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Influence of Agro-Industrial Waste Composts on Soil Characteristics, Growth Dynamics, and Yield of Red Cabbage and Broccoli

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Abstract: In this work, environmentally sound technologies for converting organic wastes into fertilizers to improve soil sustainability and crop yield have been identified and assessed. Wet wastes were combined with 50% wood sawdust and 50% wet wastes (Compost 1) or (10% Straw + 90% wet wastes) (Compost 2) to produce soil improvers with a balanced level of nutrients, and their effectiveness on soil ecosystem functioning have been tested and compared to horse manure (HM) and nitrogen–phosphorous–potassium (NPK) fertilizers. Unfertilized soil was used as a control. Soil chemical and biological properties have been detected after the harvesting of broccoli and red cabbage (90 days from the initial treatments). Three independent experiments have been conducted in an open field in a randomized complete block design with three replications (n = 9). The results showed that Compost 1 had the highest C/N ratio and cation exchange capacity (CEC), indicating a better humification of the wet material. Compost 1, even if it contained a minor amount of organic carbon, as well as less activity of fluorescein diacetate (FDA) and dehydrogenase (DHA) than Compost 2, was the most effective in improving soil quality, significantly increasing the labile fraction of organic matter, the oxidative enzyme (DHA), microbial biomass, and crop yield. Both composts increased crop productivity.

Keywords: waste compost; soil fertility; broccoli calabrese; red cabbage; soil amendments

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1. Introduction

In the face of global challenges, such as population growth, climate change, and diminishing agricultural resources, there is an increasing imperative to develop sustainable agricultural practices that simultaneously enhance soil fertility, mitigate waste-disposal issues, and reduce environmental impacts [1]. Based on the latest UN projections, the world's population may rise to roughly 8.5 billion by 2030, 9.7 billion by 2050, and could peak around 10.4 billion in the 2080s. Consequently, our yearly food supply needs to sustainably meet the demands of this growing populace [2]. Sustainable agricultural methods offer ways to produce food and other agricultural products with minimal environmental impact. This ensures consistent food access and availability and environmental and human health safeguards. Sustainable agriculture is linked to food security, which encompasses consistent food availability; adequate production; affordability; sufficient nutrition in terms of energy, proteins, and micronutrients; safety; and the economic stability to maintain these factors [3]. It is imperative to identify and analyze well-established approaches aimed at fostering sustainable agriculture, many of which prioritize ecosystem health.

These approaches are characterized by clear principles and encompass environmental, economic, and social objectives. They have evolved as methodological strategies over time, like agroecology and sustainable intensification, or were prioritized from the outset, such as carbon farming.

Composting represents a promising solution, offering a means to recycle organic materials while generating nutrient-rich soil amendments [4]. In essence, composts derived from waste management within the context of the circular economy, such as biowaste, organic waste, and green waste, are considered acceptable for use in organic agriculture under Regulation EU 2021/1165 [5].

This allowance is contingent upon these composts originating from a recognized separate collection system within the respective EU member state and adhering to specified limits for heavy metal content. Compost, when used as a fertilizer or soil conditioner, can significantly enhance soil quality [6,7]. It accomplishes this by improving aeration, optimizing water content, enhancing aggregate stability, and thereby bolstering resistance against erosion. Furthermore, compost enriches the soil with both macro and micronutrients, fostering healthier plant growth, and augments the cation exchange capacity, as demonstrated by Muscolo et al. (2018) [6] and Ghimire et al. (2023) [8]. Activating the soil microbiota and increasing its biomass are additional benefits, although the extent of these effects relies heavily on the quality and quantity of organic matter, as observed by Bonanomi et al. (2020) [9] and Sunman et al. (2022) [10]. When it comes to the risk of nitrate leaching, composted organic waste is generally considered to pose minimal risk [11].

This manuscript explores the scientific dimensions of composting through the lens of a specific approach: the utilization of wood sawdust and vegetable wastes as composting materials.

The selection of wood sawdust and vegetable wastes for composting is rooted in their unique compositional characteristics. Wood sawdust, a by-product of various woodworking processes, is recognized for its high carbon content and lignocellulosic structure [12]. This provides an excellent source of carbon, crucial for establishing an optimal carbon-to-nitrogen ratio in the composting process. Additionally, wood sawdust represents to the wood industry a waste to be disposed of with economic implications. In contrast, vegetable wastes, including kitchen scraps and garden trimmings, contribute nitrogen-rich organic matter. When these materials are co-composted, they hold the potential to create a well-balanced mixture, essential for the efficient decomposition of organic matter [13].

The science of composting hinges upon the microbial-driven biological transformation of organic materials into stabilized organic matter known as humus. This process involves a complex interplay of organisms, including bacteria, fungi, actinomycetes, and earthworms that break down the organic compounds present in the feedstock. In the case of wood sawdust and vegetable-waste composting, the intricate lignocellulosic structure of sawdust provides an intriguing substrate for microbial colonization and degradation, leading to the release of carbon and other nutrients [14].

The resulting compost, characterized by a dark, crumbly texture, not only sequesters carbon but also embodies essential nutrients such as nitrogen, phosphorus, and potassium, as well as micronutrients required for plant growth. Beyond its nutrient content, the compost enhances soil structure, moisture retention, and microbial diversity, ultimately fostering improved soil health and agricultural productivity. Furthermore, this manuscript a part to delve into the scientific aspects of composting management, addressing critical factors such as temperature dynamics, aeration, moisture content, and composting timeframes, explore the effects of compost as fertilizer on broccoli and cabbage growth and yield. Particularly, the growth parameters related to productivity and the parameters related to plant performance have been detected and discussed. This manuscript explores the scientific intricacies of this composting method, shedding light on its potential to transform wastes into a valuable resource, mitigate greenhouse-gas emissions, and enhance soil fertility and crop yield, and provides a compelling avenue toward a more sustainable and resilient agricultural future.

2. Materials and Methods

2.1. Feeding Materials

The raw organic materials employed for composting comprised a variety of components and precise vegetable wastes (like rocket salad, lettuce, cabbage, carrots, and valerian).

The two composts have been prepared using different percentages of the vegetable residues (Table 1).

Table 1. Compostable raw materials of different composts used.

Compost ID	Compostable Raw Material
Compost 1 (C1)	50% wood sawdust + 50% wet waste, such as kitchen and restaurant scraps.
Compost 2 (C2)	10% Straw + 90% wet wastes, such as kitchen and restaurant scraps.

2.2. Composting Process Setup

Sawdust and vegetable residues, as well as straw and vegetable residues, were carefully deposited into dedicated electric composters and subjected to the composting process. The electric composter contains multiple chambers for a better composting process. The waste in the second chamber does not come into contact with the fresh waste; the temperatures of the two chambers are managed independently for the better development of microbial populations. The tank dimensions were 350 cm × 100 cm × 131 cm and had a capacity of 10 tons/year. This composting protocol was replicated three times for each compost mixture. The composting conditions were controlled as follows: an initial mesophilic phase for 8 days at 29 °C followed by a thermophilic phase lasting 20 days at 50 °C.

A second mesophilic phase extended for 92 days at 27 °C. The temperature increases during the composting process resulted from the robust microbial activity, facilitated by efficient ventilation within the mixture.

The ventilation process is maintained and accelerated by the continuous supply of air and the continuous movement of the organic material. This ventilation process guaranteed the presence of ample oxygen levels, thereby promoting biological processes while maintaining optimal aerobic conditions, as documented by Liang et al. (2003) [15]. Following this mesophilic phase, a stabilization transitioning phase with a stable temperature of 20 °C for 30 days was settled to stabilize the compost until the conclusion of the composting cycle. This stability was attributed to reduced microbial activity and a diminishing quantity of organic substrate available for decomposition. The moisture content was upheld at 50%, and the oxygen percentage consistently exceeded 15%. Temperature, moisture, and oxygen levels were monitored daily using a probe strategically placed in the center of the composting mass, ensuring they remained within the predefined parameters. Water was added as needed to sustain the 50% moisture level. Daily agitation of the mixtures was performed to guarantee oxygen levels above 15%, thereby promoting the aerobic decomposition of organic matter into stable humus. Comprehensive decomposition and stabilization of the materials were accomplished over a span of 4 months. Subsequently, all compost batches underwent an air-drying process, were finely crushed to pass through a 2 mm sieve, and underwent thorough blending to ensure uniformity.

2.3. Chemical Characterization of Composts

The chemical analysis of the composts was conducted in accordance with the protocols outlined in the ANPA manual from 2001 [16]. To evaluate the rate of organic matter mineralization, the reduction in organic matter content over time was assessed by using the following equation (Equation (1)):

$$\text{Organic matter loss (\%)} = [(\text{Initial mass of carbon} - \text{Final mass of carbon})/\text{Initial mass of carbon}] \times 100 \quad (1)$$

The determination of fluorescein 3,6-diacetate hydrolase activity followed the procedure established by Adam and Duncan [17]. The results were expressed as mg fluorescein released per gram of dry soil, following Perucci et al. (1992) [18].

Dehydrogenase (DHA) activity was determined as outlined by von Mersi and Schinner (1991) [19]. The absorbance of the soil filtrate was measured at 490 nm.

Water-soluble phenols (WSP) were detected by extracting the soil with water and determining their concentration using the Folin–Ciocalteau reagent, following Box's method from 1983 [20]. The cation exchange capacity (CEC) was determined using an aqueous solution of $BaCl_2$ buffered to pH 7.0 to saturate the soil-exchange complex, following Hendershot and Duquette (1986) [21].

Compost maturity was assessed by employing cucumber (*Cucumis sativus* L.) seeds, following the method described by Gariglio et al. (2002) [22]. The Germination Index (GI), which combines measures of relative seed germination (%) and relative root elongation (%), was used to evaluate compost toxicity. This method is particularly sensitive and capable of detecting both low-level and high-level toxicity affecting root growth and germination, respectively. A GI value higher than 60% indicates the non-phytotoxicity of the compost, as established by Zucconi et al. (1981) [23].

The organic matter mineralization rate was assessed by evaluating the loss of organic matter over time, Organic matter loss was calculated following Equation (1).

