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Sustainable Nutrient Optimization Through Home-Generated Compost: Comparative Evidence for Enhanced Agroecosystem Performance

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Abstract

The recycling of organic waste is a key element of the circular economy, particularly in response to the increasing generation of biodegradable residues. Composting provides a sustainable solution that supports waste management while improving soil fertility; however, its agronomic value depends on the feedstock origin, composting method, and maturity. This study compares three compost types, two home-produced (C1, C2) and one industrial (C3), to assess their suitability for agricultural application. The chemical characterization included macronutrients and micronutrients, heavy metals, and the humus content, while biological performance was evaluated through seed germination and root growth tests. C1 was nutrient-poor, especially in nitrogen and calcium, indicating the need for supplementation. C2 exhibited high potassium and moisture levels but elevated sodium concentrations, suggesting potential salinity issues. C3 showed high calcium and magnesium contents, moderate nitrogen, and low sodium, making it suitable for calcium-demanding crops. Overall, the home-produced composts demonstrated superior humus quality and more positive effects on plant development than the industrial compost, highlighting their potential as sustainable soil amendments.

Keywords: circular economy; compost quality; nutrient composition; soil fertility; sustainable agriculture

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1. Introduction

According to the Quebec Bureau of Standardization, compost is defined as a solid, mature product obtained through composting, an aerobic bio-oxidative process involving heterogeneous organic substrates and a thermophilic phase [1]. During composting, organic waste undergoes microbial-driven decomposition and transformation, resulting in a stabilized material containing more than 25% humus, primarily derived from microbial biomass. Mature compost exhibits minimal biological activity; does not reheat, generate odours, or attract insects; and typically presents a carbon-to-nitrogen (C:N) ratio between 10 and 15 [2].

Composting represents a controlled biological oxidation process in which organic matter is transformed through physical, chemical, biochemical, and microbial mechanisms into

a homogeneous, humus-like product [2,3]. These transformations are strongly influenced by aeration and moisture, which govern the stabilization and maturity of the final material.

Accelerated urbanization has significantly increased municipal solid waste (MSW) generation, including in Romania. In 2022, Romania generated approximately 303 kg of MSW per capita, while maintaining a low recycling rate (~12%) and landfilling more than 74% of collected waste. This situation highlights the need for integrated waste management strategies consistent with circular economy and zero-waste principles [4–6], emphasizing waste prevention, material recovery, and a reduced reliance on landfilling.

The European Union produces an estimated 118–138 million tonnes of bio-waste annually [7]. In Romania, approximately 3 million tonnes of biodegradable waste are generated each year, of which about 35% is treated through composting or anaerobic digestion, with composting remaining the predominant method [8]. Organic waste is commonly classified into bio-waste (food and garden waste) and biodegradable waste (including paper, agricultural residues, and sewage sludge), a distinction essential for optimizing treatment and recovery strategies [9].

Due to the variability in the feedstock composition and processing conditions, the compost quality must be assessed prior to agricultural application [10]. In Romania, composting is practiced at both industrial and household scales. While commercial composts are subject to certification and regulatory control, household composts generally lack formal quality assessments [11,12]. Only stable and mature composts contribute positively to soil fertility and plant growth, whereas immature composts may contain phytotoxic compounds and pathogenic microorganisms [13,14].

Compost maturity and stability are key quality indicators and are commonly evaluated using physical, chemical, microbiological, and biological methods [15,16]. Regulatory frameworks governing compost quality differ internationally, particularly with respect to heavy metal limits, pathogen control, and maturity criteria. In addition, mineral salts (Na, K, Ca, and Mg) naturally accumulate during composting and may limit the compost application depending on crop sensitivity and end uses [17].

In this study, compost quality was evaluated according to Polish regulations, which require a minimum organic matter content of 30% and specified minimum concentrations of nitrogen, phosphorus, and potassium [18,19]. Three composts—two home-produced and one industrial—were assessed using selected chemical and biological indicators to determine their fertilization potential and suitability for agricultural, horticultural, and land rehabilitation applications [20]. Compost mixtures were standardized by target C:N ratios (≈25–30:1) and moisture contents (≈50–60%), ensuring comparability between composting systems. This approach provides a practical framework for evaluating compost quality across different operational scales and supports the use of compost as a sustainable soil amendment.

2. Materials and Methods

2.1. Composting Process Procedure and Organic Inputs

Parts of the experimental data used in this study were previously reported by Popescu et al. (2025) [14], where the initial chemical characterization of home-produced composts was presented. The present work extends that research by including additional compost types, incorporating biological assays (seed germination and root growth tests), and providing a comparative evaluation of the agronomic suitability of each compost. To this end, additional compost quality indicators were introduced, and three composts produced from different organic waste streams using distinct processing approaches were assessed.

