	2	16.614	203.841	<0.001
CP3	1.433	2	0.716	0.705	0.501
CP4	1.552	2	0.776	0.766	0.473

As with the univariate ANOVA reported above, the observed multivariate separation reflects exploratory contrasts among clusters derived from the same 37 distinct, non-replicated formulations. Accordingly, these results should not be interpreted as evidence of replicated treatment effects in the classical experimental-design sense.

Overall, the study demonstrated that processing by-products from the sugar industry and other agro-industrial sources can generate organic amendment formulations with markedly divergent physicochemical profiles. This compositional heterogeneity provides a basis for identifying candidate functional profiles for subsequent agronomic validation, thereby supporting a transition from predominantly empirical use of organic amendments toward more systematic, evidence-based approaches to their characterization and valorization.

The correlation analysis revealed several strong patterns of association among the physicochemical variables. In particular, organic matter and total carbon were very strongly and positively correlated (r = 0.982), while both variables showed a strong inverse association with ash content (r = −0.975). These relationships indicate substantial compositional redundancy among these variables within the observed formulation dataset and may have implications for variable selection in subsequent analytical characterization.

The multiple linear regression model also identified a statistically significant association between total nitrogen and the combined predictors organic matter and phosphorus ($F(2,34) = 46.88$, $p < 0.001$), with the model explaining 73.4% of the observed variation in total nitrogen ($R^2 = 0.734$). Thus, within the present formulation set, organic matter and phosphorus jointly accounted for a substantial proportion of the variation in total N. This finding suggests that these variables may have potential utility as complementary indicators in preliminary physicochemical screening; however, it should not be interpreted as evidence that OM and P causally determine total N or that they can replace direct N determination. Any reduction in analytical requirements would require independent validation of the model across additional formulations and analytical datasets.

The clusters were derived from the physicochemical dataset itself, with each formulation represented by a single, non-replicated observation. Consequently, the MANOVA provides exploratory evidence of distinct physicochemical profiles within the observed formulation set, but it does not establish that the corresponding processing or formulation pathways would yield reproducibly different outcomes under independently replicated experimental conditions.

4.5.7. Interpretation of the Exploratory Statistical Framework

Taken together, the descriptive statistics, hierarchical clustering, PCA, and cluster-level ANOVA/MANOVA consistently indicate pronounced physicochemical heterogeneity among the 37 formulations. However, because each formulation was represented by a single, non-replicated case, these analyses cannot establish reproducible treatment effects or causal differences attributable to specific biological transformation pathways.

Statistical analyses are therefore best interpreted as an exploratory screening framework for identifying physicochemical contrasts and candidate formulation profiles within

the observed dataset. In particular, the differentiation among organic-matter-rich formulations, ash/lime-rich alkaline formulations, and the potassium-rich BIOL formulation provides a rational basis for selecting candidate formulations for subsequent replicated agronomic experiments.

The strong associations among organic matter, total carbon, ash, phosphorus, potassium, and nitrogen further indicate coherent physicochemical gradients across the formulation set. Nevertheless, these associations represent covariation among the observed formulations and should not be interpreted as causal relationships or as evidence that modifying one formulation component will necessarily produce a predictable change in another response variable.

The exploratory cluster-level ANOVA and MANOVA further quantified the numerical separation among the identified formulation profiles; however, their statistical significance should not be interpreted as confirmation of treatment effects. This limitation is particularly important because the clusters were derived from the same physicochemical information subsequently used to quantify their separation. Independent replication of formulations and repeated production cycles will therefore be required to determine whether the observed physicochemical profiles are reproducible and robust across batches.

Overall, the physicochemical differentiation and exploratory functional classification of the 37 filter mud-based formulations from the Córdoba–Gulf sugarcane-growing region provide a basis for prioritizing candidate formulations for subsequent agronomic, safety, and technological validation. The observed compositional patterns suggest three preliminary strategic application niches:

1. Organic nutrient-rich amendments: Worm composts based on filter mud mixed with manure (especially V, W, X, Y, and compost C). They have a neutral pH, high organic matter content, an excellent C/N ratio, and an outstandingly high total phosphorus concentration.
2. Soil Correction Amendments (Alternatives to Liming or physicochemical profile consistent with potential acidity-correcting applications amendment): Bokashi products (B1 through B6 and B10) and mixtures with ashes (Q, R, S). Due to their pH > 11 and extremely high calcium content, they should not be considered "compost" in the traditional biological context, but rather organic amendments designed to neutralize acidic tropical soils.
3. Concentrated liquid nutrient amendments (BIOL). Its low nitrogen content but extremely high potassium and soluble carbon content classify it strictly as an end-of-cycle fertilizer, always requiring prior dilution due to its high electrical conductivity. The above also applies to recovered worm leachates with the composition shown in [43,44] (Table 13).

