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Agronomic Use of Urban Composts from Decentralized Composting Scenarios: Implications for a Horticultural Crop and Soil Properties

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Abstract

Circular economy in the context of municipal organic waste management has boosted the emergence of novel composting scenarios, such as community composting and decentralized urban composting in small installations, which favors localized management and valorization of organic waste streams. However, there is little information about the agronomic use of the composts obtained from these new organic waste management systems as an alternative for inorganic fertilization in crop production. In this work, municipal solid waste-derived composts from two decentralized composting scenarios (CM1 and CM2 from community composting, and CM3 and CM4 from decentralized urban small-scale composting plants) were applied and mixed in the top layer of a calcareous clayey-loam soil to assess their effects as alternative substitutes for conventional soil inorganic fertilization (IN) during two successive cultivation cycles of lettuce (*Lactuca sativa* L.) grown in pots with the amended soils. These treatments were also compared with an organic waste (goat–rabbit manure, E) and a control treatment without fertilization (B). The effects of the fertilizing treatments on the crop yield and quality, as well as on the properties of the soil considered were studied. In general, the application of the different composts did not produce negative effects on lettuce yield and quality. The compost-derived fertilization showed similar lettuce yields compared to the inorganic and manure-derived fertilizations (IN and E, respectively), and higher yields than the soil without amendment (B), with increases in the initial yield values of B, for the first cycle from 34.2% for CM1 to 53.8% for CM3, and from 20.3% for CM3 to 92.4% for CM1 in the second cycle. Furthermore, the organically amended soils showed a better crop development, obtaining higher values than the control treatment in the parameters studied. In addition, the incorporation of the organic treatments improved the soil characteristics, leading to 1.3 and 1.2 times higher organic matter contents in the soils with CM2 and in the soils with CM1, CM3, and E, respectively, compared to the control soil without fertilizing treatment (B), and 2.0 and 1.8 times greater organic matter contents, respectively, compared to soil with inorganic

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fertilization (IN). Therefore, the use of municipal solid waste-derived composts from these new organic waste management systems, such as the decentralized composting scenarios studied (community composting and urban decentralized small-scale composting plants), is presented, not only as a sustainable valorization method, but also as an alternative for the use of inorganic fertilizers in lettuce cultivation, while enhancing soil properties, contributing to increasing the circularity of agriculture.

Keywords: community composting; decentralized composting plants; SPAD; soil quality; crop yield; *Lactuca sativa* L.

1. Introduction

In recent years, there has been a shift in municipal organic waste management models from a linear model to a circular model, where waste is considered as a new resource. The goal of the circular economy transition is to maximize the 'value' of the materials retained within the economy. However, the efforts toward the achievement of current targets have led to investments for processing high volumes of waste, but with low value. Therefore, the development of circular economy demands high-quality, secondary raw materials that can be fed back into production processes [1]. Thus, one of the main waste streams for its increasing generation is municipal solid waste (MSW), defined as the assorted mixture of solid discards generated by urban and rural conurbations/societies [2]. Despite the high diversity of this type of waste, the common constituents of this household waste include kitchen scraps, garden litter, and packaging [3]. MSW composts are the result of managing this type of waste by composting. This method is a win–win option that allows the management of these waste streams, also recovering nutrients essential for crop production, consequently enhancing crop yields and reducing expensive chemical fertilizer usage [4]. Traditionally, the composting of MSW has been carried out in centralized facilities, which require large areas and have environmental impacts associated with the long distances over which waste is transported [5]. In this context, the decentralized composting scenarios, such as community composting or composting in decentralized small-scale plants, have emerged as new systems for a more local method of management of organic waste streams, such as the organic fraction of MSW [5–8]. However, little information is available concerning the quality of the composts obtained in these composting scenarios, reflected in a lack of regulations and/or specific legislation [6]. On the other hand, the use of MSW composts has been widely studied in an important number of works, with different conditions and crops, due to their potential for agronomic, horticultural, and forestry applications in the agricultural sector, being mainly used as a soil amendment/enhancer or nutrient additive [2,9–11]. However, there is a lack of information concerning the use of municipal waste composts from decentralized composting scenarios as organic amendments and/or fertilizers in agriculture.

The production of leafy vegetable crops (i.e., crops whose plant leaves are eaten as a vegetable) has significantly increased in recent years around the world, lettuce (*Lactuca sativa* L.) being one of the most important leafy vegetable crops worldwide [12]. Spain constitutes one of the main producers of this crop, with a lettuce production that exceeds 1 million tones and an area dedicated to its cultivation of around 34,000 ha [13]. However, the intensive crop production based on non-sustainable agricultural practices has produced different environmental impacts, such as those associated with soil degradation, overexploitation of natural resources, and/or groundwater contamination [14]. Leafy vegetable production such as lettuce must be transformed to a sustainable production, mainly based on increasing the amount and quality of the organic matter incorporated into the agricultural soils [15]. Thus, the use of fertilizing strategies based on municipal solid waste composts from decentralized composting scenarios can constitute a sustainable alternative for conventional inorganic fertilization in the production of leafy vegetables such as lettuce, favoring a closed-loop system without causing an impact on the environment. In this sense, it is essential to quantify the effects of these materials not only on the crop yield, but also on the plant development parameters, such as the leaf canopy cover, a fundamental visible growth indicator that measures the spatial area covered by plants [16,17]. This indicator provides important information concerning lettuce quality, since a broader leaf corresponds to maturity as part of its phenological development [17], and thus, foliar surface area of lettuce can be considered as a physiological indicator of its growth.

Therefore, the main aim of this work was to assess the effects of the characteristics of MSW composts from decentralized composting scenarios as organic amendments compared to other conventional treatments (inorganic fertilization, manure) for lettuce cultivation during two successive growing cycles. For this, the effects were studied on the following aspects: (i) soil physico-chemical, chemical, and biological properties; (ii) lettuce crop yield and plant development parameters, mainly evaluated using canopy cover (CANOPY) and leaf chlorophyll intensity (SPAD).