The absorption capacity of the composts, in relation to Na^+ and Cl^- ions, has been calculated using the following Formula (2):

$$AC = (Ci - Cf)\ m \times VAC = m(Ci - Cf) \times V \quad (2)$$

where:

- AC is absorption capacity;
- Ci is the initial concentration of ions;
- Cf is the final concentration of ions;
- m is the compost weight;
- V is the volume of the solution (40 mL).

2.4. Soil Characteristics and Treatments

The experiment was carried out in sandy-loam soil belonging to Cambisol (WRB, 2022) [24], located in Motta San Giovanni, Loc. Liso, Italy (37.9991° N. 15.6999° E).

The average temperature of the coldest months, January and February, stands at +11.9 °C; that of the hottest month, August, is +26.1 °C. The average annual precipitation is around 493 mm, with a minimum in summer and a peak in autumn–winter. The fertilization experiments consisted of three replicate plots for each condition. Each plot measured 18 m^2 and was set up using a single-factor randomized complete block design. The soil received a fertilization treatment using the two composts distributed at a depth of 10/15 cm. In each designated plot, composts were incorporated based on the organic matter content precisely at rates of 3.1 Mg/ha for composts, horse manure (HM, 4.3 Mg/ha), and NPK (20:10:10) at 1.7 Mg/ha. To maintain consistent moisture levels, the plants were regularly irrigated to ensure a water content of 70% of field capacity across all parcels. The experiment was replicated three times. Two different crops have been used to test the effectiveness of the two produced composts, namely ramous Calabria broccoli and red cabbage.

The differently treated crops were collected when they reached ripeness level, based on visual characteristics such as size, shape, and color. Cabbage cultivated with Compost 1 matured in a range of 78 days, while those grown with Compost 2 maturated in 85 days, with HM in 88 days, and with NPK taking 90 days to mature. Broccoli was ready to be harvested 70 days after transplanting when cultivated with Compost 1, 79 days when cultivated with Compost 2, 83 days when grown with NPK, and 80 days with HM. Within each plot, for both crops (broccoli and cabbage), 3–4 plants/m^2 were planted for each treatment. The spacing between individual plants was set at 40 cm, with 60 cm between rows. Throughout the experiment, the parcels were irrigated to maintain the soil moisture at 70% of field capacity. Soil humidity was continuously monitored using a direct-read soil pH/moisture meter—R181 to ensure consistent soil moisture levels in both soil types.

2.5. Soil Analysis

Soils were collected in each parcel at the end of the experiment (90 days), as reported below for the specific crop species and fertilization used. Soils have been air-dried and sieved through a 2 mm sieve for chemical analyses, while fresh soil sieved to 2 mm was used for microbiological analyses. The soil water content was expressed in percentage. The water content was determined at the beginning of the experiment and every 15 days during the entire experiment for all soil treatments. Particle-size analysis was carried out by using the method of Bouyoucos et al. (1962) [25]. Dry matter (dm) was determined by weighing the samples after 24 h at 105 °C; pH and EC were measured as reported in Muscolo et al. (2017) [26]. Organic carbon was determined by oxidimetric method following the Walkley–Black procedure [27]; total nitrogen was determined by the digestion procedure, using sulfuric acid at temperatures of 380 °C following the method of Kjeldahl et al. (1883) [28]. The amount of microbial biomass carbon (MBC) was determined by using the chloroform fumigation extraction procedure [29] with field-moist samples (equivalent to 20 g dry wt.). The filtered soil extracts of both fumigated and unfumigated samples were analyzed for soluble organic C using the methods of Walkley and Black [27]. Microbial biomass C was estimated on the basis of the differences between the organic C extracted from the fumigated soil and that from the unfumigated soil, and an extraction efficiency coefficient of 0.38 was used to convert soluble C into biomass C [29]. The microbial population was extracted following the method of Insam and Goberna [30]. Two grams of soil and 30 glass beads were mixed with 20 mL 0.90% NaCl and shaken for 20 min at 20 °C, then centrifuged at 4 °C for 1 h at 12,000× *g* to separate the bacteria from the solid particles. The supernatant was used for further dilutions with a sterile one-fourth-strength Ringer solution so as to standardize the inoculum density. The soil's bacterial population was estimated by Waksman et al. (1952) [31] with method using the nutrient agar medium at 10^5 dilutions. The fungal population was estimated by the dilution-plate method using Martin's Rose Bengal agar medium at 10^3 dilutions in water [32]. The activities of fluorescein 3,6-diacetate hydrolase (FDA), and dehydrogenase (DHA), as well as the water-soluble phenol amount, ion concentrations, and cationic exchange capacity (CEC), were determined as reported in Section 2.3. Three soil samples for each crop and each specific fertilization have been collected. All the analyses were performed in triplicates. Thus, for each cultivar and condition, n = 9.

2.6. Crop Growth Assessment

Each cultivar was analyzed for the following growth parameters: plant height (PH) from the soil level to the highest point of the plant, leaf area (LA, cm^2), leaf length (LL, cm), leaf width (LW, cm), leaf humidity (LH, %) from the basal leaves to the last open leaf, fruit-head diameter (HD, cm) and yield (tons/hectare). For the estimation of total chlorophyll content, 100 mg of leaf tissue were finely ground in liquid nitrogen and suspended in dimethyl sulfoxide (DMSO). The suspension was maintained at 65 °C for 30 min. The final volume was adjusted to 10 mL with DMSO, and the absorbance was recorded at 645 and 663 nm. The total chlorophyll content was calculated as reported by Hiscox et al. (1979) [33].

2.7. Mineral Assay

Cations (Na, K, Ca, Mg) were extracted from samples and analyzed using ion chromatography (DIONEX ICS-1100, Thermo Fisher Scientific, Waltham, MA, USA). One g of dry material was ashes at 550 °C for 6 h in a porcelain capsule. The ash was then acidified for 30 min at 100 °C using 1M of HCl solution (10 mL). Finally, it was filtered using Whatman 1 and measured using the ion chromatograph with 20 mM methane–sulfonic acid as an eluent. The Fe concentration was determined using atomic absorption spectrophotometry (model 2380, PerkinElmer Co., Waltham, MA, USA). Four mixed standard solutions with concentrations of 1, 5, 25, and 50 ppm of each of the four desired anions were used to plot the calibration curve. The linear relationship between the peak area and concentration

was confirmed experimentally. The amount of each cation was calculated using its own standard curve. The amount of each anion was calculated using ion chromatography (DIONEX) and comparing the results with a multi-ion cation standard curve (Multi Ion Cation IC standard solution, Specpure®, Dionex, Thermo Fisher, Milan, Italy) [34].

All solvents and reagents were purchased from Panreac (Barcelona, Spain). The bioconcentration factor (cation or anion in root/cation or anion in soil), bioaccumulation coefficient (cation or anion in leaves/cation or anion in soil), and translocation factor (cation or anion in leaves/cation or anion in roots) were detected.

2.8. Chlorophyll Fluorescence Imaging

The photosynthetic efficiency of cabbage and broccoli leaves, differently fertilized, was evaluated by using an Imaging PAM Fluorometer (Walz). The chlorophyll fluorescence parameters detected were as follows: maximum quantum yield of PSII photochemistry (Fv/Fm); effective quantum yield of PSII photochemistry (Y(II)); quantum yield of regulated energy dissipation at PSII (Y(NPQ)); quantum yield of non-regulated energy dissipation at PSII (Y(NO)); non-photochemical quenching coefficient (NPQ), and electron transport rate (ETR). The maximum PSII quantum yield (Fv/Fm), photochemical fluorescence quenching (qP), non-photochemical fluorescence quenching (NPQ), and ETR have been evaluated and analyzed for the indication they give. Fv/Fm showed the maximum efficiency of energy conversion in PSII. qP indicates the rate of photochemical reactions in the chloroplast electron transport chain in vivo. NPQ indicates the amount of excess energy that was absorbed by chlorophyll but was not used by the electron transport chain and was converted to heat [35]. The ETR electron transport rate is proportional to the photosynthetic activity, and a higher value indicates higher carbon fixation activity. These parameters are measured in relative units.

2.9. Statistical Analyses

Data are expressed as the means of three analyses for each treatment and three analyses for different compost analyses. Significant difference tests were carried out to analyze the effects of fertilizers on each of the various parameters measured. Homogeneity of variance and normality were tested, respectively, with the tests by Bartlett and Shapiro with a p value of 0.05. For all other variables, a one-way ANOVA ($p < 0.05$) was performed, followed by Tukey's post hoc test tests, to find significant differences between treatments ($p < 0.05$). The ANOVA and t-test were carried out using XLStat. To explore the relationships among different fertilizers on the soil, broccoli, and red cabbage, we analyzed parameter datasets using principal component analysis (PCA) with XLStat.