Two composting methods were applied: aerobic composting (AC) and combined aerobic–anaerobic composting (AANC). Aerobic composting was carried out primarily in wooden composters using garden and park residues (grass clippings, leaves, shredded branches, and plant material), household vegetable waste, paper and cardboard, and agricultural by-products. The composting mixture (*w*/*w*) consisted of 20% grass clippings, 10% leaves, 10% shredded branches, 25% vegetable peels, 15% paper and cardboard, 10% straw, and 10% sawdust, with an initial moisture content of approximately 50% and an elemental composition of about 0.68% N; 0.10% P; 0.59% K; 0.07% S; and 46.5% C (C:N ≈ 69:1). All materials were mechanically reduced to particle sizes of 15–40 mm prior to composting. The mixture was placed in wooden crates and plastic containers, and the moisture content was monitored and adjusted to 60–70% to maintain optimal microbial activity (Table 1).

Table 1. Methods used and organic inputs for individual composts (AC: aerobic composting and AANC: aerobic–anaerobic composting).

Compost Type	Organic Inputs	Method	Ripening Period
C1	Mixture of biological waste (kitchen food scraps (banana peels, oranges, potatoes) plus beech sawdust	AANC	Approximately 4 months, depending on weather conditions, and included the use of vermicomposting techniques
C2	Biological mixture waste (kitchen food scraps (banana peels, oranges, potatoes), grass clippings, paper, cardboard, sawdust, vine leaves	AANC	About 4 months depending on weather conditions and the use of vermicompost
C3	Biodegradable mixed waste (wood, paper, cardboard, forestry, agricultural residues), biodegradable waste (garden, park waste, food, kitchen waste from households, restaurants) collected separately by pupils	AC	About 6 months depending on weather conditions

The aerobic–anaerobic composting process was conducted in thermoplastic composters intended for household garden use. Organic materials were size reduced to 15–40 mm and layered sequentially without bulk mixing. The compost maturity was monitored over a period exceeding six months using temperature measurements, with a stabilization near ambient temperature following the thermophilic phase serving as a primary indicator. Additional maturity criteria included a dark brown color, an earthy odor, a crumbly structure, and the absence of recognizable feedstock particles. Upon reaching maturity, the compost mass was homogenized and transferred to dark plastic bags to complete the maturation phase. Variations in compost maturity were observed among the samples, reflecting differences in the feedstock composition and processing conditions.

Compost samples (100–300 g) were hygienically collected from separate composting units after the completion of the maturation phase. Each sample was divided into two subsamples: one was analyzed as fresh compost at its natural moisture content, while the other was oven-dried at 105 °C to a constant mass to determine the moisture content and to obtain dry material for subsequent physicochemical analyses. Each compost type (C1, C2, and C3) was evaluated in triplicate, with three independent subsamples collected from different locations within each composting unit to account for biological variability. For each replicate, analytical determinations (pH, electrical conductivity, nutrient concentrations, and germination rate) were performed in duplicate to ensure analytical accuracy and reproducibility. The compost characteristics are presented in another paper (Popescu et al., 2025, Sustainability [14]).

2.2. The Chemical Characterization of the Compost Samples

2.2.1. Chemical Analysis

Chemical analyses were performed on oven-dried compost samples. The organic matter (OM) content was determined gravimetrically as the difference between total solids and ash. Total solids were measured by drying the samples at 105 °C to a constant mass, while the ash content was determined by incinerating the dried material at 550 °C for 6 h in a muffle furnace. The resulting ash was used to quantify macronutrients (Ca, K, Mg, Na) and micronutrients (Zn, Mn, Cu) by atomic absorption spectrometry. The moisture content was determined by oven drying at 105 °C according to ISO 10390:2021 [21]. Baseline chemical parameters for composts C1 and C2, previously reported by Popescu et al. [14], are presented in Table 2 and were used as reference data for this study.

Table 2. Parameters of compost samples C1, C2, and C3.

Physicochemical Parameters	C1	C2	C3
pH extract 1:5 (upH)	6.9	7.6	8.2
Conductivity 1:5 (µS/cm)	1982	2450	2782
Moisture content(%)	6.57%	61.67%	59.78%
Ca (mg/kg)	15,313.74	20,569.98	31,176.70
Mg (mg/kg)	1916.60	1909.19	4028.54
Na (mg/kg)	994.44	1519.68	581.90
K (mg/kg)	5249.40	7322.39	5028.67
Zn (mg/kg)	84.99	137.76	144.58
Mn (mg/kg)	279.75	16.81	237.10
Cu (mg/kg)	28.65	23.22	24.80
Particle size (mm)	25	18	20

Home-produced composts (C1 and C2) were included as reference materials from a previous household-scale experiment [13]. Compost C3 was selected as a representative industrial aerobic compost produced under controlled aeration, temperature, and moisture. The inclusion of C3 allowed for a comparative evaluation of composts produced under different operational conditions and scales, reflecting real-world differences between domestic and industrial systems. While a fully controlled comparison under identical conditions would isolate process effects more clearly, this was beyond the scope of the present study and is suggested for future work.