2. Materials and Methods

2.1. Characteristics of the Organic Amendments and Soil Used

A total of five organic amendments were used in this study, four composts from decentralized composting scenarios and an organic waste, a mixture of two animal manures. Two of the composts came from community composting areas, located in the Valencian Community (Spain) (CM1 and CM2), and the other two were from decentralized urban composting plants located in Catalonia and Navarre (CM3 and CM4, respectively). The organic waste used to compare the effects of the composts on the soil and on the lettuce crop was a mixture (50:50, volume:volume, V:V) of goat and rabbit manure (E). This waste was obtained from the experimental farm placed at the EPSO campus (Miguel Hernández University, Orihuela, Spain). The principal characteristics of the organic amendments used are summarized in Table 1.

All the composts were prepared using the organic fraction of separately collected municipal organic waste mixed with urban pruning waste, obtained from the maintenance of public green areas at the corresponding municipalities. A more detailed description of the composting mixtures and the composting processes for CM1 and CM2 has been explained in previous research [5]. In the case of CM3 and CM4, the composting process was a standardized process with a proportion 1:1 (V:V) of the raw materials mentioned, carried out at two different decentralized plants. The composts used had suitable degrees of maturity and stability for their use as soil amendments, according to the criteria established by different authors, such as the following: total organic C to total N ratio (TOC/TN) < 20 [18] (Table 1); absence of phytotoxicity, with values $> 50\%$ [19] (96.2%, 109%, 99% and 115% for CM1, CM2, CM3 and CM4, respectively); and adequate stability (class V for all the composts), according to the self-heating stability test [20]. Furthermore, all the composts showed absence of *Salmonella* spp. and *E. coli* contents below the limit value (1000 MPN/g compost), as well as low contents of heavy metals, according to the limits established by the European legislation [21].

The soil used in this experiment was obtained from the surface layer (0–25 cm) of an agricultural soil located at the Research Station of the EPSO campus, Miguel Hernández University, Orihuela, Alicante, Spain) (38°4′0′′ N, 0°58′0′′ W and elevation 24 m above sea level). The soil was a calcareous clayey-loam soil classified as Xerofluvent [22], with alkaline pH, poor concentrations in organic C, and low electrical conductivity values (Table 2).

Table 1. Characteristics of the organic treatments used in the experiment (dry weight basis).

	E	CM1	CM2	CM3	CM4
pH	7.6 ± 0.1	8.6 ± 0.1	8.1 ± 0.1	8.0 ± 0.1	7.6 ± 0.1
EC (dS m^{-1})	6.80 ± 0.26	6.07 ± 0.13	3.20 ± 0.09	5.19 ± 0.11	1.12 ± 0.02
OM (%)	84.1 ± 1.0	37.8 ± 0.5	38.2 ± 0.5	56.2 ± 0.9	40.8 ± 0.8
TOC (%)	40.8 ± 0.6	25.3 ± 0.3	23.5 ± 0.4	31.5 ± 0.4	24.6 ± 0.4
TN (%)	2.65 ± 0.03	2.11 ± 0.03	1.76 ± 0.02	2.85 ± 0.06	1.89 ± 0.03
TOC/TN ratio	15.3 ± 0.2	11.9 ± 0.2	13.3 ± 0.3	11.0 ± 0.2	13.0 ± 0.2
P_2O_5 (%)	2.07 ± 0.03	1.72 ± 0.03	2.09 ± 0.03	2.17 ± 0.03	1.44 ± 0.03
K_2O (%)	2.35 ± 0.04	2.50 ± 0.04	1.06 ± 0.03	1.34 ± 0.02	0.86 ± 0.01
Mg (g kg^{-1})	6.10 ± 0.14	13.7 ± 0.2	8.89 ± 0.24	3.00 ± 0.08	3.91 ± 0.07
Ca (g kg^{-1})	17.8 ± 0.4	136 ± 3	152 ± 2	51 ± 1	112 ± 3
Na (g kg^{-1})	4.71 ± 0.08	7.02 ± 0.04	3.29 ± 0.09	5.49 ± 0.03	1.29 ± 0.03
Fe (g kg^{-1})	0.94 ± 0.01	4.33 ± 0.07	2.36 ± 0.03	6.79 ± 0.12	7.13 ± 0.32
Cu (mg kg^{-1})	58.8 ± 1.3	56.5 ± 1.0	20.7 ± 0.4	38.8 ± 0.9	31.7 ± 0.6
Mn (mg kg^{-1})	214 ± 6	211 ± 4	80 ± 3	153 ± 5	230 ± 3
Zn (mg kg^{-1})	441 ± 7	83.1 ± 1.3	65.7 ± 1.4	101 ± 2	102 ± 1
Cd (mg kg^{-1})	0.23 ± 0.00	0.34 ± 0.01	0.37 ± 0.03	0.51 ± 0.01	0.31 ± 0.01
Cr (mg kg^{-1})	8.28 ± 0.55	54.2 ± 9.8	22.0 ± 1.9	52.8 ± 2.0	70.7 ± 3.6
Ni (mg kg^{-1})	5.23 ± 0.11	18.1 ± 3.7	7.27 ± 0.35	18.5 ± 1.0	19.2 ± 1.3
Pb (mg kg^{-1})	1.61 ± 0.05	20.5 ± 8.2	9.07 ± 0.33	15.8 ± 0.4	15.0 ± 0.5

E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; EC: electrical conductivity; OM: total organic matter; TOC: total organic carbon; TN: total nitrogen. Data expressed as mean value ± standard deviation.

Table 2. Characteristics of the soil used for the lettuce crop production during two growing seasons. Data expressed on a dry weight basis.

Parameter	Value
pH	8.1 ± 0.2
EC (dS m^{-1})	0.40 ± 0.02
Cox (%)	0.50 ± 0.02
Cw (%)	0.12 ± 0.51
Total Kjeldahl N (mg kg^{-1})	595 ± 1
$NH_4{}^+$-N (mg kg^{-1})	7.9 ± 0.36
$NO_3{}^-$-N (mg kg^{-1})	51.1 ± 6.5
Available P (mg kg^{-1})	60.3 ± 4.7
Soil texture	Clayey-loam
% Coarse sand	60
% Silt	12.5
% Clay	27.5

EC: electrical conductivity; Cox: oxidizable organic carbon; Cw: water-soluble organic C. Data value expressed as mean value ± standard deviation.