The functional categories identified in this study represent physicochemical hypotheses regarding potential application niches and should not be interpreted as evidence of agronomic efficacy.

Table 13. Earthworm leachates.

Physicochemical Variable	Value
Moisture	98.855
pH	8.055
Electrical conductivity	8.33
Ashes	0.86
Organic Matter	0.335
Total Carbon	0.2

Table 13. *Cont.*

Physicochemical Variable	Value
Total Nitrogen	0.03
C/N	5.665
Calcium (CaO)	0.045
Magnesium (MgO)	0.07
Sodium (Na_2O)	0.075
Potassium (K_2O)	0.165
Phosphorus (P_2O_5)	0.005
Iron (Fe)	0.385
Copper (Cu)	0
Zinc (Zn)	0.01
Manganese (Mn)	0.765

5. Limitations of the Study

Despite its contributions, this study has several limitations that should be acknowledged. First, the principal statistical limitation is the absence of true biological or production-level replication. The 37 formulations represent 37 distinct, non-replicated formulation-level cases and should not be regarded as replicated observations of a common treatment. Consequently, the present dataset does not permit reliable estimation of within-formulation variance, batch-to-batch reproducibility, or uncertainty associated with reproducible treatment effects. The cluster-level ANOVA, Kruskal–Wallis, and MANOVA analyses were therefore used exclusively to characterize the exploratory separation of physicochemical profiles among the observed formulations. Their statistical significance should not be interpreted as evidence of replicated treatment effects, causal effects attributable to specific processing technologies, or generalizable superiority of one formulation class over another.

Furthermore, because the clusters were derived from the same physicochemical variables subsequently used in the between-cluster comparisons, the resulting statistical contrasts are subject to an inherent data-reuse limitation. Accordingly, the associated *p*-values should be regarded as exploratory and hypothesis-generating rather than confirmatory. Independent production batches, biological replication, and repeated experimental cycles will be required to determine whether the physicochemical differences identified here are reproducible and can be attributed to specific formulation or processing factors.

Second, the study was restricted to the physicochemical characterization of the resulting formulations and did not include phytotoxicity bioassays, seed germination index (GI) tests, or pot and field trials with sugarcane or other crops. Consequently, the agronomic performance suggested by physicochemical indicators such as C/N ratio, pH, electrical conductivity, and macronutrient content could not be experimentally validated [45,46]. In particular, the absence of a biological germination assay represents an important limitation because physicochemical indicators, although useful for characterizing stabilization and compositional status, are insufficient on their own to rule out phytotoxicity or establish agronomic maturity. Therefore, the current evidence supports only a physicochemical assessment of the candidate formulations, and their biological safety and agronomic effectiveness remain to be experimentally established. Future germination, phytotoxicity, greenhouse, and field studies will be necessary to determine their safe application rates and agronomic performance.

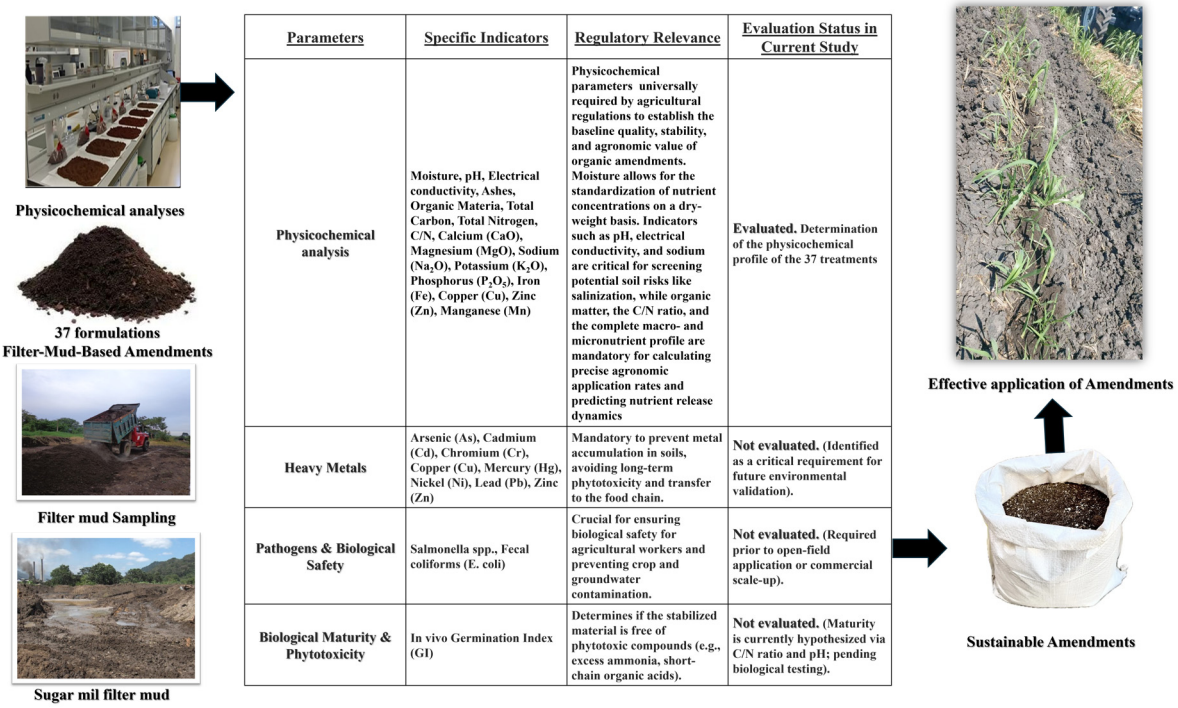
Third, sanitary safety was not quantitatively assessed. Regulated potentially toxic elements, including Pb, Cd, Cr, Hg, and As, as well as relevant microbiological indicators such as fecal *Coliforms* and *Salmonella* spp., were not systematically quantified. Consequently, the