New analyses in the present study included biological assays (seed germination and root growth), an evaluation of soil–compost mixtures, and the full characterization of C3. Together, these data enabled an integrated assessment of the compost quality, maturity, and agronomic performance.

2.2.2. Measurement of pH and Electrical Conductivity

The pH and electrical conductivity (EC) of the composts were measured using a standardized 1:5 (w/v) compost-to-water extraction. For each sample, 10 g of compost was mixed with 50 mL of deionized water and stirred for 30 min to ensure a complete interaction between solid and liquid phases. The suspension was then filtered, and the pH and EC of the filtrate were measured using calibrated pH and EC meters. This procedure provides a reliable evaluation of compost properties, facilitating an assessment of its suitability for agricultural and environmental applications.

2.2.3. Measurement of Total Cations and Trace Minerals

Total cation and trace element contents in compost samples were determined after microwave-assisted acid digestion. Briefly, 0.5 ± 0.05 g of oven-dried compost was placed

in a Teflon vessel, to which 6 mL of concentrated nitric acid (65%) and 1 mL of hydrogen peroxide (30%) were added. Digestion was performed in an Analytik Jena TOPwave microwave system using a three-stage program: (i) 170 °C for 10 min under 40 bar with a 5 min ramp and (ii) 200 °C for 15 min under 40 bar with a 1 min ramp, followed by cooling. The digested samples were quantitatively transferred to 50 mL volumetric flasks with ultrapure water (18.2 µS/cm). Concentrations of Ca, Mg, K, Na, Mn, Zn, and Cu were measured by flame atomic absorption spectroscopy (NO-VAA 300, Analytik Jena, Jena, Germany). Calibration was performed using ICP Multi-Element Standard Solution XVI (100 mg L^{-1}, Certipur, Merck, Darmstadt, Germany), with correlation coefficients > 0.995. All reagents were of spectroscopic grade. Data from previous composting trials [13] were used as reference values for comparative interpretation.

2.2.4. Biological Assays: Germination and Growth Indices

Compost phytotoxicity was evaluated using two bioassays: the germination index (GI) and growth index, employing open and closed test configurations. In the open test, seeds were placed in direct contact with compost, whereas the closed test also captured effects of compost-emitted gases. Wheat and bean seeds were used in the assays, with garden soil enriched with mineral fertilizers serving as the reference substrate.

For the closed test, 500 g of compost and 1 g of seeds was evenly distributed across the pot surface, including edges to monitor root development. In the open test, shoot biomass was measured, while root length was recorded in the closed test. Compost extracts were prepared by mixing 10 g of fresh compost with 100 mL of distilled water and stirring for 2 h at room temperature. For the GI assay, 10 seeds were placed in 10 cm Petri dishes lined with absorbent paper saturated with 5 mL of extract and incubated in the dark at 25 °C for 48 h. Controls used 5 mL of distilled water. Seed germination was defined as the emergence of a primary root $\geq$ 5 mm. All assays were conducted under controlled light and temperature conditions, and growth was monitored over 7 days. This approach allowed comparison of compost effects across different seasons and environmental conditions.

Relative seed germination (RSG), relative root growth (RRG), and the germination index (GI) were then calculated using standard formulas [18]:

$$\text{RSG}\ (\%) = \frac{\text{average number of seeds germinated in compost extract}}{\text{average number of germinated seeds in control}} \cdot 100 \quad (1)$$

$$\text{RRG}\ (\%) = \frac{\text{Average Root Length in Compost Extract}}{\text{average root length in control}} 100 \quad (2)$$

$$\text{IG}\ (\%) = \frac{\text{RSG} \cdot \text{RRG}}{100} \quad (3)$$

3. Results and Discussion

Organic waste is commonly classified into two main categories: bio-waste and biodegradable waste, a distinction that supports effective waste management and optimized composting processes.

Bio-waste, which is collected separately, includes garden, park, and food waste from households and restaurants. Biodegradable waste comprises materials such as paper and cardboard, residues from agricultural and forestry activities, and by-products of municipal wastewater treatment, including sewage sludge [19].

Because the chemical composition of organic waste varies widely depending on its source and processing method, the compost quality must be assessed before the soil application.

In Romania, composting is practiced both in commercial facilities and household systems. While certified composts are used in agriculture, horticulture, land reclamation, and urban green spaces, household-produced compost is generally not subject to quality control.

The results for the two samples are presented in Table 2 and compared with previously analyzed compost types.

Table 3 presents a comparison of the measured parameters of the compost samples with the recommended ranges defined by the Compost Quality Alliance (Ontario, Canada) [2], indicating that the samples generally meet the established quality standards for compost.

Table 3. Features of the compost according to the Compost Quality Alliance in Ontario [2].