2.2. Experimental Set Up

Seven treatments were set up in polyethylene pots of 1 L using a completely randomized design with six replicates per treatment during two successive cultivation cycles. The treatments were as follows: control soil without fertilization (B), goat–rabbit manure (E), compost from decentralized composting scenarios (CM1 and CM2 from community composting, and CM3 and CM4 from decentralized urban composting plants), and inorganic fertilization (IN) using inorganic NPK fertilizer 15–15–15. The fertilizing treatments were applied considering the N requirements of the lettuce [23], following a normalized and single N application dose of 210 kg N ha^{-1} for the organic amendments, while the inorganic fertilization was applied at an equivalent dose of 150 kg N ha^{-1}, considering a mineralization rate of 18% for the composts. For this, the polyethylene pots were filled with 1 kg of soil, previously air-dried and passed through a 2 mm mesh to remove any large particles and plant debris. Thus, the treatments were incorporated and mixed superficially. Prior to this, the organic amendments were dried in an oven at 60 °C and sieved to a particle size of less than 5 mm. Deionized water was added to all the treatments to reach 50% of the soil water holding capacity, which was maintained throughout the experiment. The treatments were incorporated into the soil one week before planting. Then, commercial seedlings of lettuce (*Lactuca sativa* L.) var. Little Gem Incitatos with uniform size were planted in the pots one week after establishing the treatments. This lettuce variety is a baby-leaf lettuce, whose cultivation period is around 30–50 days, and it requires well-drained, moist soils. This variety has elongated leaves that generally show an intermediate green color, with whitening towards the inside, and are small, tight, and wrinkled, with a smooth edge and a highly developed and prominent central nerve. They form closed, compact heads of 10–15 cm in height and approximately 8–10 cm in diameter, usually having a maximum weight between 125 and 190 g [24,25]. After planting, the pots were placed in a controlled environment chamber under non-leached conditions, with an average temperature of 21 °C, relative humidity of 60%, and with a photoperiod of 12 h of light and 12 h of darkness. This was achieved using artificial lamps (RX600, Solray® 385, Helsinki, Finland). The treatments were randomly distributed in the growth chamber and regularly rotated. The first growing cycle was considered finished when most of the plants reached the commercial size (on day 30 after planting). Then, the plants were harvested and soil samples were collected from the pots prior to planting again for the second growing cycle, which also ended one month after planting.

The effects of the different treatments on the soil characteristics, as well as the residual effects of the treatments after harvest, were determined at the beginning of the experiment (T1), end of the first cultivation cycle, which coincided with the beginning of the second cultivation cycle (T2), and end of the second cultivation cycle (T3). Thus, soil samples were collected at T1 (0 days), T2 (30 days), and T3 (60 days) after the incorporation of the treatments as destructive samples, and the soil samples were divided into two subsamples: one was immediately frozen at −4 °C for biological determinations, while the second subsample was air-dried for the remaining analytical determinations. In the lettuce samples, crop yield was assessed by cutting and weighing all of the aerial biomass at samplings T2 and T3, prior to washing and drying the plants at 45 °C in an air-forced oven for 72 h to determine dry weight. A portion of each plant was also stored at −80 °C for other determinations. Afterwards, the plant samples were ground to a 0.5 mm powder for analytical characterization.

2.3. Analytical Determinations

In the soil samples, pH and electrical conductivity were determined using aqueous extracts prepared at ratios of 1:2.5 (weight:volume, W:V) and 1:5 (W:V), respectively, using a pH meter and conductimeter, respectively (Crison Instruments, S.A., Barcelona, Spain). Total Kjeldahl N and oxidizable organic C (Cox) were assessed by the Kjeldahl and Walkley and Black modified methods, respectively, while soil texture, soil respiration, and available P were determined with the methodology described by Bustamante et al. [26]. The inorganic forms of N ($N\text{-}NO_3$ and $N\text{-}NH_4$+) were determined using a K-365 Dist Line multiparameter analyzer (BÜCHI Labortechnik AG). To this end, the concentration of these forms was determined in a 0.2 M 1:5 (W:V) KCl extract using the MgO-Devarda alloy steam distillation method [27]. The physico-chemical and chemical characterization of the organic amendments were conducted following the methods used by Álvarez-Alonso et al. [5], while the contents of NPK in the plant samples and the nitrogen use efficiency (NUE index) were determined according to Vico et al. [14]. All the analyses were conducted in triplicate.

Plant development parameters, including canopy cover (CANOPY) and leaf chlorophyll intensity (SPAD), were monitored at 15-day intervals until the end of the experiment. A total of 6 CANOPY values were recorded at 15, 28, 44, and 61 days for each treatment with a non-destructive approach to estimate the foliar surface area of the lettuce plants, using the CANOPY app © developed for Matlab by Patrignani and Ochsner [28]. In addition, 12 SPAD values were measured, at the same periods as the CANOPY determinations, for each plant with a chlorophyll meter (SPAD-502, Minolta Co., Ltd., Osaka, Japan), in accordance with the methodology described by Wang et al. [29].

2.4. Statistical Analysis

The statistical analysis was carried out using the Infostat software v. 2020. Prior to conducting the one-way ANOVA analysis, the normality of the results was assessed using the Shapiro–Wilk test. The post hoc analysis was conducted using the Tukey test at $p < 0.05$, to ascertain the significance of the observed differences between the mean values.