present study does not provide sufficient evidence to establish compliance with applicable regulatory requirements for agricultural use or commercialization. Before field application or commercialization, these parameters should be quantitatively determined and evaluated against the regulatory limits applicable to the intended product category and jurisdiction.

Fourth, the study did not include a techno-economic assessment or a life-cycle assessment (LCA) to quantify economic feasibility, resource efficiency, or potential environmental impacts. Therefore, the relative attractiveness of the different formulation and processing routes for implementation at sugar-mill scale cannot yet be objectively ranked beyond the qualitative considerations presented in the Discussion. Future studies integrating process economics, energy and material balances, greenhouse-gas emissions, and other relevant environmental indicators would provide a stronger basis for technology selection and scale-up.

Fifth, the raw materials were collected during a single harvest season (2024–2025) from sugar mills located within one production region (Córdoba–Gulf, Veracruz, Mexico). Because filter mud composition can vary according to sugarcane variety, soil characteristics, processing conditions, and mill-specific practices, the physicochemical profiles identified in this study may not be fully transferable across seasons, mills, or sugarcane-growing regions. Multi-season and multi-site sampling, together with independent production batches, will therefore be necessary to evaluate the robustness and external validity of the proposed formulation profiles.

Finally, post-application behavior of the formulations in soil was not evaluated. In particular, nutrient-release kinetics, mineralization dynamics, changes in soil pH, and persistence of potential acidity-correcting effects remain unknown. These parameters are essential for establishing agronomically appropriate application rates, timing, and frequency under realistic field conditions. Accordingly, soil-incubation, greenhouse, and field experiments are required to determine the short- and long-term behavior of the candidate formulations and to support evidence-based recommendations for their agricultural use (Figure 26).



Parameters	Specific Indicators	Regulatory Relevance	Evaluation Status in Current Study
Physicochemical analysis	Moisture, pH, Electrical conductivity, Ashes, Organic Materia, Total Carbon, Total Nitrogen, C/N, Calcium (CaO), Magnesium (MgO), Sodium (Na_2O), Potassium (K_2O), Phosphorus (P_2O_5), Iron (Fe), Copper (Cu), Zinc (Zn), Manganese (Mn)	Physicochemical parameters universally required by agricultural regulations to establish the baseline quality, stability, and agronomic value of organic amendments. Moisture allows for the standardization of nutrient concentrations on a dry-weight basis. Indicators such as pH, electrical conductivity, and sodium are critical for screening potential soil risks like salinization, while organic matter, the C/N ratio, and the complete macro- and micronutrient profile are mandatory for calculating precise agronomic application rates and predicting nutrient release dynamics	**Evaluated.** Determination of the physicochemical profile of the 37 treatments
Heavy Metals	Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), Zinc (Zn)	Mandatory to prevent metal accumulation in soils, avoiding long-term phytotoxicity and transfer to the food chain.	**Not evaluated.** (Identified as a critical requirement for future environmental validation).
Pathogens & Biological Safety	Salmonella spp., Fecal coliforms (E. coli)	Crucial for ensuring biological safety for agricultural workers and preventing crop and groundwater contamination.	**Not evaluated.** (Required prior to open-field application or commercial scale-up).
Biological Maturity & Phytotoxicity	In vivo Germination Index (GI)	Determines if the stabilized material is free of phytotoxic compounds (e.g., excess ammonia, short-chain organic acids).	**Not evaluated.** (Maturity is currently hypothesized via C/N ratio and pH; pending biological testing).