3. Results

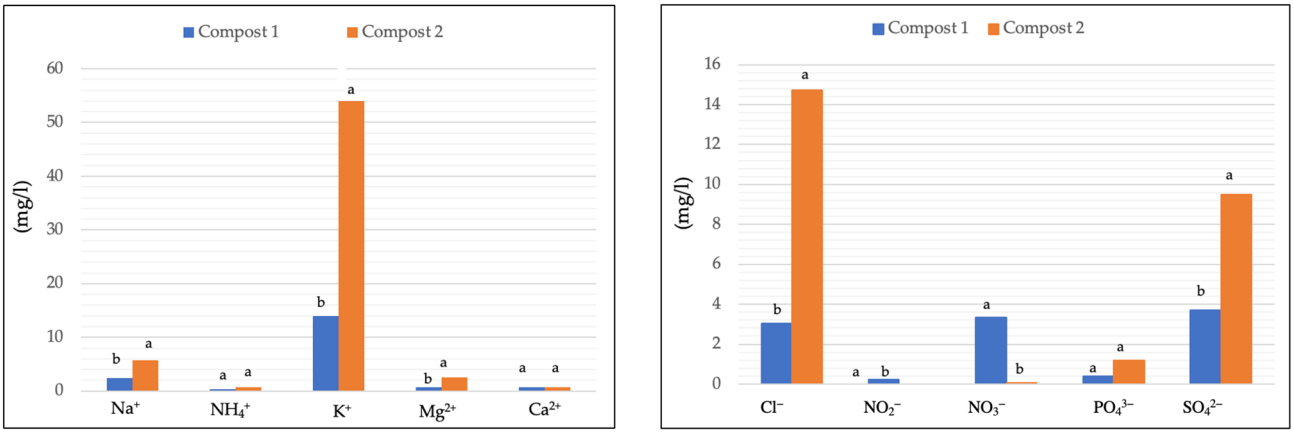
3.1. Compost Properties

The composting procedure underwent three repetitions through independent experiments. The outcomes consistently revealed that each compost derived from these experiments exhibited identical chemical characteristics. This observation strongly indicated that the adopted procedure has been successfully standardized, ensuring the reproducibility of the results over time. After a 4-month composting period, the analysis revealed noteworthy distinctions between the two composts obtained using the same methodology (Table 2). Both C1 and C2 composts displayed highly alkaline pH levels. C2 exhibited the highest total organic carbon and total nitrogen, while C1 and C2 differed in their C/N ratio (21.57 for C1 and 11.97 for C2). The N-NH_4^+/N-NO_3^- ratio was the highest in C2, whereas the ON/TN ratio was significantly greater in C1 than in C2 (Table 2). Despite all composts being nutrient-rich (Figure 1a,b), C2 contained more nutrients than C1, in particular potassium and magnesium (Figure 1a), C1 contained the highest amount of NO_2 and NO_3. Conversely, C2 had the greatest amount of phosphates and sulfates (Figure 1b). Notably, C2 contained eight times more water-soluble phenols (WSP) and concurrently exhibited a greater cation exchange capacity and FDA and DHA activities than C1 (Figure 2). Assessing compost

maturity through phytotoxicity, as indicated by the germination index (Figure 3), revealed that C1 did not exhibit phytotoxicity in *Cucumis sativus*. The germination index measured 6 days post-germination at 25%, 50%, and 75% compost concentrations consistently exceeded 80%, classifying it as phytonutrient. These findings align with the overall germination index, ranging from 67.5% to 95%, confirming the non-phytotoxic nature of both composts.

Table 2. Physico-chemical properties of the two composts obtained from different raw materials Compost 1 (50% wood sawdust + 50% wet wastes) and Compost 2 (10% Straw + 90% wet wastes) 120 days after the composting process. pH (H_2O and KCl); electric conductivity (EC, mS cm^{-1}); water content (WC, %); total organic carbon (TOC, %); Total Nitrogen (TN, %); carbon–nitrogen ratio (C/N); ammonium-nitrogen–nitrate-nitrogen ratio (NH_4^+-N/NO_3^--N); organic nitrogen–total nitrogen ratio (ON/TN, %), water-soluble phenols (WSP µg GAE g^{-1} d.s). Data are the means of three replicates ± standard deviation. Different letters in the same row indicate significant differences at $p \leq 0.05$.

Physico-Chemical Properties	COMPOST 1	COMPOST 2
pH_{H_2O}	9.05 ^{b} ± 0.1 very strongly alkaline	9.90 ^{a} ± 0.1 very strongly alkaline
pH_{KCl}	8.39 ^{b} ± 0.1	9.28 ^{a} ± 0.1
E.C.	5.01 ^{a} ± 0.12	5.06 ^{a} ± 0.11
Water content	56.8 ^{a} ± 2	45.9 ^{b} ± 1.5
TOC	16.8 ^{b} ± 0.9	24.0 ^{a} ± 1
TN (%)	0.78 ^{b} ± 0.05	2.0 ^{a} ± 0.1
C/N	21.57 ^{a} ± 1	11.97 ^{b} ± 0.9
NH_4^+-N/NO_3-N	1.30 ^{b} ± 0.3	2.80 ^{a} ± 0.2
ON/TN	90 ^{a} ± 2	60 ^{b} ± 1
WSP	0.90 ^{b} ± 0.05	7.03 ^{a} ± 0.3



(**a**) (**b**)

Figure 1. Cation concentration (mgL^{-1}) (**a**) and anion concentration (mgL^{-1}) (**b**) detected in Compost 1 (50% wood sawdust + 50% wet wastes) and Compost 2 (10% Straw + 90% wet wastes) 120 days after the composting process at the end of the composting process. Different letters indicate significant differences (Turkey's test $p \leq 0.05$).

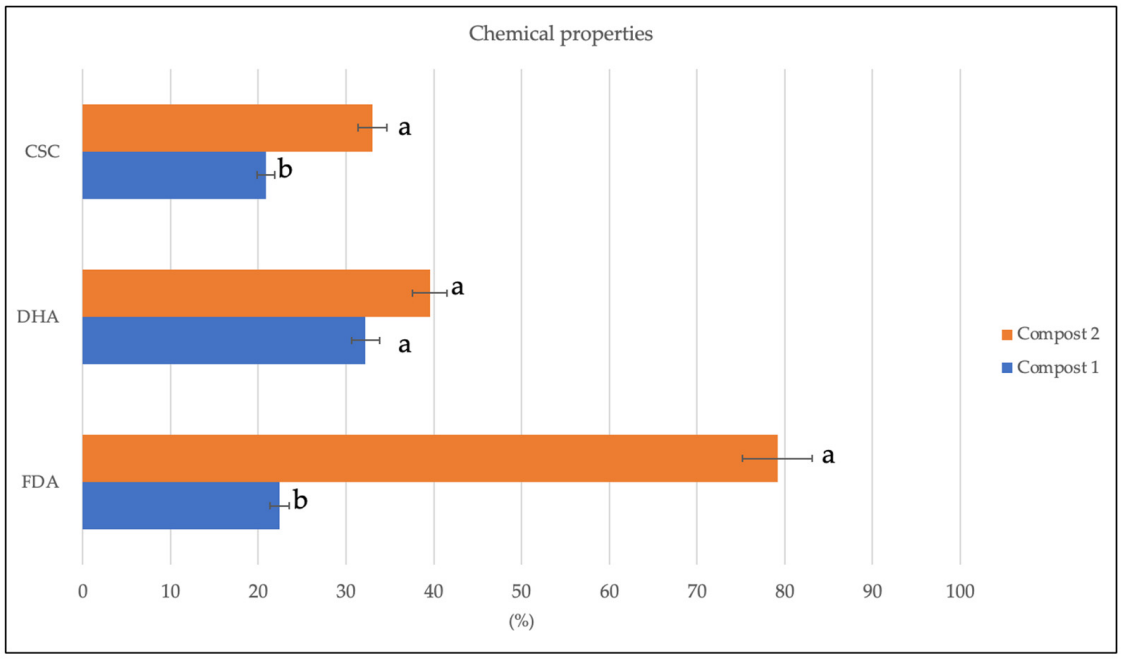


Figure 2. Fluorescein diacetate hydrolase (FDA, µg fluorescein g^{-1} d.w.), dehydrogenase (DHA, µg TTF g^{-1} h^{-1}d.w.), cation exchange capacity (CEC, $cmol^{(+)}$ Kg^{-1}) detected in Compost 1 (50% wood sawdust + 50% wet wastes) and Compost 2 (10% Straw + 90% wet wastes) 120 days after the composting process. Different letters indicate significant differences (Turkey's test $p \leq 0.05$).

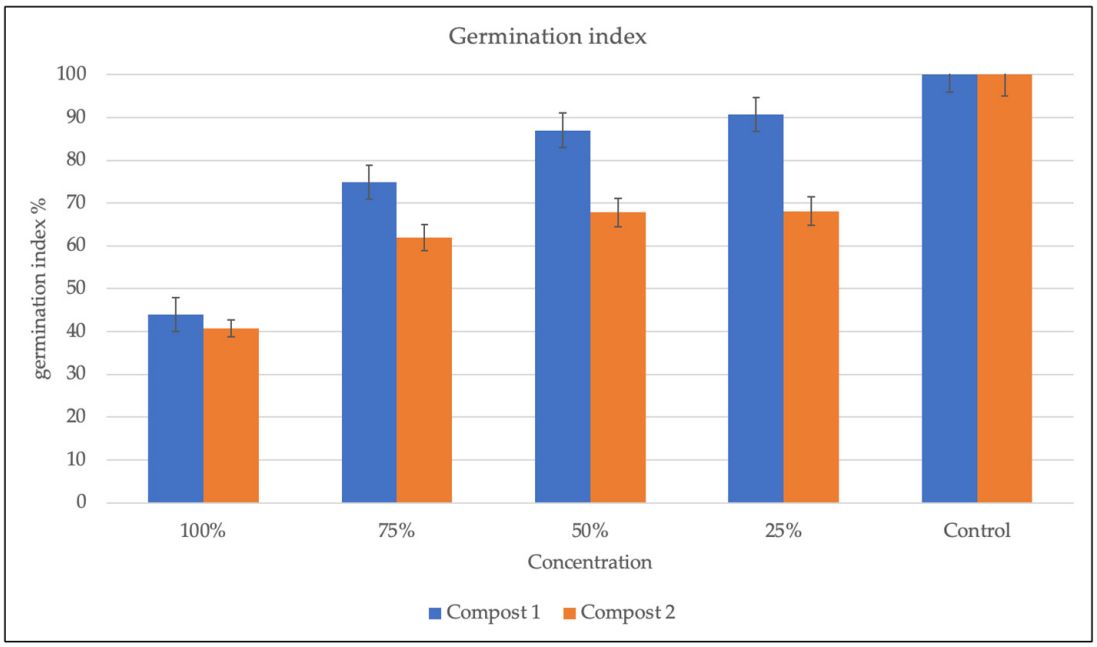


Figure 3. Germination index in Compost 1 (50% wood sawdust + 50% wet wastes) and Compost 2 (10% Straw + 90% wet wastes) 120 days after the composting process.

In terms of adsorption capacity for composts, it was observed that all the composts exhibited the ability to adsorb both sodium and chloride, albeit to varying degrees. The phenomenon of negative values recorded at 0 mM of sodium and chloride can be explained by considering that, in the absence of the addition of these two ions in the solutions, other ions remain adsorbed in the compost-available surfaces. This process leads to the generation of negative adsorption values for sodium and chloride. Notably, C2 demonstrated the

highest sodium adsorption capacity, outperforming the other compost. Meanwhile, C1 exhibited an optimal sodium removal capacity at 50 mM NaCl, with a subsequent decline in efficiency as the sodium concentration increased (Table 3). Turning attention to chloride adsorption capacity, it was observed that all composts possessed the capability to remove chloride ions. As the chloride concentration increased, the adsorption capacity of all composts gradually intensified. Notably, C2 displayed the most significant adsorption capacity for chloride ions, further emphasizing its efficacy in the removal of both sodium and chloride.