Feature	Value
Particle size:	<25 mm
Moisture content:	40–50%
Total organic matter:	>30% on a dry weight basis
C/N Report:	<22
pH:	5.5–8.5
Conductivity	<7.39 µS/cm
Sodium (Na):	<2% relative to dry weight
Soluble salts (of a saturated paste):	<4 mS/cm

In this study, the compost quality was evaluated according to Polish standards specified in the Regulation of the Minister of Agriculture and Rural Development. These standards require a minimum organic matter content of 30%, as well as minimum concentrations of nitrogen (N) and potassium (K_2O) of 0.3% and 0.2%, respectively. All analyzed composts complied with these requirements.

Potassium levels exceeded the minimum threshold in all samples, ranging from 0.5% in composts C1 and C3 to 0.7% in compost C2, confirming adequate nutrient availability. Despite variations in the macro- and micronutrient composition, no statistically significant differences were observed among the composts, and all showed comparable effects on seed germination and root growth [22].

Carbon (C) and nitrogen (N) play key roles in compost quality, with an optimal initial C/N ratio between 25 and 30. During aerobic composting, carbon is preferentially lost as CO_2, resulting in a reduced C/N ratio in the final product. Experimental results showed carbon contents of 13.33% in C1, 22.18% in C2, and 25.12% in C3, indicating substantial carbon loss, particularly in C1. The lower nitrogen content in C1 reflects the reduced proportion of biological material used in its preparation.

The bar chart (Figure 1) shows the elemental composition (C, N, H) of the three compost samples (C1, C2, C3), which are key indicators of compost quality and suitability for agricultural use. The carbon content was highest in C3 (25.12%), followed by C2 (22.18%) and C1 (13.33%), reflecting differences in the organic matter and decomposition stage. Nitrogen levels followed a similar trend, C3 (1.52%) > C2 (1.41%) > C1 (1.18%), indicating C3 as the most nutrient-rich. The hydrogen content was equal in C2 and C3 (3.32%) and lower in C1 (2.22%), suggesting less organic integrity in C1.

The C/N ratio highlighted decomposition and nutrient release dynamics: C1 (≈11.3) suggests rapid decomposition and immediate nutrient availability, whereas C3 (≈16.5) indicates slower degradation and sustained nutrient release. C2 showed intermediate characteristics.

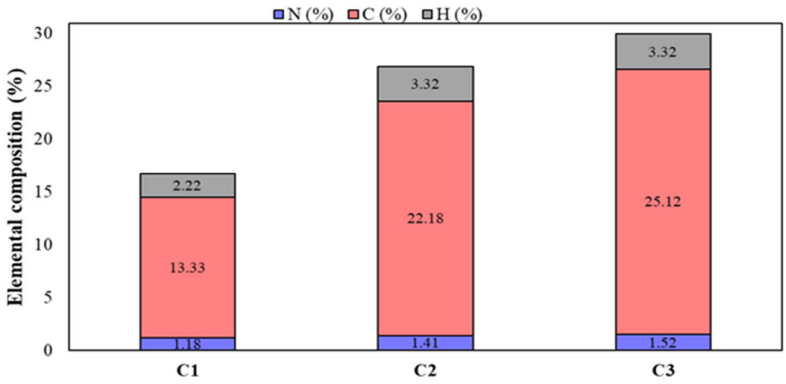

Figure 1. A graphical representation of the characteristic parameters for C1, C2, and C3.

Overall, C3 is best suited for long-term soil improvement, C2 for general-purpose use, and C1 for short-term nutrient supplementation. These findings align with previous reports that less stabilized compost releases nutrients quickly but with a higher risk of losses and phytotoxicity.

Figure 2 shows the C:N, C:H, and N:H ratios for compost samples C1, C2, and C3, which indicate the stability, decomposition rate, and nutrient availability.

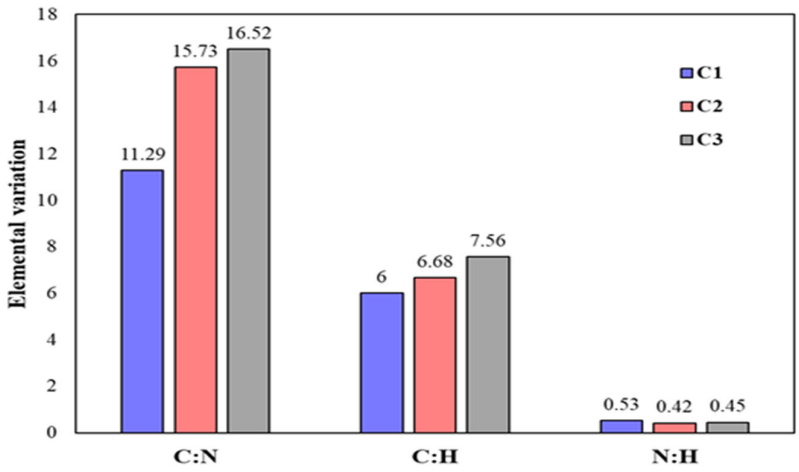

Figure 2. Variation in C:N, C:H, and N:H ratios for compost examples C1, C2, and C3.