Figure 26. Normative safety and maturity parameters required for agronomic certification of organic amendments from filter mud.

6. Future Research Directions

Building on the gaps identified above, future research should prioritize: (i) phytotoxicity and seed-germination bioassays, together with greenhouse, pot, and field trials involving sugarcane and other tropical crops, to experimentally evaluate the agronomic performance and application safety of the candidate formulations identified through physicochemical screening; (ii) quantitative assessment of regulated potentially toxic elements and relevant microbiological indicators in the most promising formulations (e.g., vermicomposts V–Z, Bokashis B1–B6, and BIOL B11) to assess their suitability for regulatory compliance and potential commercialization; and (iii) development of predictive multivariate or machine-learning models linking initial mixture proportions (filter mud:manure:biomass) with the resulting physicochemical profiles. After independent validation across formulations and production batches, such models could help prioritize analytical characterization and reduce unnecessary testing of formulations with predictable compositional profiles.

Additional priorities include replicating the physicochemical characterization across multiple harvest seasons, sugar mills, and production regions to assess the robustness, reproducibility, and transferability of the formulation profiles identified in this study. Techno-economic and life-cycle assessments should also be conducted to compare production costs, resource requirements, potential substitution of synthetic fertilizers, and environmental impacts, including greenhouse-gas emissions, across the proposed biotechnological pathways. Further research should characterize nutrient-release kinetics, mineralization dynamics, and the persistence of pH-modifying effects following soil application to establish evidence-based application rates and schedules. Finally, pilot-scale implementation at sugar-mill level should evaluate the technical, logistical, and economic feasibility of segmenting production into differentiated processing lines, including a nutrient-rich organic-amendment line and an alkaline mineral–organic amendment line, under real operating conditions [47–49].

7. Conclusions

This study establishes an exploratory physicochemical framework for differentiating 37 filter mud-based formulations derived from sugarcane agro-industrial residues. The marked variability in pH, electrical conductivity, organic matter, C/N ratio, and macro- and micronutrient composition enabled the identification of distinct formulation profiles. Three preliminary candidate application niches emerged from their physicochemical characteristics: (i) organic nutrient-rich amendments, particularly vermicompost-derived formulations; (ii) alkaline mineral–organic amendments with potential acidity-correcting functionality; and (iii) a potassium-rich liquid formulation represented by BIOL B11. Rather than demonstrating agronomic or commercial performance, these findings provide a basis for prioritizing candidate formulations for subsequent validation. The most promising profiles should therefore undergo systematic assessment of phytotoxicity and maturity, potentially toxic elements and relevant pathogens, salinity, nutrient-release dynamics, and agronomic performance through controlled greenhouse and field trials, complemented where appropriate by techno-economic and life-cycle assessments before field-scale deployment or commercialization is considered.

The cluster-level ANOVA, Kruskal–Wallis, and MANOVA analyses were used exclusively to quantify the exploratory separation of physicochemical profiles among the observed formulations. Their statistical significance should not be interpreted as evidence of replicated treatment effects, causal effects attributable to specific processing technologies, or generalizable superiority of one formulation class over another. Furthermore, because the clusters were derived from the same physicochemical variables subsequently used in the between-cluster comparisons, the resulting statistical contrasts and p-values should be

regarded as exploratory and hypothesis-generating rather than confirmatory. Independent production batches and replicated experimental designs will be required to determine whether the physicochemical differences identified here are reproducible and attributable to specific formulation or processing factors.

Taken together, the results suggest that there is no single optimal valorization route for filter mud and associated sugarcane agro-industrial by-products. Rather, the observed physicochemical heterogeneity supports a cascade-valorization framework in which formulations are differentiated according to their compositional characteristics and subsequently matched to candidate functional uses, subject to independent agronomic, safety, and technological validation.

The vermicompost formulations based on filter mud and manure (e.g., profiles V–Z) exhibited physicochemical characteristics consistent with candidate organic nutrient amendments, particularly because of their relatively high organic matter, nitrogen, and phosphorus contents. These profiles warrant further investigation as potential soil amendments for tropical agricultural systems. However, claims regarding improved nutrient availability, soil restoration, or plant performance require direct biological and agronomic validation, including germination, greenhouse, and field experiments.