Table 3. The data regarding the absorption capacity of the analyzed compost related to sodium and chloride. Data are the means of three replicates ± standard deviation. Different letters in the same row indicate significant differences (Turkey's test $p \leq 0.05$).

	0 mM	25 mM	50 mM	100 mM	150 mM
ID	Na^+	Na^+	Na^+	Na^+	Na^+
C1	$-4.56^{e} \pm 0.15$	$8.09^{d} \pm 0.76$	$12.60^{c} \pm 0.23$	$53.58^{b} \pm 0.24$	$93.95^{a} \pm 1.4$
C2	$-3.26^{e} \pm 0.2$	$88.11^{d} \pm 0.6$	$109.51^{c} \pm 0.2$	$243.50^{a} \pm 0.4$	$212.88^{b} \pm 1.3$
ID	Cl^-	Cl^-	Cl^-	Cl^-	Cl^-
C1	$-5.86^{e} \pm 0.2$	$53.23^{d} \pm 0.16$	$120.59^{c} \pm 1.6$	$138.23^{b} \pm 1.8$	$367.99^{a} \pm 3.6$
C2	$-4.330^{e} \pm 0.1$	$87.40^{d} \pm 0.5$	$124.08^{c} \pm 0.1$	$311.51^{b} \pm 0.1$	$461.24^{a} \pm 0.2$

3.2. Soil Characteristics

Table 4 shows the analysis of the soil at time zero, before initiating the various fertilization treatments. It was an alkaline sandy-loam soil, with 2.37% organic matter, poor in anions and cations, and with a CEC of 13 $cmol^{(+)}\ kg^{-1}$. Bacteria were more abundant than fungi and actinomycetes, as also evidenced by a greater DHA with respect to FDA.

Table 4. Chemical and biochemical properties of soil located in Motta San Giovanni before fertilization. WC (water content %), pH $_{H_2O}$ in water and pH_{KCl} in potassium chloride; EC = electric conductivity (dS/m); WSP = water-soluble phenols (µg TAE g^{-1} ds): OC = organic carbon (%); TN = total nitrogen (%); C/N = carbon–nitrogen ratio; OM = organic matter (%); MBC = microbial biomass carbon (µg C g^{-1} f.s.); Dehydrogenase (DHA, µg TTF g^{-1} h^{-1} d.s.), fluorescein diacetate hydrolase (FDA, µg fluorescein g^{-1} d.s.), BACT (bacteria, UFC g^{-1} f.s.), FUN (fungi (UFC g^{-1} f.s.), ACT (Actinomycetes, UFC g^{-1} f.s.), CEC = cation exchange capacity ($cmol^{(+)}\ Kg^{-1}$ d.s.). Data are the means of three replicates ± standard deviation.

	SOIL
Skeleton (%)	45 ± 0.01
Sandy %	65 ± 0.02
Clay %	23 ± 0.12
Silt %	12 ± 0.23
Textural Class	Sandy-loam
WC	18 ± 0.4
pH (H_2O)	8.5 ± 0.32
pH (KCl)	7.8 ± 0.53
EC	307.3 ± 12.3
CEC ($cmol^{(+)}\ kg^{-1}$)	16 ± 1.7
OC	1.37 ± 0.13
TN	0.19 ± 0.14
C/N	7.21 ± 0.13
WSP	276.1 ± 4.5
MBC	376 ± 8.6

Table 4. *Cont.*

	SOIL
FDA	2.1 ± 0.12
DHA	15.11 ± 0.22
BACT	0.9×10^5
FUN	2.6×10^4
ACT	2.7×10^4
Na^+	0.117 ± 0.32
K^+	0.100 ± 0.26
Ca^{2+}	0.311 ± 0.06
Mg^{2+}	0.011 ± 0.16
Cl^-	0.222 ± 0.11
$NO_2{}^-$	nd
$NO_3{}^-$	nd
$PO_4{}^{3-}$	nd
$SO_4{}^{2-}$	0.134 ± 0.11

All the fertilizers used (both composts, NPK, and HM) affected the soil's chemical properties with respect to the control, except for texture, which remained unchanged.

The pH did not change with the treatments. Instead, the EC increased in a particular way with the additions of both composts and much more with C2, suggesting an addition of nutrients. Adding composts to the soil can provide a great quantity of nutrients in the form of hydrated salts, helping to increase the percentage of water in the soils.

The Pearson correlation coefficient also evidenced synergies between cations and among cations and anions. Shortly, potassium was correlated with calcium, suggesting a synergism among them and also with anions, in particular with sulfate (Tables 5 and 6).

Table 5. Soil ions and cations correlation matrix. Pearson values in bold are different from 0 with a significance level alpha = 0.05.

Variables	**Na^+**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**$NO_2{}^-$**	**$NO_3{}^-$**	**$PO_4{}^{3-}$**	**$SO_4{}^{2-}$**
Na^+	**1**	**0.908**	0.125	0.326	0.582	**0.998**	**0.998**	**0.998**	**0.931**
K^+	**0.908**	**1**	0.408	0.582	0.759	**0.893**	**0.893**	**0.893**	**0.980**
Ca^{2+}	0.125	0.408	**1**	**0.887**	0.793	0.090	0.090	0.090	0.441
Mg^{2+}	0.326	0.582	**0.887**	**1**	0.672	0.309	0.309	0.309	0.635
Cl^-	0.582	0.759	0.793	0.672	**1**	0.540	0.540	0.540	0.751
$NO_2{}^-$	**0.998**	**0.893**	0.090	0.309	0.540	**1**	1.000	**1.000**	**0.921**
$NO_3{}^-$	**0.998**	**0.893**	0.090	0.309	0.540	**1.000**	**1**	**1.000**	**0.921**
$PO_4{}^{3-}$	**0.998**	**0.893**	0.090	0.309	0.540	**1.000**	**1.000**	**1**	**0.921**
$SO_4{}^{2-}$	**0.931**	**0.980**	0.441	0.635	0.751	**0.921**	**0.921**	**0.921**	**1**

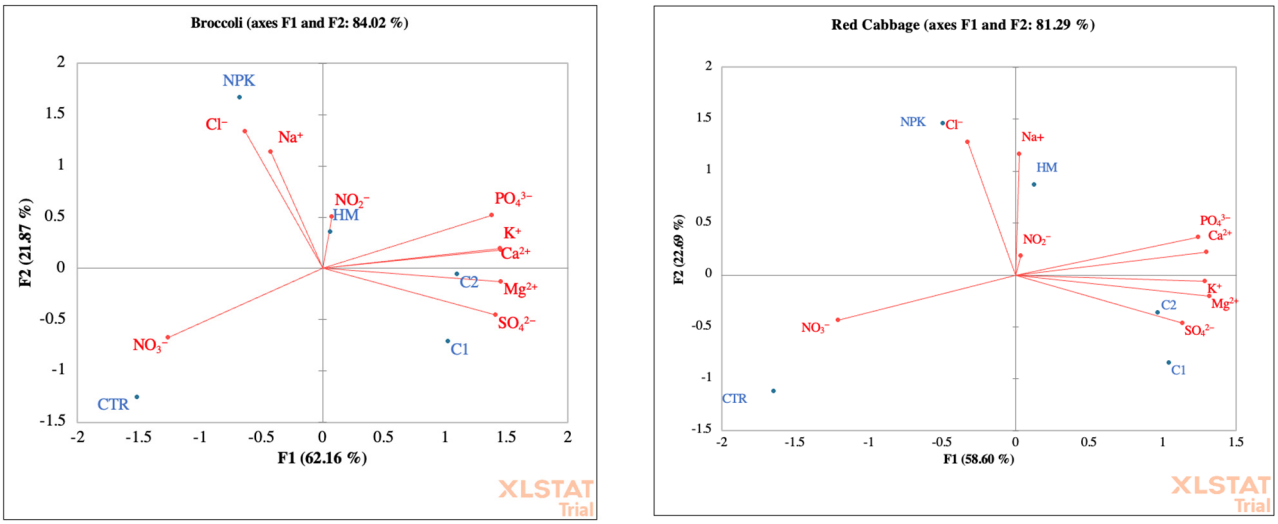
Table 6. Cations and anions concentrations (mg/L) detected 90 days after treatments with the different fertilizers. CTR (control) soil without fertilizer; NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% straw + 90% wet wastes Na^+ (sodium), K^+ (potassium), Ca^{2+} (calcium), Mg^{2+} (magnesium), Cl^- (chloride), $NO_2{}^-$ (nitrite), $NO_3{}^-$ (nitrate), $PO_4{}^{3-}$ (phosphate), $SO_4{}^{2-}$ (sulfate). Data are the means of three replicates ± standard deviation. Different letters in the same row indicate significant differences (Turkey's test $p \leq 0.05$).