3. Results and Discussion

3.1. Effects of the Treatments on Crop Yield and Quality

The treatments applied showed a clear differential effect on the lettuce yield in both cultivation cycles (Figure 1). All the treatments showed higher yields than the control treatment without fertilization, B (25.0 g for the first cycle and 5.35 for the second cycle), with values in the range of 33.6–38.5 g for the first cycle, and between 6.43 g and 21.8 g for the second cycle. In the initial vegetative cycle (growing cycle 1), higher yield values were found in the soils with the compost CM3 (from decentralized small-scale urban plants) (38.5 g) and the organic amendment E (37.8 g), which were statistically similar to the lettuce yield value obtained with the inorganic fertilizer (IN) (37.5 g), probably due to the greater presence of plant-available nutrients in these materials [30].

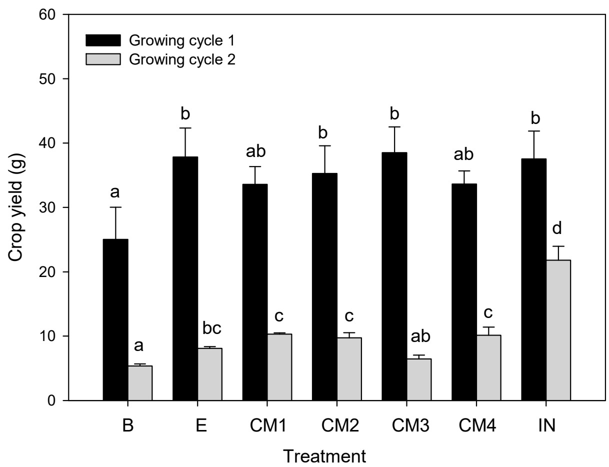
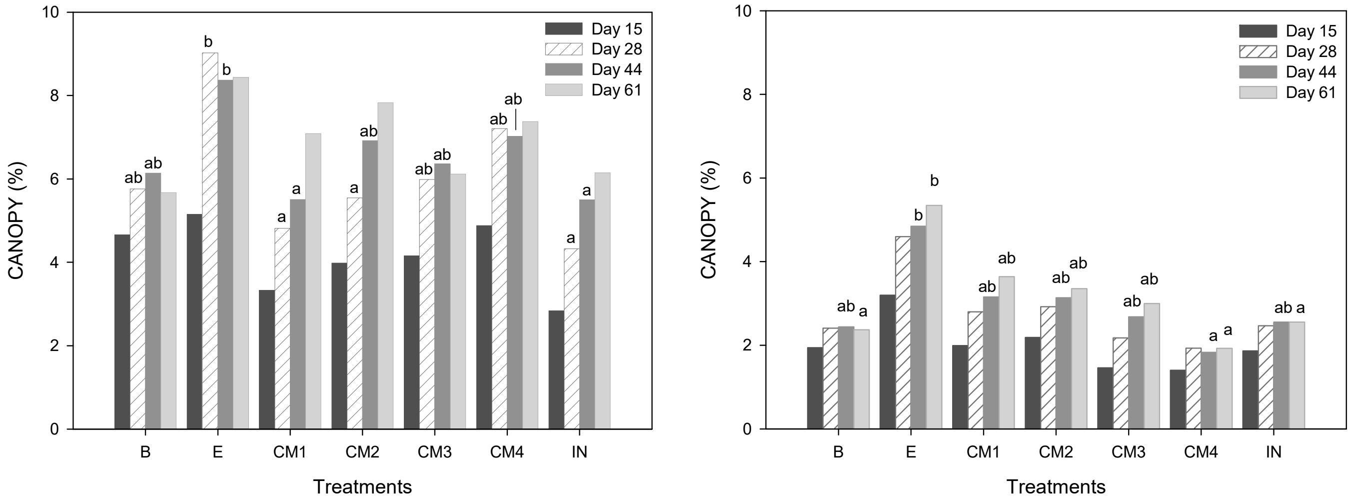


Figure 1. Lettuce yield (g) for each treatment studied in the two growing cycles. B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer. Values with different letters in the same growing cycle indicate statistical differences between treatments by Tukey test ($p > 0.05$).

Concerning the mean leaf coverage (CANOPY) of the cultivation cycle 1 (Figure 2a), it was observed that during the initial two weeks of the crop, the recorded values did not exhibit statistically significant differences among the studied treatments. In all cases, the values were similar to those of the control treatment, which was only marginally surpassed by treatments E and CM4.



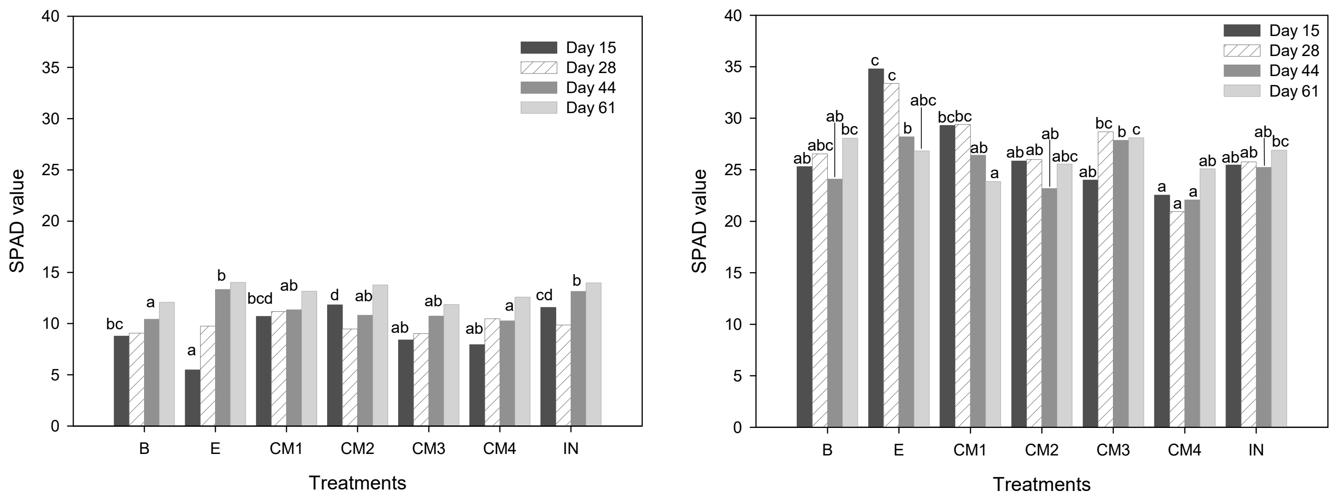
(**a**) (**b**)

Figure 2. CANOPY evolution in the lettuce during the two cultivation cycles. Average values for each treatment studied in (**a**) growing cycle 1; (**b**) growing cycle 2. B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer. Values with different letters in the same day of measurement in each treatment indicate statistical differences between treatments by Tukey test ($p > 0.05$). Columns without letter in the same day for each treatment indicate non-significant differences (Tukey test, $p > 0.05$).