Bokashi-type formulations supplemented with agricultural lime and ash (e.g., B1–B6) were characterized by high alkalinity and calcium content. Their physicochemical profiles therefore suggest potential use as acidity-correcting mineral–organic amendments rather than as conventional nutrient-oriented organic fertilizers. This represents a potentially relevant circular-economy pathway for partially substituting conventional liming materials; however, their effectiveness, appropriate application rates, effects on nutrient availability, and long-term influence on soil pH must be established experimentally before agronomic recommendations can be made.

From a bioeconomy perspective, the differentiated valorization of filter mud and other sugarcane-processing by-products could contribute to diversifying sugar-mill product portfolios and creating additional value chains from materials that are currently treated primarily as residual streams. BIOL B11, characterized by a high K_2O concentration and elevated electrical conductivity, represents a distinct candidate liquid formulation. However, its suitability as a biostimulant, fertigation input, or foliar product cannot be inferred from its physicochemical composition alone. Before such applications are considered, appropriate dilution ranges, salinity tolerance, nutrient-release behavior, phytotoxicity, crop response, and regulatory compliance should be systematically evaluated.

From an operational perspective, the results suggest that sugar mills may benefit from moving away from undifferentiated mixing of heterogeneous by-products toward differentiated processing streams based on the intended physicochemical functionality of the resulting formulations. A preliminary two-line production concept could comprise: (i) an organic amendment line based on filter mud, bagasse or sugarcane residues, and locally available manure, targeting nutrient- and organic-matter-rich formulations; and (ii) an alkaline mineral–organic line incorporating ash and agricultural lime, targeting acidity-correcting formulations. The feasibility of such segmentation, including its logistical, economic, environmental, and regulatory implications, remains to be demonstrated at pilot and mill scale.

Overall, the findings demonstrate the value of physicochemical characterization combined with exploratory multivariate screening for differentiating heterogeneous filter mud-based formulations and identifying candidate functional profiles for cascade valorization. The proposed framework provides a rational basis for prioritizing formulations and designing subsequent validation studies, while avoiding premature agronomic or commercial claims. Its principal contribution is therefore not the demonstration of finished biofertilizer

products, but the establishment of an evidence-based screening approach that can support the development, validation, and scale-up of differentiated amendment formulations from sugarcane agro-industrial by-products.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript/study, the author did not use AI. The author has reviewed and edited the output and takes full responsibility for the content of this publication.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CONADESUCA	Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar

References

1. Clemente-Suárez, V.J.; Beltrán-Velasco, A.I.; Redondo-Flórez, L.; Martín-Rodríguez, A.; Tornero-Aguilera, J.F. Global impacts of western diet and its effects on metabolism and health: A narrative review. *Nutrients* **2023**, *15*, 2749. [CrossRef] [PubMed]
2. Chen, Z.; Wei, C.; Lamballais, S.; Wang, K.; Mou, Y.; Xiao, Y.; Zhou, S. Artificially sweetened beverage consumption and all-cause and cause-specific mortality: An updated systematic review and dose-response meta-analysis of prospective cohort studies. *Nutr. J.* **2024**, *23*, 86. [CrossRef] [PubMed]
3. Aita, G.; Bhatnagar, D.; Bruni, G.O.; Deliberto, M.; Eggleston, G.; Finger, A.; White, P.M., Jr. Creating a bio-based circular economy from Louisiana sugarcane byproducts. *Agric. Environ. Lett.* **2024**, *9*, e20140. [CrossRef]
4. Nisnik, M.; Fishman, T.; Makov, T.; Russell, J.D.; Ortez, M.A.; Shepon, A. Global flows, losses, and circularity of sugar from cultivation to end users. *Resour. Conserv. Recycl.* **2026**, *233*, 109000. [CrossRef]
5. Bano, S.; Singh, K.; Chaudhary, A.; Purchase, D.; Chandra, R. Physicochemical and microbial analysis of sugarcane press mud reveals ligninolytic and plant growth-promoting bacteria with soil amendment potential. *World J. Microbiol. Biotechnol.* **2026**, *42*, 61. [CrossRef] [PubMed]
6. Mohan, S.; Chithra, L.; Nageswari, R.; Selvi, V.M.; Mathialagan, M. Sugarcane Wax—A Par Excellent by-Product of Sugar Industry—A Review. *Agric. Rev.* **2021**, *42*, 315–321. [CrossRef]
7. Gupta, N.; Tripathi, S.; Balomajumder, C. Characterization of pressmud: A sugar industry waste. *Fuel* **2011**, *90*, 389–394. [CrossRef]
8. Mohamad, M.; Osman, N.H.; Rahim, M.K.I.A.; Abustan, I.; A Zainol, M.R.R.M.; Samuding, K.; Zakaria, S.N.F.; Abu, F. Suitability of pressmud as an adsorption material in wastewater treatment and as a booster in soil fertility and productivity. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2023; Volume 1143, p. 012001. [CrossRef]
9. Abubakar, A.Y.; Ibrahim, M.M.; Zhang, C.; Tayyab, M.; Fallah, N.; Yang, Z.; Pang, Z.; Zhang, H. Filtered mud improves sugarcane growth and modifies the functional abundance and structure of soil microbial populations. *PeerJ* **2022**, *10*, e12753. [CrossRef] [PubMed]
10. Bridhikitti, A.; Kaewsuk, J.; Karaket, N.; Friend, R.; Sallach, B.; Chong, J.P.; Redeker, K.R. Balancing agriculture and industry through waste utilization for sugarcane sustainability. *Sustainability* **2023**, *15*, 14711. [CrossRef]
11. Uchimiya, M.; Hay, A.G.; LeBlanc, J. Chemical and microbial characterization of sugarcane mill mud for soil applications. *PLoS ONE* **2022**, *17*, e0272013. [CrossRef] [PubMed]
12. Asava, S.; Sharma, D.; Parab, C.; Nema, A.; Donzo, O.L.; Kumar, A.; Yadav, K.D. Exploring sustainable waste solutions: Evaluating mixing ratios in agitated pile composting with sugarcane agro-industrial waste. *Pollution* **2025**, *11*, 117–133. [CrossRef]
13. Soares, A.D.A.V.L.; Prado, R.D.M.; Bertani, R.M.D.A.; da Silva, A.P.R.; Deus, A.C.F.; Kano, C.; Furlaneto, F.D.P.B. Contribution of using filter cake and vinasse as a source of nutrients for sustainable agriculture—A review. *Sustainability* **2024**, *16*, 5411. [CrossRef]
14. Khaliq, A.; Hashim, S.; Ali, Z. Composting dynamics under different compost pile recipes and turning mechanisms: A comparative study. *J. Mater. Cycles Waste Manag.* **2026**, *28*, 3190–3206. [CrossRef]
15. Pinheiro Junior, C.R.; Carvalho, J.L.N.; Canisares, L.P.; Bordonal, R.D.O.; Cerri, C.E.P.; Cherubin, M.R. Bioenergy Production from Sugarcane Straw: Implications for Soil-Related Ecosystem Services. *GCB Bioenergy* **2025**, *17*, e70032. [CrossRef]
16. Chakraborty, T.; Akhtar, N. Biofertilizers: Characteristic features and applications. In *Biofertilizers: Study and Impact*; Wiley Online Library: Hoboken, NJ, USA, 2021; pp. 429–489. [CrossRef]