Soil Cations	**CTR**	**Soil + NPK**	**Soil + HM**	**Soil + C1**	**Soil + C2**
Na^+	$0.124^{b} \pm 0.02$	$0.119^{b} \pm 0.08$	$0.101^{b} \pm 0.10$	$0.155^{b} \pm 0.09$	$0.91^{a} \pm 0.07$
K^+	$0.116^{c} \pm 0.07$	$0.165^{b} \pm 0.03$	$0.145^{bc} \pm 0.12$	$0.199^{a} \pm 0.11$	$0.290^{a} \pm 0.06$
Ca^{2+}	$0.254^{b} \pm 0.32$	$0.234^{b} \pm 0.22$	$0.346^{b} \pm 0.27$	$0.495^{b} \pm 0.19$	$3.53^{a} \pm 0.16$
Mg^{2+}	$0.019^{a} \pm 0.23$	$0.021^{a} \pm 0.31$	$0.027^{a} \pm 0.12$	$0.029^{a} \pm 0.22$	$0.027^{a} \pm 0.12$
Soil Anions	CTR	Soil + NPK	Soil + HM	Soil + C1	Soil + C2

Table 6. *Cont.*

Soil Cations	CTR	Soil + NPK	Soil + HM	Soil + C1	Soil + C2
Cl^-	0.222 ^{b} ± 0.23	0.206 ^{b} ± 0.34	0.208 ^{b} ± 0.21	0.310 ^{a} ± 0.07	0.298 ^{a} ± 0.02
NO_2^-	nd	nd	nd	nd	0.01 ± 0.01
NO_3^-	nd	nd	nd	nd	0.06 ± 0.02
PO_4^{3-}	nd	nd	nd	nd	0.003 ± 0.01
SO_4^{2-}	0.134 ^{c} ± 0.32	0.339 ^{b} ± 0.12	0.479 ^{b} ± 0.17	0.769 ^{b} ± 0.19	1.65 ^{a} ± 0.18

A PCA analysis demonstrated that C1 and C2 in red cabbage soil correlated with sulfate, magnesium, and potassium. NPK correlated with chloride; CTR with nitrate; and HM with the nitrite, phosphate, calcium, and sodium (Figure 4b). The scenario changed in soil with broccoli. C1 and C2 were both correlated with magnesium and sulfate. HM correlated as for red cabbage with the addition of potassium (Figure 4a).



(**a**) (**b**)

Figure 4. Principal component analyses of ions and cations soil with broccoli (**a**) and red cabbage (**b**). CTR (Control) soil without fertilizer; NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% straw and 90% wet wastes.

Organic carbon was the highest with composts. Total nitrogen was the greatest in NPK treatment. The C/N value was higher in soil fertilized with HM and composts with respect to CTR and NPK. WSP was the lowest in compost treatments, while DHA, MBC, bacteria, and actinomycetes were the highest. Fungi and FDA were more abundant in CTR and soil treated with NPK and HM (Table 7). A PCA analysis evidenced a strong positive correlation between C1 MBC, DHA, CEC, OC, and C/N, while C2 correlated better with bacteria, actinomycetes, and OC. HM and NPK were instead correlated with FDA, fungi, and WSP (Figure 5).

Pearson correlation coefficient evidenced a positive, significant similar tendency between organic matter, MBC, CEC, DHA, bacteria, and actinomycetes, suggesting that increasing the SOM amount also increased the amount of microbial biomass as well as the enzymes belonging to the oxo-reductase category, as also demonstrated by the increase in bacteria and actinomycete colonies (Table 8).

Table 7. Chemical and biochemical properties of soil located in Motta San Giovanni, 90 days after treatments with the different fertilizers. CTR (control) soil without fertilizer; NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% straw and 90% wet wastes. WC (water content %), pH_{H_2O} in water and pH_{KCl} in potassium chloride; EC = electric conductivity (dS/m); WSP = water-soluble phenols (µg TAE g^{-1} ds); OC = organic carbon (%); TN = total nitrogen (%); C/N = carbon nitrogen ratio; OM = organic matter (%); MBC = microbial biomass carbon (µg C g^{-1} f.s.); dehydrogenase (DHA, µg TTF g^{-1} h^{-1} d.s.), fluorescein diacetate hydrolase (FDA, µg fluorescein g^{-1} d.s.), BACT (bacteria, UFC g^{-1} f.s.), FUN (fungi (UFC g^{-1} f.s.), ACT (Actinomycetes, UFC g^{-1} f.s.), CEC = cation exchange capacity ($cmol^{(+)}$ Kg^{-1}d.s.).

Soil Chemical Analyses	CTR	Soil + NPK	Soil + HM	Soil + C1	Soil + C2
WC (%)	21.4 ^{b} ± 0.02	22.2 ^{b} ± 0.01	25.6 ^{a} ± 0.03	25.2 ^{a} ± 0.01	25.5 ^{a} ± 0.01
pH (H_2O)	8.45 ^{a} ± 0.12	8.46 ^{a} ± 0.02	8.47 ^{a} ± 0.05	8.44 ^{a} ± 0.05	8.41 ^{a} ± 0.01
pH (KCl)	7.1 ^{a} ± 0.07	7.01 ^{a} ± 0.06	6.99 ^{a} ± 0.05	6.94 ^{a} ± 0.04	6.97 ^{a} ± 0.05
EC	350 ^{c} ± 0.23	301 ^{c} ± 0.22	297 ^{c} ± 0.12	530 ^{b} ± 0.17	740 ^{a} ± 0.14
OC	1.78 ^{b} ± 0.19	1.69 ^{b} ± 0.22	2.13 ^{ab} ± 0.11	2.9 ^{a} ± 0.09	3.3 ^{a} ± 0.09
TN	0.19 ^{a} ± 0.17	0.23 ^{a} ± 0.09	0.21 ^{a} ± 0.13	0.19 ^{a} ± 0.12	0.20 ^{a} ± 0.11
C/N	9.4 ^{b} ± 0.15	7.39 ^{c} ± 0.15	19.1 ^{a} ± 0.16	15.2 ^{a} ± 0.11	16.5 ^{a} ± 0.14
WSP	282 ^{b} ± 0.32	320 ^{a} ± 0.52	315 ^{a} ± 0.42	138 ^{c} ± 1.12	170 ^{c} ± 0.92
MBC	433.3 ^{c} ± 0.52	733 ^{b} ± 0.17	798 ^{b} ± 0.42	897.33 ^{a} ± 0.52	961.4 ^{a} ± 0.32
FDA	5.14 ^{a} ± 0.44	5.44 ^{a} ± 0.33	5.33 ^{a} ± 0.27	4.88 ^{b} ± 0.36	4.81 ^{b} ± 0.18
DHA	20.1 ^{b} ± 0.72	22.1 ^{b} ± 0.32	24.1 ^{b} ± 0.42	32.92 ^{a} ± 0.32	38.09 ^{a} ± 0.42
BACT	1.3×10^{5} ^{c} ± 1.42	1.1×10^{5} ^{c} ± 2.12	1.6×10^{5} ^{c} ± 3.32	5×10^{5} ^{b} ± 3.13	8.3×10^{5} ^{a} ± 2.12
FUN	4.6×10^{4} ^{a} ± 3.12	4.5×10^{4} ^{a} ± 1.42	4.6×10^{4} ^{a} ± 2.62	2.7×10^{4} ^{b} ± 2.11	3×10^{4} ± 2.02 ^{b}
ACT	5.7×10^{4} ^{a} ± 2.12	3.7×10^{4} ^{b} ± 4.12	6.7×10^{4} ^{a} ± 1.12	1.3×10^{5} ^{c} ± 3.16	1.5×10^{5} ^{c} ± 2.21
CEC	16 ^{b} ± 0.13	12 ^{c} ± 0.12	19 ^{ba} ± 0.18	22 ^{a} ± 0.11	22.9 ^{a} ± 0.15

Different letters in the same row indicate significant differences (Turkey's test $p \leq 0.05$). Values are the mean of three replicates (n = 15) ± standard deviation.

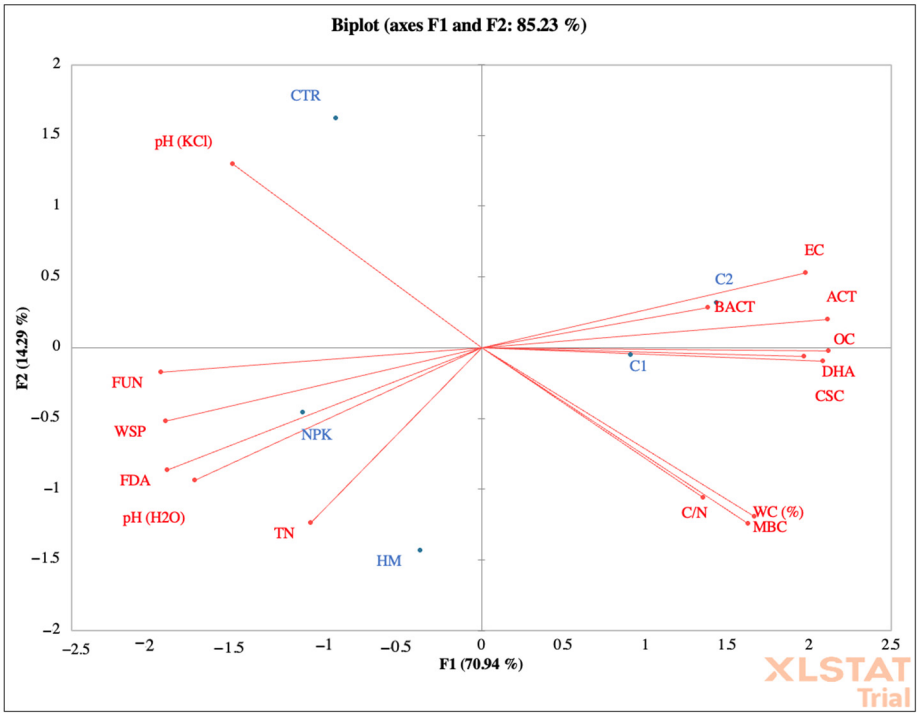


Figure 5. Principal component analyses of chemical and biochemical properties of soil located in Motta San Giovanni before fertilization. CTR (control) soil without fertilizer; NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% straw and 90% wet wastes.

Table 8. Correlation matrix (Pearson) of chemical and biochemical properties of soil located in Motta San Giovanni, 90 days after treatments with the different fertilizers. CTR (control) soil without fertilizer; NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% Straw and 90% wet wastes. Values in bold are different from 0 with a significance level of alpha = 0.05.