The results of the measurements on day 28 indicated a general increase in leaf cover across all the treatments, compared to the 15-day measurement. Nevertheless, statistically significant discrepancies were discernible between the different treatments. While the control treatment remained within the same range as the CM3 and CM4 treatments, the treatment with manure (E) showed the highest leaf cover. Conversely, the treatments with CM1, CM2, and IN exhibited the poorest development, even showing lower levels of success than the control treatment (B). The results of the determination on day 44 showed statistically significant differences between the different treatments. The highest value was observed in the plants with the treatment with manure (E), followed by the treatments with CM2, CM3 and CM4, which were within the range of the control treatment. Thus, the treatments comprising CM1 and IN exhibited diminished outcomes compared to the control treatment. However, at the end of the growing cycle 1 (day 61), no statistically significant differences were identified among the various treatments. However, a reduction in leaf cover was observed in the control treatment (B) and CM3 compared to the previous measurements. Conversely, the rest of the compost treatments showed an increase in leaf cover. The observed increase at the end of the crop cycle may indicate that, after the application of organic amendments to the soil, a period of time is required for the nutrients present in the compost to take on forms that can be assimilated by the plants, thereby allowing for greater leaf development [29].

In the second growing cycle, the two first measurements of CANOPY (at 15 and 28 days) revealed no statistically significant differences among the different fertilizing treatments and the control soil without amendment (B) (Figure 2b). From day 28 onwards, two distinct dynamics were observed. The plants with the treatments B, IN, and CM4 showed values that exceeded the initial sampling, but with minimal variation throughout the rest of the sampling period. Conversely, treatments CM1, CM2, CM3, and E showed a progressive increase until the end of the two growing cycles, observing the highest values for the treatment E. Leaf cover is closely associated with crop development and the residual impact of compost applied during the initial cycle, which has a favorable influence on the subsequent cycle [31].

Regarding the leaf chlorophyll intensity (SPAD) during the initial lettuce cultivation cycle (Figure 3), an increase was found in all the treatments as the growing cycles progressed. This may be attributed to the different rates of nitrogen release observed in the various treatments, which appear to increase in line with the duration of the experiment [29]. In the first growing cycle, statistically significant differences were only observed between the treatments in the measurements taken on days 15 and 44 (Figure 3a). At 15 days, the treatment E showed the lowest value, which contrasts with the findings observed in the CANOPY case. However, the treatments CM2 and IN demonstrated the most favorable outcomes, surpassing the control in all instances. On day 44, the lowest values were observed in treatments B and CM4, followed by treatments incorporating CM1, CM2, and CM3. However, the treatments E and IN showed the highest SPAD values. In a compost trial on lettuce, Reis et al. [31] observed a rapid effect on SPAD values following the application of inorganic fertilization, which was subsequently overcome by the effect of compost fertilization. The final SPAD sampling, conducted on day 61 of the experiment, revealed no statistically significant differences between the various treatments. In the second growing cycle (Figure 3b), statistically significant differences were observed between the treatments in all the measurements carried out, with initial values higher than those recorded at the end of the initial crop cycle. This also suggests the progressive release of nutrients in the various treatments [32].



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

Figure 3. SPAD evolution in the lettuce crop during the experiment. Average values for each treatment studied in (**a**) growing cycle 1; (**b**) growing cycle 2. B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer. Values with different letters in the same day of measurement in each treatment indicate statistical differences between treatments by Tukey test ($p > 0.05$). Columns without letter in the same day for each treatment indicate nonsignificant differences (Tukey test, $p > 0.05$).

In general, during the second cycle, the highest SPAD values were recorded in the lettuce plants grown in the soils with the treatments E, CM1, and CM3. At the end of the second growing cycle (on day 61), a decrease was observed in the SPAD values of the soils with treatments E and CM1, while an increase was noted in the remaining treatments. In this sense, SPAD meters facilitate the quantification of leaf nitrogen content based on leaf chlorophyll concentration [33]. Thus, it can be considered that the observed dynamics at the end of the growing cycles may be attributed to a deficiency of nitrogen, which can result in leaf yellowing [34] and consequently yield low SPAD values. Conversely, the gradual release of nutrients [31], in conjunction with optimal irrigation and N management, can influence crop yield and nutrient accumulation in the leaves, leading to elevated SPAD values.

3.2. Effects of the Treatments on Lettuce Nutrient Contents and N Use Efficiency

At the end of the growing cycle 1, significant differences in the TN content in the lettuce plants were found among the different treatments, showing the highest value in the CM1 treatment as well as the inorganic fertilization (IN) treatment (Table 3). However, after the two cropping seasons, the N concentration was higher in the treatments E, CM1, and CM3. These values are in line with the trend observed in the parameters associated with crop development (CANOPY and SPAD), indicating that N in the plant is utilized for both tissue development and chlorophyll formation [23]. Furthermore, statistically significant differences were observed in the TP and TK contents of the plants in the different treatments in each cycle. In both cases, the treatment with E showed the highest results. In a trial of different composts in lettuce cultivation, Alromian [35] found that the concentrations of total nitrogen (TN) and total phosphorus (TP) were within the range of those obtained in the present study. However, the concentration of total potassium (TK) was found to be lower than that recorded in the present study. This discrepancy may be associated with the difference in the materials used. As also reported by Vasileva et al. [36], the use of compost as a substitute for chemical fertilizers in lettuce cultivation leads to an increase in N, P, and K concentrations in plant tissues.