17. Johnson Jeyaraj, N.; Sankararajan, V. Sustainable utilization of solid waste byproducts in agricultural amendments as soil conditioner: A state-of-the-art review. *Int. Rev. Appl. Sci. Eng.* **2025**, *16*, 155–168. [CrossRef]
18. Stephen, G.S.; Shitindi, M.J.; Bura, M.D.; Kahangwa, C.A.; Nassary, E.K. Harnessing the potential of sugarcane-based liquid byproducts—molasses and spentwash (vinasse) for enhanced soil health and environmental quality. A systematic review. *Front. Agron.* **2024**, *6*, 1358076. [CrossRef]
19. Quiroz, M.; Céspedes, C. Bokashi as an Amendment and Source of Nitrogen in Sustainable Agricultural Systems: A Review. *J. Soil Sci. Plant Nutr.* **2019**, *19*, 237–248. [CrossRef]
20. NOM-021-RECNAT-2000. Que establece las Especificaciones de Fertilidad, Salinidad y Clasificación de Suelos. Diario Oficial de la Federación DOF: 31/12/2002. Estados Unidos Mexicanos. Secretaría de Medio Ambiente y Recursos Naturales. Available online: https://www.ordenjuridico.gob.mx/Documentos/Federal/wo69255.pdf (accessed on 25 June 2026).
21. NMX-FF-109-SCFI-2008. Humus de Lombriz (Lombricomposta)-Especificaciones y Métodos de Prueba. DOF: 10/06/2008. Estados Unidos Mexicanos. Secretaría de Economía. Available online: https://platiica.economia.gob.mx/normalizacion/nmx-ff-109-scfi-2008/ (accessed on 25 June 2026).
22. Zhang, C.; Zhang, X.; Zhao, N. Shifts in Soil Nutrient Availability and C: N: P Stoichiometry During Long-Term Vegetation Restoration in Mu Us Sandy Land. *Agronomy* **2026**, *16*, 815. [CrossRef]
23. Hernandez-Sánchez, U.A.; Meléndez-Armenta, R.Á.; González-Moreno, H.R.; López-Méndez, M.C.; Rico-Barragán, A.A. Impacts of sugarcane industry on air quality and public health in a rural area of Atoyac, México. *Urban Clim.* **2025**, *64*, 102700. [CrossRef]
24. Sandoval-Romero, F.; Cuevas-Alvarado, C.M.; Montiel-Batalla, B.M.; Altamirano-Cárdenas, J.R. Evaluación del rendimiento agroindustrial del azúcar de los ingenios azucareros de México. *Rev. Mex. Cienc. Agrícolas* **2025**, *16*, e3735. [CrossRef]
25. Cebada-Merino, M.; Crescencio-Andrade, Y.; Serna-Lagunes, R.; Del Rosario-Arellano, J.L.; Andrés-Meza, P.; Presa-Parra, E.; Hernández-Salinas, G.; Díaz-José, J.; Leyva-Ovalle, O.R. Soil characteristics modeling of a sugarcane plantation in Veracruz, Mexico. *Rev. Geogr. Agrícola* **2023**, *72*, 1–18. [CrossRef]
26. García-Hernández, M.I.; Morales-Pablo, R.; Guízar-Serrano, V.; Sandoval-Romero, F. Unified analysis of the technical efficiency of sugar production in Mexico. *Rev. Mex. Cienc. Agrícolas* **2026**, *17*, e3958. [CrossRef]
27. Lima, I.M.; Beacorn, J.A. Targeting a sustainable sugar crops processing industry: A review (Part II): Reuse and conversion technologies. *Sugar Tech* **2022**, *24*, 1010–1028. [CrossRef]
28. Singh, P.; Kumar, P.; Singh, M.; Kumar, K.; Awasthi, S. Utilization of sugarcane and sugar industry wastes for sustainable sugarcane production and post-harvest quality management. *Sugar Tech* **2025**, *27*, 1430–1443. [CrossRef]
29. da Silva, J.H.B.; Mielezrski, F.; da Silva, J.F.; da Silva, L.D.R.; de Lima Cruz, J.M.F.; de Oliveira Santos, J.P.; de Andrade, F.H.A.; da Silva, J.S.L.; de Lima Farias Silva, M.; Targino, V.A.; et al. Use of Enriched Filter Cake and its Residual Effect on Sugarcane. *J. Soil Sci. Plant Nutr.* **2026**, *26*, 4739–4754. [CrossRef]
30. Dotaniya, M.L.; Datta, S.C.; Biswas, D.R.; Dotaniya, C.K.; Meena, B.L.; Rajendiran, S.; Regar, K.L.; Lata, M. Use of sugarcane industrial by-products for improving sugarcane productivity and soil health. *Int. J. Recycl. Org. Waste Agric.* **2016**, *5*, 185–194. [CrossRef]
31. Silva, J.H.B.; Almeida, L.J.M.; Silva, A.V.; Araújo, J.R.E.S.; Santos, J.P.O.; Silva, A.J.; Silva, C.M.; Targino, V.A.; Santos, S.C.S.; Pessoa, R.M.S.; et al. Filter cake increases sugarcane yield. *Braz. J. Biol.* **2023**, *83*, e273414. [CrossRef] [PubMed]
32. Yeater, K.M.; Duke, S.E.; Riedell, W.E. Multivariate Analysis: Greater Insights into Complex Systems. *Agron. J.* **2015**, *107*, 799–810. [CrossRef]
33. Klinsukon, C.; Boonlue, S.; Juntahum, S.; Laloon, K. Valorization of Sugar Industry Waste into Pelletized Soil Amendments for Enhanced Plant Growth and Soil Improvement. *Results Eng.* **2025**, *28*, 107068. [CrossRef]
34. Mohamad, M.; Osman, N.H.; Abdul Rahim, M.K.I.; Abustan, I.; Mohd Arif Zainol, M.R.R.; Samuding, K.; Zakaria, S.N.F.; Abu, F. Potentiality of Pressmud as an Additional Material in Soil Amendments to Enhance Soil Fertility and Strength Ability. *Key Eng. Mater.* **2022**, *938*, 189–200. [CrossRef]
35. Singh, S.P.; Jawaid, M.; Chandrasekar, M.; Senthilkumar, K.; Yadav, B.; Saba, N.; Siengchin, S. Sugarcane wastes into commercial products: Processing methods, production optimization and challenges. *J. Clean. Prod.* **2021**, *328*, 129453. [CrossRef]
36. Tumbure, A.; Pisa, C.; Muchaonyerwa, P. Co-application of vermicompost with other amendments for the improvement of infertile/degraded soils. In *Vermicomposting for Sustainable Food Systems in Africa*; Springer Nature: Singapore, 2023; pp. 227–247. [CrossRef]
37. Manyanga, M.A.; Marumure, J.; Chigede, N.; Mubvuma, M.; Mudzengi, C.P.; Nyambiya, I.; Muteveri, M. Vermicomposting for improved soil health: Prospects for degraded soils. In *The Marginal Soils of Africa: Rethinking Uses, Management and Reclamation*; Springer Nature: Cham, Switzerland, 2024; pp. 325–337. [CrossRef]
38. Moussa, A.W.N.; Sawadogo, B.; Konate, Y.; Heran, M. Critical state of the art of sugarcane industry wastewater treatment technologies and perspectives for sustainability. *Membranes* **2023**, *13*, 709. [CrossRef] [PubMed]