The C:N ratio reflects the decomposition and nitrogen release. C1 had the lowest ratio (11.29), indicating rapid microbial activity and quick nitrogen availability, suitable for short-term crop needs. C2 (15.73) showed a balanced decomposition, while C3 (16.52) decomposed slowly, supporting long-term soil organic matter buildup.

The C:H ratio indicates organic matter stability. C1 (6.00) had the least stable material, C2 (6.68) was moderately stable, and C3 (7.56) had the most stable organic matter, implying slower decomposition and lasting soil benefits.

The N:H ratio reflects the nitrogen availability relative to hydrogen. C1 (0.53) had the highest, making it ideal for immediate fertilization. C2 (0.42) and C3 (0.45) released nitrogen more gradually, supporting medium- and long-term soil improvement, respectively.

Application recommendations:

C1: Rapid decomposition and high nitrogen contents make it suitable for the fast-acting fertilization of leafy vegetables, brassicas, and nitrogen-demanding crops, especially in sandy or nitrogen-deficient soils. The quick nutrient release may limit long-term soil benefits (Table 4).

C2: Moderate decomposition and a balanced nutrient release make it ideal for general-purpose use, fruiting vegetables, root crops, and legumes in loamy soils; it may require supplemental nitrogen for high-demand crops (Table 4).

C3: Slow decomposition and high organic matter stability favour long-term soil improvement, suitable for perennial crops, fruit trees, and degraded or clayey soils. This compost is not recommended for crops needing immediate nutrients (Table 4).

These results align with previous studies, confirming that compost maturity strongly influences nutrient release, soil improvement potential, and crop suitability.

Table 4. Final summary for the composting type [23–29].

Compost Type	Primary Agronomic Function	Representative Suitable Crops	Recommended Soil Context
C1	Rapid nutrient mineralization and short-term fertility enhancement	Leafy vegetables (e.g., lettuce, spinach), maize, brassicas	Sandy soils with low nitrogen availability
C2	Balanced nutrient provision supporting sustained plant growth	Solanaceous crops (e.g., tomato), root vegetables (e.g., carrot, beet), legumes	Loamy soils of moderate natural fertility
C3	Gradual nutrient release and long-term improvement of soil structure and fertility	Perennial crops (e.g., fruit trees, grapevines)	Clayey, degraded, or acidic soils requiring structural and chemical amelioration

3.1. Nutrient Composition and Agronomic Implications

The chemical composition of the three composts (C1, C2, and C3) revealed distinct profiles with implications for crop fertilization and soil management.

Macronutrients: Sample C1 was characterized by moderate calcium (15.31 $g \cdot kg^{-1}$), potassium (5.25 $g \cdot kg^{-1}$), and magnesium (1.92 $g \cdot kg^{-1}$), with low sodium (0.99 $g \cdot kg^{-1}$) (Figure 3). While the calcium content supports soil structure and crop calcium requirements, the limited nitrogen and magnesium indicate that additional supplementation may be needed to sustain vegetative growth and photosynthesis. Sample C2 exhibited the highest potassium concentration (7.32 $g \cdot kg^{-1}$), along with elevated calcium (20.57 $g \cdot kg^{-1}$) and magnesium (1.91 $g \cdot kg^{-1}$), making it particularly suitable for potassium-demanding crops, such as Solanaceae, legumes, and tubers. However, its relatively high sodium content (1.52 $g \cdot kg^{-1}$) may pose salinity risks, requiring careful management [30]. Sample C3 presented the most balanced nutrient profile, with high calcium (31.18 $g \cdot kg^{-1}$), magnesium (4.03 $g \cdot kg^{-1}$), and nitrogen (1.52 $g \cdot kg^{-1}$); moderate potassium (5.03 $g \cdot kg^{-1}$); and the lowest sodium (0.58 $g \cdot kg^{-1}$). This composition supports soil fertility enhancement, structural improvement, and vigorous vegetative growth while minimizing salinity risks [31–33].

Micronutrients: Mn, Cu, and Zn occur in low concentrations (<0.01% of dry matter) and are reported in ppm: Mn (167–280), Cu (23–29), and Zn (85–145) (Figure 4). Overall micronutrient levels were low but within international thresholds [34,35]. Zn was higher in C2 and C3, potentially benefiting zinc-demanding crops such as cereals due to its role in enzyme activation, protein synthesis, and hormone regulation. Mn was highest in C1, suggesting its suitability for vegetables, soybeans, and leafy vegetables. Copper (Cu) levels were consistently low; given its importance in lignin biosynthesis, enzymatic activity, and reproduction, external supplementation may be necessary for copper-sensitive species such as wheat, citrus, and grapevine [34,35].