Table 3. Contents in macronutrients (NPK) in the lettuce crop during the two growing seasons and N use efficiency (NUE).

	Cultivation Cycle 1			
	TN (%)	TP (%)	TK (%)	NUE Index [1] (%)
B	1.29 a ± 0.04	0.13 ab ± 0.02	3.23 a ± 0.25	
E	1.65 b ± 0.04	0.14 b ± 0.00	4.53 d ± 0.05	15.67 ± 4.2
CM1	1.87 c ± 0.13	0.14 ab ± 0.01	3.63 bc ± 0.07	15.78 ± 14.7
CM2	1.40 a ± 0.01	0.12 ab ± 0.01	3.40 ab ± 0.12	3.55 ± 3.7
CM3	1.35 a ± 0.10	0.12 a ± 0.00	3.32 ab ± 0.18	3.26 ± 4.8
CM4	1.33 a ± 0.06	0.11 a ± 0.01	3.18 a ± 0.04	5.62 ± 4.6
IN	2.04 c ± 0.02	0.12 ab ± 0.01	3.84 c ± 0.12	12.36 ± 5.2
F-ANOVA	***	**	***	n.s.
	Cultivation cycle 2			
	TN (%)	TP (%)	TK (%)	NUE index (%)
B	0.50 a ± 0.05	0.14 a ± 0.03	1.73 a ± 0.10	
E	0.79 c ± 0.11	0.24 b ± 0.04	2.73 c ± 0.61	20.4 c ± 2.1
CM1	0.68 bc ± 0.05	0.19 ab ± 0.02	2.36 bc ± 0.10	4.60 bc ± 0.61
CM2	0.56 ab ± 0.03	0.15 a ± 0.04	1.87 ab ± 0.09	1.54 ab ± 1.10
CM3	0.73 c ± 0.05	0.19 ab ± 0.03	2.19 abc ± 0.31	1.44 ab ± 0.81
CM4	0.57 ab ± 0.08	0.18 ab ± 0.02	1.80 a ± 0.20	0.01 a
IN	0.57 ab ± 0.03	0.16 a ± 0.04	1.98 ab ± 0.12	0.84 a ± 0.51
F-ANOVA	***	**	***	***

[1] Nitrogen use efficiency (NUE) expressed as the percentage of fertilizer N applied that was taken up by the lettuce crop [14,37]. B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer; TP: total phosphorous; TK: total potassium. Data value expressed as mean value ± standard deviation. Values with different letters indicate statistical differences between treatments for each cycle by Tukey test ($p > 0.05$). **, ***: significant at $p < 0.01$, 0.001, respectively; n.s.: not significant.

On the other hand, nutrient use efficiency represents a pivotal concern in the domain of sustainable agriculture, wherein the objective is to achieve optimal crop yield while minimizing economic investment and nutrient loss within the soil system [38]. The application of high rates of nitrogen can result in a reduction in the quality of lettuce and an acceleration in the loss of leaves [23]. It is therefore crucial to achieve an optimal balance of nitrogen input in order to avoid any detrimental effects on the crop and the environment, while also minimizing the economic cost to agriculture [39]. Thus, in order to conduct a study on the use efficiency of N or other nutrients, such as P and K, it is essential to consider that a proportion of the applied nutrient will be used by the crop for the development of its total biomass, while another proportion will remain immobilized in the soil and will be available for subsequent crops [40]. In the present study, the efficiency of the use of nitrogen (NUE) by the crop only showed statistically significant differences among the treatments in the second growing cycle (Table 3), with the highest value observed for the treatment with manure (E) compared to the rest of the organic amendments (composts), which may be attributed to the prolonged release of nutrients provided by the compost treatments over time [26]. The NUE values clearly declined from cycle 1 to cycle 2, except for the treatment E, indicating a reduction in the N assimilation, which may be indicative of N immobilization in the soil, or a reduction in nutrient assimilation due to salt accumulation in the roots [37,39]. López-Bellido et al. [37] also reported a reduction in nitrogen assimilation when the dose was applied entirely at the beginning of sowing, which may have occurred in the present study.

3.3. Effects of the Treatments on Soil Properties

The soil pH values increased slightly during the first growing cycle in all the treatments (Table 4), without exhibiting statistical differences among the treatments at the beginning (T1) and end (T2) of this growing cycle. However, during the second growing cycle, the pH values decreased, showing slight statistical differences among the treatments at the end of the second growing cycle (T3), possibly due to the buffering effect of the calcareous soil. This effect has also been reported in previous studies using organic amendments (composts and/or manures) on calcareous soils [26,41].

On the other hand, the EC values decreased during the experiment from initial values between 0.53 and 0.4 dS m^{-1}, with statistically significant differences between the different treatments at the beginning and end of the first growing cycle (T1 and T2), to final values in the range of 0.33 to 0.39 dS m^{-1}, with no statistically significant differences found at the end of the second growing cycle. Thus, the application of compost as organic soil amendment did not result in a notable increase in salinity, even for materials with a moderately elevated EC, as also reported by Alromian [35] in a study of the effect of the compost type and application rate on the growth and quality of lettuce. This could be a consequence of nutrient uptake by the crop, immobilization of inorganic N, and/or ion leaching. Thus, Paredes et al. [41] also reported a decrease in the soil EC values during a field experiment to study the effects of spent mushroom substrates and inorganic fertilization on lettuce production and soil properties, while this effect was also found by Bustamante et al. [26] in a long-term experiment on the incorporation of winery composts in a Mediterranean vineyard.