Variables	WC (%)	pH (H_2O)	pH (KCl)	EC	OC	TN	C/N	WSP	MBC	FDA	DHA	BACT	FUN	ACT	CEC
WC (%)	**1**	−0.315	−0.841	0.529	0.770	−0.175	**0.934**	−0.525	0.863	−0.473	0.740	0.403	−0.593	0.714	0.825
pH (H_2O)	−0.315	**1**	0.312	**−0.971**	−0.831	0.441	−0.189	0.794	−0.468	**0.879**	−0.847	−0.815	0.774	−0.848	−0.651
pH (KCl)	−0.841	0.312	**1**	−0.506	−0.715	−0.059	−0.602	0.602	**−0.959**	0.403	−0.752	−0.229	0.736	−0.655	−0.609
EC	0.529	**−0.971**	−0.506	**1**	**0.939**	−0.444	0.390	−0.860	0.641	**−0.912**	**0.947**	0.806	−0.861	**0.942**	0.787
OC	0.770	−0.831	−0.715	**0.939**	**1**	−0.463	0.637	**−0.895**	0.794	**−0.894**	**0.988**	0.677	**−0.913**	**0.992**	**0.921**
TN	−0.175	0.441	−0.059	−0.444	−0.463	**1**	−0.314	0.641	0.100	0.758	−0.341	−0.093	0.466	−0.565	−0.659
C/N	**0.934**	−0.189	−0.602	0.390	0.637	−0.314	**1**	−0.372	0.631	−0.406	0.561	0.351	−0.383	0.598	0.813
WSP	−0.525	0.794	0.602	−0.860	**−0.895**	0.641	−0.372	**1**	−0.591	**0.947**	−0.874	−0.394	**0.977**	**−0.934**	−0.819
MBC	0.863	−0.468	**−0.959**	0.641	0.794	0.100	0.631	−0.591	**1**	−0.456	0.841	0.485	−0.729	0.720	0.648
FDA	−0.473	**0.879**	0.403	**−0.912**	**−0.894**	0.758	−0.406	**0.947**	−0.456	**1**	−0.850	−0.558	**0.879**	**−0.942**	−0.861
DHA	0.740	−0.847	−0.752	**0.947**	**0.988**	−0.341	0.561	−0.874	0.841	−0.850	**1**	0.704	**−0.919**	**0.968**	0.851
BACT	0.403	−0.815	−0.229	0.806	0.677	−0.093	0.351	−0.394	0.485	−0.558	0.704	**1**	−0.416	0.636	0.521
FUN	−0.593	0.774	0.736	−0.861	**−0.913**	0.466	−0.383	**0.977**	−0.729	**0.879**	**−0.919**	−0.416	**1**	**−0.928**	−0.784
ACT	0.714	−0.848	−0.655	**0.942**	**0.992**	−0.565	0.598	**−0.934**	0.720	**−0.942**	**0.968**	0.636	**−0.928**	**1**	**0.932**
CEC	0.825	−0.651	−0.609	0.787	**0.921**	−0.659	0.813	−0.819	0.648	−0.861	0.851	0.521	−0.784	**0.932**	**1**

3.3. Crop Growth Data

In the presence of both composts, red cabbage exhibited a significant augmentation in leaf width, leaf area, leaf length, and plant height compared to the control, NPK, and HM treatments. The fruit-head diameter when C1 and C2 were applied shows an approximate 50% increase compared to the control and a 25% increase compared to HM and NPK. Productivity, measured in tons per hectare, experienced a noteworthy enhancement of 15% compared to NPK and HM in the presence of both composts. Notably, C1 demonstrated the most substantial effect on productivity, boasting a 35% increase compared to the control and a 30% increase compared to HM and NPK (Table 9).

Table 9. Growth parameters and productivity (tons per hectare) of red cabbage and broccoli grown in not-amended soil (control, CTR), NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% Straw + 90% wet wastes.

Red Cabbage	CTR	NPK	HM	C1	C2
Leaf humidity (%)	$84^{a} \pm 0.11$	$84^{a} \pm 0.62$	$86^{a} \pm 0.42$	$86^{a} \pm 0.32$	$85^{a} \pm 0.46$
Leaf width (cm)	$5.7^{a} \pm 0.56$	$8.8^{ab} \pm 0.25$	$1^{a} \pm 0.42$	$14^{a} \pm 0.15$	$13^{a} \pm 0.52$
Leaf length (cm)	$4.4^{a} \pm 0.12$	$7.8^{ab} \pm 0.41$	$10^{a} \pm 0.68$	$9.5^{a} \pm 0.42$	$10^{a} \pm 0.23$
Leaf area (cm^2)	$45^{c} \pm 0.25$	$65^{b} \pm 0.42$	$75^{b} \pm 0.13$	$96^{a} \pm 0.32$	$91^{a} \pm 0.15$
Plant height (cm)	$20^{c} \pm 0.125$	$30^{b} \pm 0.14$	$35^{b} \pm 0.12$	$43^{a} \pm 0.12$	$40^{a} \pm 0.43$
Head diameter (cm)	$10^{b} \pm 1.42$	$12^{a} \pm 2.32$	$12^{a} \pm 1.72$	$15^{a} \pm 2.52$	$15^{a} \pm 1.52$
Yield (Tons/ha)	$36^{b} \pm 1.51$	$42^{a} \pm 1.42$	$42^{a} \pm 1.32$	$49^{a} \pm 2.12$	$47^{a} \pm 2.32$

Table 9. *Cont.*

Red Cabbage	CTR	NPK	HM	C1	C2
Broccoli Calabrese	CTR	NPK	HM	C1	C2
Leaf humidity (%)	84 ^{a} ± 0.15	84 ^{a} ± 0.18	86 ^{a} ± 0.62	86 ^{a} ± 0.43	85 ^{a} ± 0.65
Leaf width (cm)	9 ^{a} ± 3.32	12 ^{a} ± 3.44	11 ^{a} ± 2.32	15 ^{a} ± 2.23	14 ^{a} ± 1.12
Leaf length (cm)	14 ^{a} ± 2.42	17 ^{a} ± 3.22	18 ^{a} ± 2.12	18 ^{a} ± 0.22	18 ^{a} ± 0.16
Leaf area (cm^2)	70 ^{b} ± 0.29	165 ^{a} ± 0.59	175 ^{a} ± 0.54	196 ^{a} ± 0.44	191 ^{a} ± 0.12
Plant height (cm)	50 ^{b} ± 0.34	60 ^{b} ± 0.14	65 ^{ab} ± 2.42	80 ^{a} ± 2.12	75 ^{a} ± 2.32
Head diameter (cm)	10 ^{b} ± 2.12	16 ^{a} ± 2.32	15 ^{a} ± 3.10	19 ^{a} ± 3.11	19 ^{a} ± 3.12
Yield (Tons/ha)	5 ^{c} ± 3.12	15 ^{b} ± 4.01	19 ^{ab} ± 2.12	22 ^{a} ± 4.2	21 ^{a} ± 3.11

Different letters in the same row indicate significant differences (Turkey's test $p \leq 0.05$). Values are the mean of three replicates (n = 15) ± standard deviation.

Similarly, broccoli calabrese, when exposed to C1 and C2, exhibited a significant surge in growth. The leaf area tripled in comparison to the control, surpassing NPK and HM by 20%. Productivity, experiencing a fourfold increase compared to the control, surpassed NPK by 40% and HM by 15% (Table 9).

Chlorophyll (Table 10) data evidenced a greater amount of total chlorophyll and Cha/Chb ratio in broccoli and red cabbage treated with C1 and C2 with respect to CTR, HM, and NPK. Regarding the photosynthetic parameters of chlorophyll fluorescence, Fv, Fm, F0, and Y(NPQ) were the lowest in broccoli and red cabbage treated with both composts. Conversely, the Fv/Fm ratio, Y(NO), and ETR were instead the highest both in broccoli and red cabbage treated with both composts.

Table 10. Content of chlorophyll a (Chl a, mg 100 g^{-1}FW), chlorophyll b (Chl b, mg 100 g^{-1}FW), total chlorophyll (TChl, mg 100 g^{-1}FW), chlorophyll a/chlorophyll b (Chl a/Chl b) and photosynthetic parameters (FV, Fm, Y(NPQ), Y(NO) and ETR are expressed as µmol m^{-2} s^{-1}) in leaves of bed cabbage and broccoli calabrese.

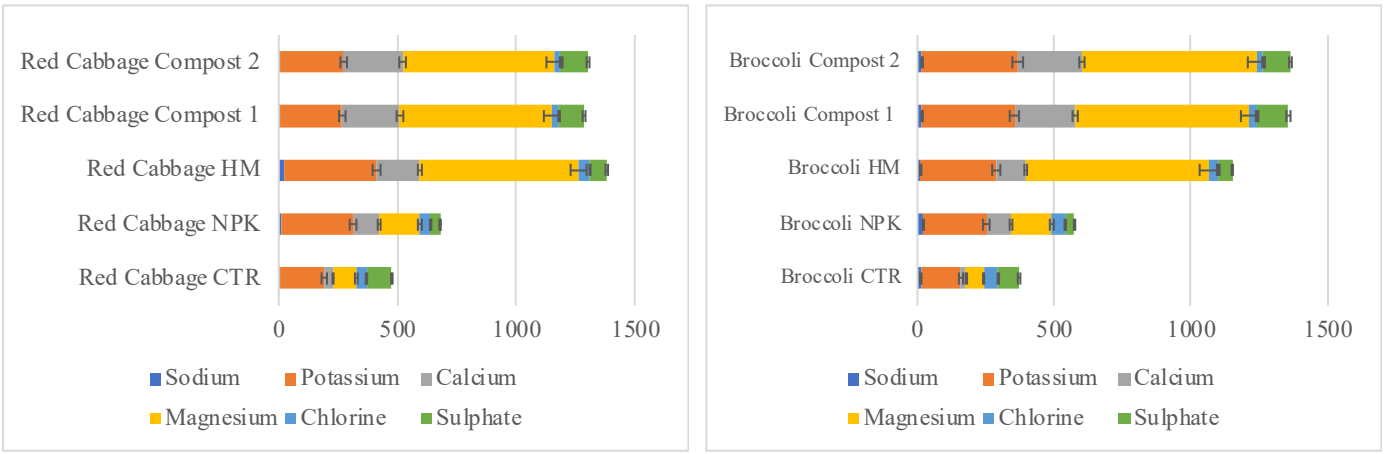
Broccoli Calabrese	CTR	NPK	HM	C1	C2
Chl a	114 ^{b} ± 0.43	120 ^{b} ± 0.12	142 ^{a} ± 0.02	158 ^{a} ± 0.12	167 ^{a} ± 0.19
Chl b	60 ^{a} ± 2.25	54 ^{a} ± 3.11	55 ^{a} ± 1.11	57 ^{a} ± 1.45	59 ^{a} ± 1.24
Chla/Chlb	1.9 ^{b} ± 1.11	2.2 ^{b} ± 1.12	2.58 ^{a} ± 1.54	2.77 ^{a} ± 1.12	2.83 ^{a} ± 1.02
T Chl	174 ^{b} ± 5.12	174 ^{b} ± 4.12	197 ^{ab} ± 3.14	215 ^{a} ± 4.11	226 ^{a} ± 2.12
FV	0.621 ^{b} ± 0.43	0.802 ^{ab} ± 0.22	1.004 ^{a} ± 0.12	1.007 ^{a} ± 0.52	1.107 ^{a} ± 0.23
Fm	0.939 ^{a} ± 0.65	1.077 ^{a} ± 0.21	1.423 ^{a} ± 0.22	1.222 ^{a} ± 0.61	1.343 ^{a} ± 0.36
F0	0.293 ^{b} ± 0.02	0.384 ^{ab} ± 0.02	0.528 ^{a} ± 0.11	0.534 ^{a} ± 0.12	0.544 ^{a} ± 0.74
Fv/Fm	0.661 ^{a} ± 0.02	0.74 ^{a} ± 0.01	0.71 ^{a} ± 0.12	0.82 ^{a} ± 0.01	0.82 ^{a} ± 0.01
Y(NPQ)	0.443 ^{a} ± 0.01	0.329 ^{a} ± 0.11	0.216 ^{a} ± 0.02	0.215 ^{a} ± 0.04	0.219 ^{a} ± 0.01
Y(NO)	0.235 ^{b} ± 0.02	0.215 ^{b} ± 0.01	0.344 ^{a} ± 0.01	0.397 ^{a} ± 0.03	0.361 ^{a} ± 0.04
ETR	21.21 ^{c} ± 0.12	28.84 ^{b} ± 0.16	35.24 ^{b} ± 0.14	41.26 ^{a} ± 0.13	39.54 ^{a} ± 0.14