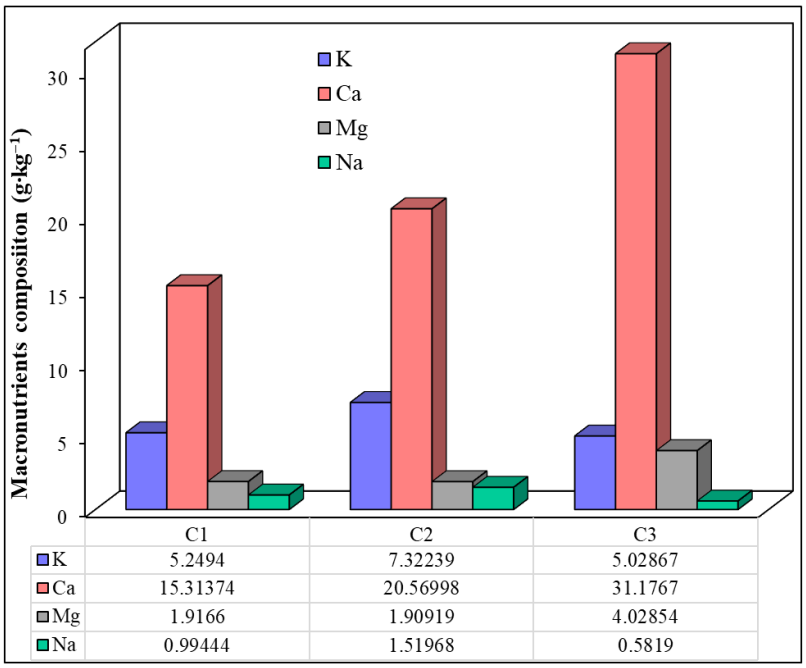

Figure 3. The macronutrient composition of the three different samples (C1, C2, and C3).

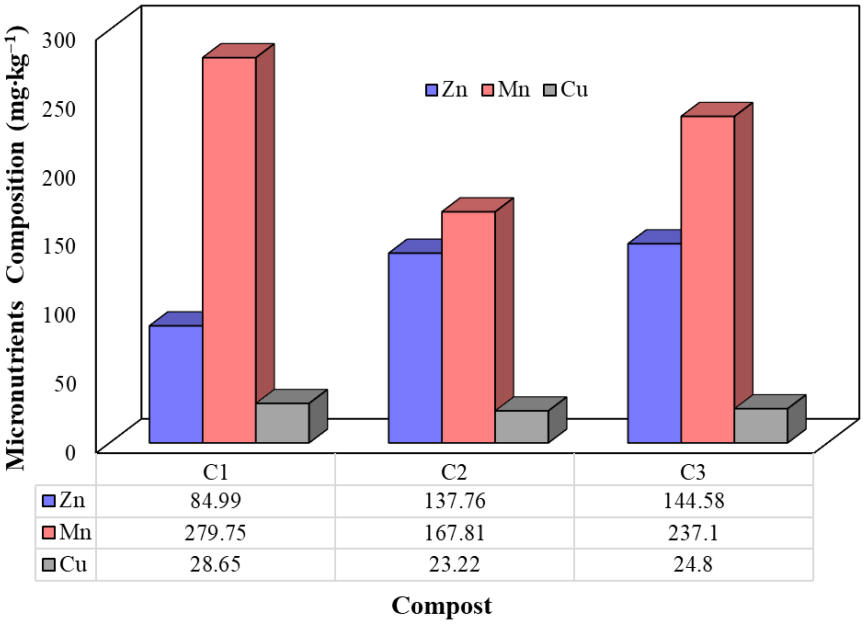

Figure 4. A graphical representation of the micronutrient content of C1, C2, and C3.

Tables 5 and 6 summarize the key macronutrient and micronutrient implications for agricultural use.

Agronomic Implications: C3 offers the most comprehensive nutrient profile, making it ideal for general soil fertility improvements and crops requiring high structural and metabolic nutrients. C2 is particularly beneficial for potassium-demanding species but requires attention to its sodium content. C1, while moderate in calcium and other macronutrients, is best suited as a supplementary soil conditioner with a minimal salinity risk [36,37].

Table 5. Agricultural recommendations for the samples.

Applicability	C1	C2	C3
Calcium-Dependent Crops	❌ Low Ca	✅ Medium Ca	🔥 Great Ca
Potassium-Dependent Crops	✅ Good K	🔥 Great K	✅ Good K
Magnesium Needs	❌ Low Mg	❌ Low Mg	🔥 Great Mg
Low-Salinity Crops	✅ Moderate Na	❌ High Na	🔥 Lowest Na
Nitrogen-Dependent Crops	❌ Low N	✅ Medium N	🔥 Good N

❌ = Low or unfavorable nutrient level, indicating limited suitability for the specified crop requirement. ✅ = Moderate to good nutrient level, indicating adequate suitability for the specified crop requirement. 🔥 = High or optimal nutrient level, indicating excellent suitability for meeting the specified crop requirement.