The evolution of the oxidizable organic C (Cox) provides valuable information concerning the organic matter contribution of the compost treatments [42]. The incorporation of the organic amendments showed a statistically significant increase in the soil Cox contents at the beginning of the first growing cycle, these values being 1.3 and 1.2 times higher in the soils with CM2 and in the soils with CM1, CM3 and E, respectively, compared to the control soil without fertilizing treatment (B), and 2.0 and 1.8 times greater, respectively, compared to soil with inorganic fertilization (IN). This initial increment in the organic C with the incorporation of organic amendments has been reported in previous works using organic materials [31,41]. The application of organic amendments to the soil has been demonstrated to increase the concentration of organic C, specifically the water-soluble fraction, which is readily transported through the soil profile [43]. At the end of the first growing cycle, all the treatments showed Cox contents statistically similar to that of the control soil (B), with only the soil amended with manure (E) maintaining the highest value. At the end of the second growing cycle, the Cox contents slightly increased in all the organic treatments based on compost, probably due to the incorporation of organic compounds from root exudates [41].

Table 4. Evolution of the physico-chemical, chemical, and biological parameters in the soils during the two growing seasons (each growing cycle had a duration of 30 days).

Beginning of cultivation cycle 1					
	pH	EC ($dS\ m^{-1}$)	Cox (%)	P ($mg\ kg^{-1}$)	Soil Respiration ($mg\ CO_2\ g^{-1}\ day^{-1}$)
B	8.1 ± 0.0	0.40 a ± 0.02	0.39 b ± 0.02	38.6 a ± 2.4	76.3 ab ± 11.8
E	8.2 ± 0.1	0.51 b ± 0.11	0.45 bc ± 0.01	69.0 b ± 4.5	138 c ± 5.8
CM1	8.2 ± 0.1	0.53 b ± 0.01	0.44 bc ± 0.01	66.6 b ± 8.7	98.2 ab ± 3.4
CM2	8.2 ± 0.1	0.49 b ± 0.01	0.51 c ± 0.02	75.9 b± 4.2	78.7 ab ± 10.7
CM3	8.2 ± 0.1	0.52 b ± 0.01	0.39 b ± 0.01	62.1 b ± 2.8	116 bc ± 4
CM4	8.2 ± 0.1	0.44 a ± 0.03	0.45 bc ± 0.05	68.8 b ± 6.0	92.3 ab ± 5.7
IN	8.1 ± 0.1	0.44 a ± 0.01	0.25 a ± 0.02	60.3 b ± 4.7	59.1 a ± 5.7
F-ANOVA	n.s.	***	***	***	***
End of cultivation cycle 1 and beginning of cultivation cycle 2					
	pH	EC ($dS\ m^{-1}$)	Cox (%)	P ($mg\ kg^{-1}$)	Soil respiration ($mg\ CO_2\ g^{-1}\ day^{-1}$)
B	8.7 ± 0.0	0.43 ab ± 0.04	0.34 a ± 0.03	26.7 a ± 0.7 a	48.2 ± 3.2
E	8.7 ± 0.0	0.43 ab ± 0.02	0.44 b ± 0.02	32.4 b ± 1.8 b	66.9 ± 15.1
CM1	8.7 ± 0.0	0.40 ab ± 0.04	0.31 a ± 0.04	33.6 b ± 1.2 b	54.5 ± 10.4
CM2	8.8 ± 0.0	0.44 ab ± 0.03	0.32 a ± 0.03	33.0 b ± 1.2 b	69.8 ± 11.5
CM3	8.7 ± 0.0	0.45 b ± 0.01	0.32 a ± 0.02	33.9 b ± 2.7 b	46.3 ± 10.2
CM4	8.8 ± 0.0	0.37 a ± 0.01	0.29 a ± 0.05	36.4 b ± 2.3 b	45.0 ± 7.2
IN	8.7 ± 0.2	0.46 b ± 0.01	0.22 a ± 0.05	32.7 b ± 2.8 b	35.0 ± 7.5
F-ANOVA	n.s.	**	***	**	n.s.
End of cultivation cycle 2					
	pH	EC ($dS\ m^{-1}$)	Cox (%)	P ($mg\ kg^{-1}$)	Soil respiration ($mg\ CO_2\ g^{-1}\ day^{-1}$)
B	8.3 a ± 0.2	0.35 ± 0.02	0.30 a ± 0.00	28.9 a ± 4.4	81.1 ± 4.1
E	8.3 ab ± 0.1	0.36 ± 0.04	0.42 b ± 0.02	79.2 b ± 2.8	137 ± 4
CM1	8.5 ab ± 0.1	0.39 ± 0.03	0.56 c ± 0.06	80.4 b ± 1.8	110 ± 11
CM2	8.6 b ± 0.1	0.37 ± 0.01	0.59 c ± 0.02	72.2 b ± 5.1	131 ± 21
CM3	8.5 ab ± 0.0	0.37 ± 0.01	0.57 c ± 0.03	71.4 b ± 4.9	87.3 ± 5.3
CM4	8.5 ab ± 0.1	0.33 ± 0.03	0.57 c ± 0.01	72.5 b ± 4.0	79.0 ± 2.4
IN	8.4 ab ± 0.0	0.34 ± 0.03	0.23 a ± 0.01	32.3 a ± 9.7	115 ± 12
F-ANOVA	*	n.s.	***	**	n.s.

B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer; EC: electrical conductivity; Cox: oxidizable organic carbon. Data value expressed as mean value ± standard deviation. Values with different letters indicate statistical differences between treatments for each cycle by Tukey test ($p > 0.05$). *, **, ***: significant at $p < 0.05$, 0.01, 0.001, respectively; n.s.: not significant.