Table 10. *Cont.*

Broccoli Calabrese	**CTR**	**NPK**	**HM**	**C1**	**C2**
Red Cabbage	CTR	NPK	HM	C1	C2
Chl a	94 ^{a} ± 0.56	100 a ± 1.52	112 ^{a} ± 4.12	118 ^{a} ± 4.67	117 ^{a} ± 5.12
Chl b	65 ^{a} ± 3.52	69 ^{a} ± 3.15	66 ^{a} ± 2.17	65 ^{a} ± 2.15	69 ^{a} ± 1.21
Chla/Chlb	1.45 ^{a} ± 0.01	1.45 ^{a} ± 0.42	1.47 ^{a} ± 0.13	1.81 ^{a} ± 0.13	1.71 ^{a} ± 0.11
T Chl	159 ^{b} ± 8.76	169 ^{a} ± 8.22	178 ^{a} ± 4.62	183 ^{a} ± 2.24	186 ^{a} ± 4.12
FV	0.644 ^{b} ± 0.02	0.776 ^{b} ± 0.01	1.016 ^{a} ± 0.01	1.027 ^{a} ± 0.02	1.144 ^{a} ± 0.02
Fm	0.899 ^{b} ± 0.03	1.000 ^{b} ± 0.25	1.227 ^{a} ± 0.26	1.392 ^{a} ± 0.11	1.465 ^{a} ± 0.12
F0	0.293 ^{b} ± 0.05	0.384 ^{b} ± 0.06	0.528 ^{a} ± 0.08	0.534 ^{a} ± 0.04	0.544 ^{a} ± 0.06
Fv/Fm	0.617 ^{a} ± 0.01	0.626 ^{a} ± 0.05	0.639 ^{a} ± 0.03	0.656 ^{a} ± 0.04	0.663 ^{a} ± 0.01
Y(NPQ)	0.433 ^{a} ± 0.02	0.409 ^{a} ± 0.08	0.216 ^{b} ± 0.03	0.225 ^{b} ± 0.07	0.256 ^{b} ± 0.09
Y(NO)	0.235 ^{b} ± 0.07	0.215 ^{b} ± 0.03	0.344 ^{a} ± 0.05	0.397 ^{a} ± 0.03	0.361 ^{a} ± 0.05
ETR	21.21 ^{c} ± 1.03	28.84 ^{b} ± 3.12	35.24 ^{b} ± 2.12	41.26 ^{a} ± 4.02	39.54 ^{a} ± 3.02

Different letters in the same row indicate significant differences (Turkey's test $p \leq 0.05$). Values are the mean of three replicates (n = 15) ± standard deviation.

The ions were predominantly present in red cabbage and broccoli treated with both composts. Magnesium, calcium, and potassium were the most abundant cations in both crop species treated with composts C1 and C2 (Figure 6).



(**a**) (**b**)

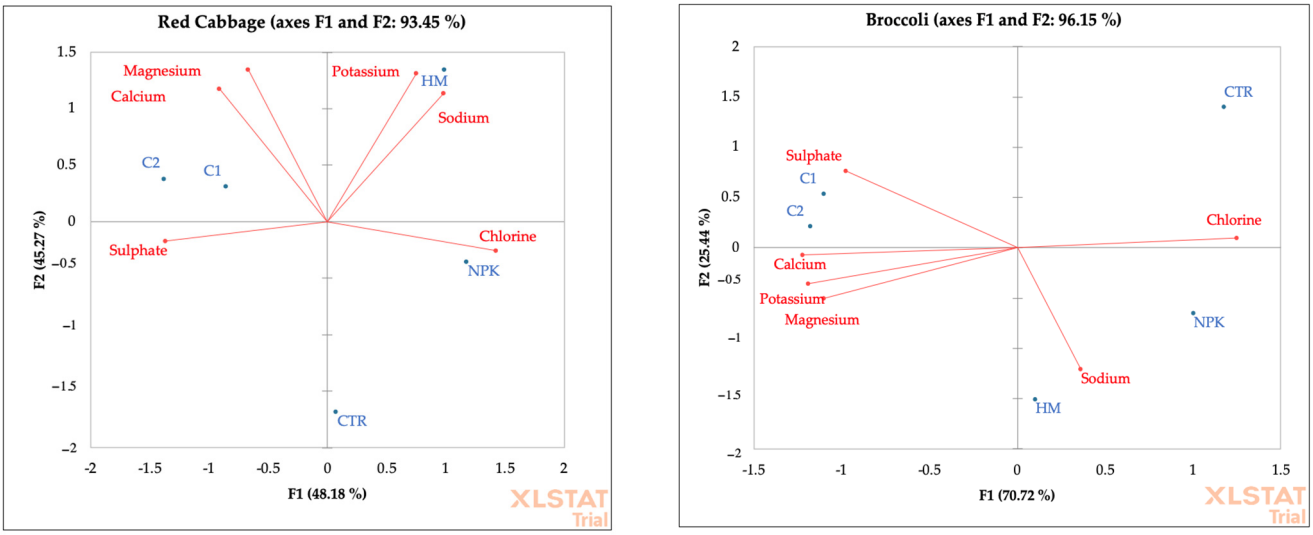
Figure 6. Bioaccumulation factor of red cabbage (**a**) and broccoli (**b**) grown in not-amended soil (control, CTR), NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% Straw + 90% wet wastes. Values are expressed as micrograms and are the mean of three replicates (n = 15) with errors standard.

Considering the bioaccumulation factor, red cabbage grown with composts 1 and 2 accumulated more magnesium, calcium, and sulfate in its leaves with respect to the other treatments. Similar results were observed for broccoli, with a greater increase even in potassium compared with the other treatments.

The best accumulation of ions has been observed in broccoli leaves treated with both composts (Figure 6).

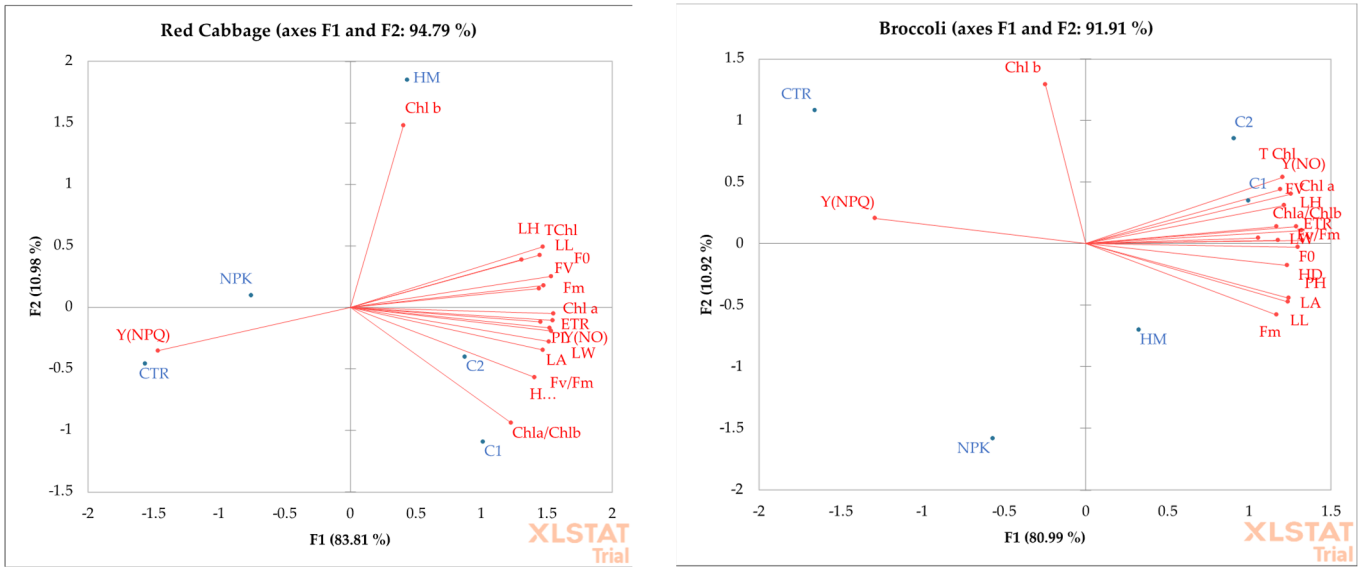
From the PCA, it emerged that broccoli cultivated with both composts accumulated sulfates, instead of HM, NPK, more sodium, and CTR chloride. (Figure 7b). The PCA related to red cabbage bioaccumulation factors evidenced an accumulation of magnesium and calcium with both composts; NPK and CTR showed an accumulation of Cl and HM of Na and K. (Figure 7a). Chlorophyll a and the photosynthesis parameters (ETR, Fm/Fv, and Y(NO) were mostly expressed in the presence of both composts in both crops. HM

correlated with total chlorophyll, chlorophyll B, F0, Fm, and Fv. No correlation between NPK and the parameters linked to photosynthesis activity has been found (Figure 8).