Table 6. Agricultural implications for the content of Zn, Cu, and Mn.

Applicability	C1	C2	C3
Zinc (Zn) Needs	❌ Lowest Zn	✅ High Zn	✅ High Zn
Manganese (Mn) Needs	🔥 Great Mn	❌ Lowest Mn	✅ Medium Mn
Copper (Cu) Needs	❌ Low Cu	❌ Low Cu	❌ Low Cu

❌ indicates a low micronutrient content with limited agronomic relevance for that specific need. ✅ indicates a medium to high micronutrient content, adequate for addressing the specific nutritional requirement. 🔥 indicates a very high micronutrient content, highlighting strong suitability or enhanced effectiveness for the targeted requirement.

Table 6 summarizes the potential agricultural implications of Zn, Cu, and Mn in the compost samples.

Sample C1 is best suited for manganese-demanding crops, such as soybeans, vegetables, and leafy vegetables, while C2 and C3, with higher zinc levels, favour zinc-demanding cereals like wheat, maize, and rice. Copper was low in all samples, suggesting supplemental copper fertilization may be needed. Elevated Zn may enhance the crop micronutrient status but risks soil accumulation, whereas the high Mn level in C1 supports enzymatic activity and redox balance but could cause phytotoxicity in acidic soils. These findings inform nutrient management to ensure crop performance and long-term soil health [38–40].

3.2. Effect of Moisture Variation in Compost Samples

The raw materials for composting initially had moisture contents above the optimal 65%, mainly due to high-water fruits and vegetables typical of southern European household waste. Adding sawdust, cardboard, and paper improved the porosity and airflow, preventing anaerobic pockets. Sample C1 was too dry at 6.57%, likely from outdoor conditions and excess sawdust, while C3 had a balanced 59.78% moisture, ideal for cereal crops.

Sample C2 (61.67% moisture) was unsuitable for moisture-sensitive crops like beans, while C1 (6.57%) was extremely dry, likely representing mineral or desiccated soil. The high moisture level in C2 and C3 (59.78%) suggests water-retentive materials from organic-rich or wet soils. The physicochemical analysis (Tables 2–6) showed a pH of 7.4–8.1; an EC of 2.1–4.3 mS cm^{-1}; and C/N ratios decreasing from ~25:1 to 14:1, indicating stable, humified compost. Sprout and root tests showed that wheat growth favoured substrates with balanced moisture; excess or low moisture levels impeded growth (Figures 5 and 6).

Figure 5. Soil, soil and compost, and compost samples for closed test.

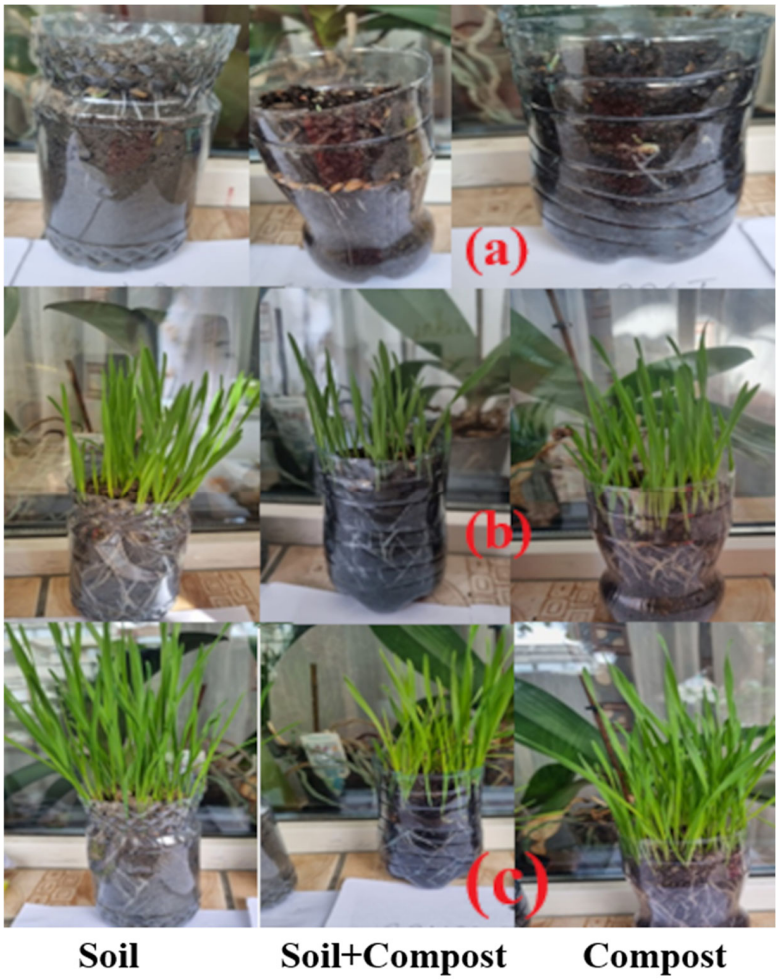

Figure 6. Wheat germination after two (**a**), four (**b**), and seven (**c**) days.