39. Yadav, S.; Singh, A.; Srivastava, P.K.; Choubey, A.K. Optimizing growth performance of *Abelmoschus esculentus* (L.) via synergistic effects of biogenic Cu/Ni/Co oxide nanoparticles in conjunction with rice straw and pressmud-based vermicompost. *Pedosphere* **2025**, *in press*. [CrossRef]
40. Liu, X.; Rashti, M.R.; Dougall, A.; Esfandbod, M.; Van Zwieten, L.; Chen, C. Subsoil application of compost improved sugarcane yield through enhanced supply and cycling of soil labile organic carbon and nitrogen in an acidic soil at tropical Australia. *Soil Tillage Res.* **2018**, *180*, 73–81. [CrossRef]
41. Fatimah, I.; Fadillah, G.; Julianto, T.S.; Syahputra, R.; Hidayat, H. Biofertilizer and Other Chemical Substitutes from Sugarcane By-products. In *Chemical Substitutes from Agricultural and Industrial By-Products: Bioconversion, Bioprocessing, and Biorefining*; Wiley Online Library: Hoboken, NJ, USA, 2024; pp. 213–234.
42. Boechat, C.L.; Santos, J.A.G.; Accioly, A.M.D.A. Net mineralization nitrogen and soil chemical changes with application of organic wastes with 'Fermented Bokashi Compost. *Acta Sci. Agron.* **2013**, *35*, 257–264. [CrossRef]
43. González-Rodríguez, G.; Preciado-Rangel, P.; Lizárraga-Bernal, C.G.; Espinosa-Palomeque, B. Análisis bibliométrico de la literatura científica sobre el abono orgánico Bokashi: Alternativa en la agricultura sostenible: Abono orgánico Bokashi: En la agricultura sostenible. *Biotecnia* **2023**, *25*, 181–193. [CrossRef]
44. Moreno-Robles, A.; Souza-Alonso, P.; Silva-Abilleira, D.; Martín, S.G.; Crecente, R.P.; García, J.B.; Herrero-Latorre, C. Beyond heavy metals: Integrating safety and agronomic performance in the classification of organic amendments. *J. Clean. Prod.* **2026**, *567*, 148598. [CrossRef]
45. Gutiérrez-Miceli, F.A.; García-Gómez, R.C.; Oliva-Llaven, M.A.; Montes-Molina, J.A.; Dendooven, L. Vermicomposting leachate as liquid fertilizer for the cultivation of sugarcane (*Saccharum* sp.). *J. Plant Nutr.* **2017**, *40*, 40–49. [CrossRef]
46. Carbajal-Rocha, V.; Domínguez-Hernández, A.; Campuzano-Cruz, H.; Domínguez-Hernández, E.; Domínguez-Hernández, M.E. Evaluation of Phytotoxicity of Manure-Derived Fertilisers Using Seed Germination and Root Elongation Bioassays. *Biol. Life Sci. Forum* **2026**, *57*, 5. [CrossRef]
47. Roques, O.; Bedell, J.P.; Le Maux, J.; Wiest, L.; Nélieu, S.; Mougin, C.; Bayard, R. Assessing the potential ecotoxicological risk of different organic amendments used in agriculture: Approach using acute toxicity tests on plants and earthworms. *Arch. Environ. Contam. Toxicol.* **2023**, *84*, 248–266. [CrossRef] [PubMed]
48. Misra, V.; Mall, A.K. Biofertilizer: Boon for Sustainable Sugarcane Production. In *Climate-Resilient Agriculture*; Hasanuzzaman, M., Ed.; Springer: Cham, Switzerland, 2023; Volume 1. [CrossRef]
49. Teferi, G.T.; Mekuria, A.T. Environmental remediation of sugarcane filter cake and vinasse via composting: Organic fertilisers to sustain agriculture. *Int. J. Environ. Stud.* **2026**, *83*, 207–223. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.