(**a**) (**b**)

Figure 7. PCA of ions and cations of red cabbage (**a**) and broccoli (**b**) grown in not-amended soil (control, CTR), NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% Straw + 90% wet wastes.



(**a**) (**b**)

Figure 8. Principal component analyses of the content of chlorophyll a (Chl a, mg 100 g^{-1}FW), chlorophyll b (Chl b, mg 100 g^{-1}FW), total chlorophyll (TChl, mg 100 g^{-1}FW), chlorophyll a/chlorophyll b (Chl a/Chl b) and photosynthetic parameters (FV, Fm, Y(NPQ), Y(NO), and ETR are expressed as µmol m^{-2} s^{-1}), in leaves of red cabbage (**a**) and broccoli (**b**) grown in not-amended soil (control, CTR), NPK = nitrogen–phosphorous–potassium; HM = horse manure; C1 50% wood sawdust + 50% wet wastes, C2 10% Straw + 90% wet wastes.

4. Discussion

4.1. Compost Effects on Soil Chemical and Biological Properties

Composts 1 and 2 significantly affected soil properties, increasing EC and significantly enhancing organic matter content, CEC, microbial biomass, bacteria, and actinomycetes. The observed decrease in phenol content in compost-treated soils compared to the other treatments suggested that composts may have an impact on soil microorganisms and their metabolic activities. In fact, an increase in bacteria and actinomycetes has been observed as well. The observed significant increase in actinomycetes is of paramount importance due to their critical role in the cycling of organic matter. Actinomycetes serve as a natural barrier against a wide array of plant pathogens within the rhizosphere, effectively suppressing their growth. Moreover, they are adept at breaking down complex polymer mixtures present in deceased plants, animals, and fungi. This breakdown process facilitates the production of a diverse array of extracellular enzymes, which have been shown to significantly benefit crop production, enhancing both yield and health [36–38].

Further expanding on their beneficial impact, it has been demonstrated that actinomycetes not only augment the levels of nutrients and organic matter in the soil but also substantially increase the soil's microbial biomass [39]. This, in turn, boosts nitrogen availability, a critical component for plant growth, by stimulating the activity of essential nitrogen-metabolizing enzymes. The enhancement of nitrogen availability is particularly noteworthy, as it directly supports the growth and productivity of crops.

The multifaceted benefits of actinomycetes, from pathogen suppression and organic matter decomposition to nutrient enhancement and nitrogen availability, underscore their invaluable contribution to sustainable agriculture. By leveraging the positive roles of actinomycetes, it is possible to advance sustainable food-production practices that are both productive and environmentally friendly. This approach not only aims at achieving higher crop yields but also emphasizes biosafety and the preservation of ecological balance, making both composts a cornerstone in the pursuit of global food security and sustainable agricultural development.

The results are corroborated by the Pearson coefficient data, which reveal a positive correlation among microbial biomass carbon (MBC), organic content, water content (WC), dehydrogenase activity (DHA), and actinomycete populations. Such correlations were observed in soil samples collected from areas cultivating red cabbage and broccoli, where both types of compost were applied. These observations highlight the intricate interplay between soil characteristics and the microbial shifts following fertilizer application. The findings align with the research conducted by Arunrat et al. (2023) [40], which demonstrated that consistent fertilizer use and tillage methods over five years markedly enhanced the diversity and abundance of soil microbial communities.

The study reveals that both bacterial and actinomycete populations were significantly affected by Compost 2, as demonstrated by a PCA analysis (Figure 5). In contrast, Compost 1 was found to have a positive correlation with microbial biomass, water content, cation exchange capacity (CEC), and dehydrogenase activity (DHA). These findings indicate that are the characteristics of each type of compost that, influencing specific soil parameters, enhance or modify soil ecosystem functions.

This research suggests that it is not the inherent soil properties that remained consistent across different crops in this study, nor is it the type of crop cultivated that primarily influences soil ecosystem functioning. Instead, the key factor appears to be the raw material chosen for compost production. During the composting process, these raw materials are transformed into various bio-compounds, each possessing distinct specificities that can lead to different effects on the soil ecosystem.

In essence, the study highlights the critical role of compost composition in shaping soil health and functionality. By selecting appropriate compost materials, it is possible to tailor soil conditions to support desired ecosystem functions, thereby optimizing agricultural productivity and sustainability.

Notable changes in enzyme activities have been also observed. However, the correlation pattern between MBC and DHA with the addition of both composts evidenced the impact of composts on the soil's oxidative processes. It is important to note that both HM and NPK failed to exhibit a significant association with the chemical and biochemical attributes related to soil fertility.

In summary, these results offer crucial insights into the complex interplay among fertilizers, soil properties, and microbial interactions, which are fundamental for developing knowledgeable soil-management strategies and promoting sustainable agricultural practices. By closely monitoring these variables, we can evaluate soil health, microbial function, and nutrient cycling within variously treated soil ecosystems, thereby enhancing environmental stewardship. This approach not only aids in optimizing agricultural output but also in preserving ecological balance, ensuring a sustainable future for farming practices.

4.2. Compost Effects on Crop Yield and Quality

The changes noted had a beneficial impact on the yield and quality of red cabbage and broccoli. It was found that both yield and quality were linked to the levels of organic matter in the soil, a key factor in soil fertility and functionality. Organic matter contains trace elements vital for the needs of soil microorganisms, enhancing microbial activities. This, in turn, influences the interactions among soil microorganisms, which indirectly affects crop productivity. Such dynamics underscore the critical role of organic matter in supporting agricultural success, highlighting its importance in both soil health and crop performance.

The differences in both crops, grown with both composts, compared to the control and the other fertilizers were more evident in parameters related to leaf area, width, and length as well as head diameter. These results were supported by photosynthesis parameters and pigments that were increased in compost-treated crops than in the control and the NPK- and HM-treated crops. Total chlorophyll increased in crops grown with composts, probably because it correlated to the greatest leaf area. The method of chlorophyll fluorometry offers significant insights into the health of photosynthetic systems in plants by measuring the variable fluorescence of photosystem II [41]. Among the photosynthetic parameters, the ratio of variable fluorescence (Fv) to maximal fluorescence (Fm), known as Fv/Fm, serves as the most commonly utilized indicator. This ratio reflects the efficiency of primary light-energy conversion and the maximal efficiency of photosystem II (PSII) photochemistry [42,43]. The presence of negative effects on plants of external inputs is indicated by a reduced number of open reaction centers, leading to a decreased Fv/Fm ratio [44,45]. In this study, the lowest Fv/Fm values were observed in the control of both crops and in both crops grown with NPK and HM, indicating significant positive effects of composts on their photosynthetic efficiency. Y(II) serves as a metric for assessing plant efficiency, denoting the amount of energy utilized by photosystem II (PSII) under consistent photosynthetic lighting conditions, and is directly linked to the electron transport rate (ETR) and the plant's ability to assimilate carbon [46]. This relationship highlights the critical role of Y(II) in understanding the dynamics of photosynthesis, particularly in how efficiently a plant can convert light energy into chemical energy through PSII, further influencing its growth and productivity by affecting carbon assimilation processes. In the PCA (principal component analysis) of broccoli and red cabbage diagrams, the positioning of C1 and C2 in the right quadrants highlights the particular efficiency of composts on these cultivars. The spatial arrangement in the diagrams clearly illustrates how much weight they have on photosynthetic efficiency and, consequently, on crop growth and productivity. NPQ, which stands for non-photochemical quenching, acts as a measure of how plants dissipate excess light energy as heat within the antenna system to prevent photodamage. It is deemed a crucial short-term photoprotective mechanism in higher plants. With composts in both crops, NPQ values were observed to decrease across all cultivars, while increasing in the control and NPK-treated crops. This suggests that NPK may be the cause of oxidative damage to the photosynthetic apparatus of both crops. This interpretation is supported by the total chlorophyll content (TChl) data, which were the

lowest in the NPK- and HM-treated crops and in the controls of both crops. Crops treated with composts exhibited enhanced ion uptake, a finding substantiated by bioaccumulation-factor data, which indicated that these plants accumulated essential mineral nutrients critical for human health, including magnesium (Mg), calcium, potassium, and sulfate. Current food-supply statistics indicate that approximately half of the global population is at risk of dietary deficiencies in calcium (Ca) and Mg, with this figure escalating to over 95% in 16 African countries. The strategy of biofortifying crops with Mg and Ca has been recommended as a means to bolster dietary intakes for humans [47] as well as livestock [48,49], enhancing overall food-system nutrition. Despite their potential benefits, such biofortification practices have not yet been broadly implemented within agricultural production systems. In summary, both composts evidenced a positive effect on the crop quality of broccoli and red cabbage in comparison to horse manure and synthetic fertilizers.

5. Conclusions

In short, this study has successfully identified and evaluated environmentally friendly technologies for transforming organic wastes into fertilizers, aiming to enhance soil sustainability and crop yields. By comparing two compost formulations (Compost 1 and Compost 2) with horse manure (HM) and synthetic NPK fertilizers, and utilizing unfertilized soil as a control, the research provides compelling evidence on the efficacy of these organic amendments. Despite Compost 1 having a lower organic carbon content and enzyme activity compared to Compost 2, it emerged as the superior soil improver. It significantly increased the labile fraction of organic matter, the activity of oxidative enzymes, microbial biomass, and, importantly, crop yield. These findings underscore the potential of using specific compost formulations, particularly those with a high C/N ratio and effective humification of wet materials, as viable alternatives to conventional fertilizers. This approach not only promises to improve soil health and productivity but also contributes to the broader goal of sustainable agriculture by recycling organic wastes into valuable soil amendments.

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