Compost must meet environmental safety regulations and be produced from biodegradable, rapidly decomposing materials. Stability and maturity are key: mature compost is microbially stable, low in volatile substances, and has a suitable C:N ratio (generally 15–20). Moisture strongly affects decomposition: <30% halts microbial activity, and >65% promotes anaerobic conditions, with 45–65% being optimal [40–44].

C1 is low moisture and requires supplementation, while C2 and C3 have sufficient moisture for hydrophilic crops, likely reflecting clay-rich or wetland origins. Table 7 recommends conditioning C1 before use, while C2 and C3 are suitable for high-water-demand crops.

Table 7. Final conclusions for the three samples.

Applicability	C1 (Dry, 6.57%)	C2 (Wet, 61.67%)	C3 (Wet, 59.78%)
Drought-Tolerant Crops	✅ Great	❌ Not Ideal	❌ Not Ideal
Water-Retaining Crops (e.g., rice, leafy greens)	❌ Not Suitable	🔥 Great	🔥 Great
Indicates Arid/Dry Soil	✅ Yes	❌ No	❌ No
Indicates High-Moisture Soil	❌ No	✅ Yes	✅ Yes

❌ = Not suitable or unfavorable condition for the specified crop or soil characteristic. ✅ = Suitable or favorable condition, adequately meeting the specified crop or soil requirement. 🔥 = Highly suitable or optimal condition, indicating excellent performance under the specified moisture regime.

3.3. Plant Growth Assays and Stability Tests

Plant growth assays were conducted using open and closed pot tests with wheat and beans, comparing compost samples to the reference soil. Open tests measured the plant weight, while closed tests tracked the root length and gas effects [43–45]. After seven days, the growth on C1, C2, and C3 composts was satisfactory, comparable to the reference soil, confirming their stability and suitability for cultivation (Figures 6 and 7). Biological assays like the GI provide a valuable complement to chemical analyses for assessing compost maturity [46–48].

Figure 7. The evaluation of germination with the open test.

Stability tests showed germination index (GI) values of 80% for all three composts, indicating acceptable maturity. A GI above 80% generally signifies mature, non-phytotoxic compost, while values over 100% suggest a positive effect on seed growth. Although rapid and sensitive, GI tests are labour-intensive, species-dependent, and lack standardized thresholds.

In the open test, the sprout weight (2–4 g) reflected substrate stability, while in the closed test, the root growth was greatest in the soil–compost mix, moderate in soil (limited by dryness), and lowest in the pure compost (excess moisture). Wheat grew slightly without intervention in the soil–compost mix, was hindered by the high moisture in the compost, and was limited by the low moisture level in the soil after 7 days (Figures 6 and 7).

An RRG score of 80% is classified as "very good," indicating a strong alignment between objectives and outcomes, but should be interpreted in context with the assessment tool, population, and research goals [49,50]. It reflects practical significance rather than full theoretical validation. This study also highlights limitations in current compost assessment methods, showing that maturity can vary depending on the evaluation index used.

4. Conclusions

The compost chemical composition was influenced primarily by organic inputs rather than by the composting technology. Composts obtained from biological waste through the INAC process were characterized by comparatively low concentrations of nutrients and organic matter; nevertheless, they exhibited favourable indicators of biochemical

stability and maturity. However, commonly employed metrics for assessing compost stability and maturity—such as the carbon-to-nitrogen (C:N) ratio—are not supported by universally accepted threshold values and, when applied in isolation, do not adequately capture the complexity of the compost quality. Consequently, a reliance on single-parameter indices may lead to incomplete or misleading evaluations of compost performance and agronomic suitability.

A comprehensive compost quality assessment requires the integration of chemical, physicochemical, and biological indicators, as single-parameter indices such as the C:N ratio are insufficient to capture compost maturity and stability. Biological assays and detailed chemical profiling provide more reliable evaluations of compost performance. Agronomically, composts represent cost-effective, locally available soil amendments that enhance soil fertility, support sustainable waste management, and reduce the reliance on mineral fertilizers. The three compost types evaluated exhibit distinct functional characteristics: C1 provides rapid nitrogen availability and is suitable for short-term soil enrichment under arid or degraded conditions but requires careful management to avoid nutrient imbalance; C2 offers balanced nutrient release and moisture retention, making it appropriate for intensively cultivated soils, although its elevated sodium content necessitates salinity control; and C3 supports long-term soil quality improvements through slow nutrient release and high calcium and magnesium contents, making it particularly suitable for sensitive agroecosystems and soil restoration. Optimizing compost applications by matching the compost type to soil properties and crop requirements enhances nutrient use efficiency, minimizes environmental risks, and supports circular bioeconomy strategies focused on resource recovery and sustainable agricultural productivity.

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