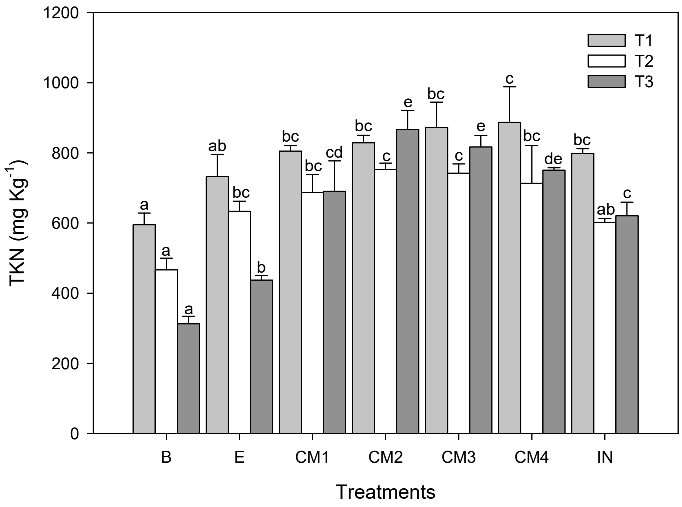
All the treatments induced an increase in the concentrations of soil-available P, with all the organic treatments showing statistically similar values to the inorganic fertilization, and higher values compared to the soil without fertilization (Table 4), indicating that the application of compost enhanced the soil P contents, with a behavior similar to that of the inorganic fertilization [44]. During the first growing cycle, the contents of available P decreased in all the soils, which is linked to the uptake of this element by the plant. However, at the end of the second growing cycle, the P contents increased in all the soils treated with organic amendments, due to the gradual release of this nutrient [45], the values being statistically similar among the organic treatments and higher than those of the control soil (B) and the inorganic treatment (IN). García-López et al. [46] also reported the improvement of P availability with compost application in an experiment to study the effect of compost on lettuce yield and the biochemical properties of soil.

On the other hand, soil respiration is a parameter commonly used to evaluate the activity of the soil microbial biomass, which allows for assessing the microbiological status of a soil, and to evaluate the effects of land management on the microorganisms [26]. In general, the organic amendments E and CM3 produced a statistically significant increase in the soil respiration values at the beginning of the first growing cycle compared to the control soil (B) (Table 4), finding the lowest respiration values in the treatment with inorganic fertilization (IN). The presence of labile organic matter in the soil has been demonstrated to increase the activity of the soil microbiota, which can result in a decrease in soluble forms of carbon and an increase in nitrogen concentration by increasing nitrification and denitrification processes in the soil [42]. At the end of both growing cycles, the values of soil respiration were not statistically different among the different treatments, showing a slight decline in T2 and an increase in T3. In a study comparing compost with inorganic fertilization for intensive lettuce production, Hernández et al. [47] also reported an increase in the soil microbial activity with the use of organic amendments, observing that the characteristics of the organic material used strongly influenced the soil microbiological activity.

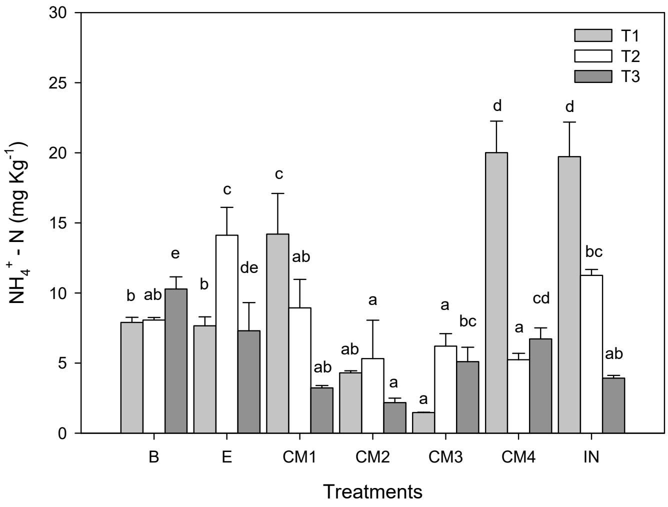
Regarding the soil N forms (total Kjeldahl N (TKN), ammonium, and nitrate N), in general, all the treatments exhibited statistically significant increases in the TKN contents in the sampling periods (T1, T2, and T3) compared to the soil without fertilization (B), observing the highest values at the beginning of the first growing cycle (Figure 4a). At the end of the first cultivation cycle (T2), there was a notable decline in the TKN values in all the treatments, which can be attributed to organic matter mineralization [41] and to the uptake of this nutrient by the plant [45], which is also associated with the observed increase in crop biomass (Figure 1). Thus, the soils amended with the composts CM2 and CM3 showed the highest TKN concentrations at both T2 and T3. The slow mineralization of compost by microorganisms to transform it into inorganic forms directly available to plants [35] avoids nutrient losses in the soil–plant system and negative consequences on the environment [31].

In the concentrations of the inorganic N (NH_4^+-N and NO_3^--N), statistically significant differences were observed among the treatments at each sampling time. At the initial sampling (T1), the NH_4^+-N values ranged from 1.5 to 20 mg kg^{-1} soil, with the lowest value observed in treatment CM3. However, it is notable that, although treatments CM1, CM4, and IN exhibited the highest initial ammonium-N concentrations, they were the only treatments that demonstrated a decrease in concentration at the conclusion of the first crop cycle (T2), with values ranging from 5.2 to 14.1 mg kg^{-1} soil. At the end of the experiment (T3, Table 4), values ranging from 2.2 to 10.3 mg kg^{-1} soil were observed, indicating a decline in ammonium concentration in all the treatments, with the exception of B and CM4.

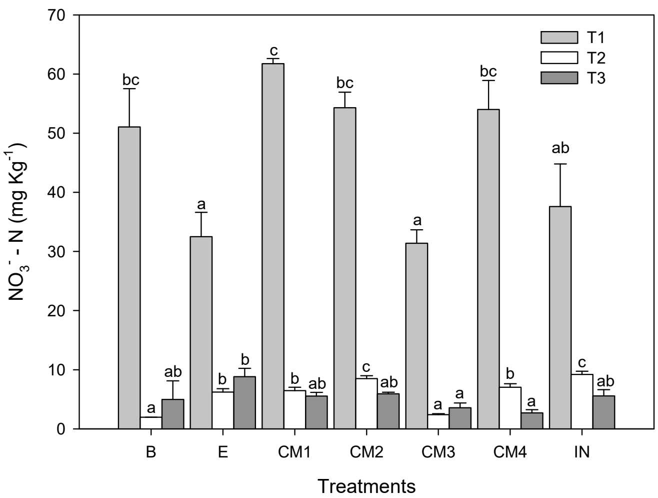
On the other hand, the initial nitrate concentration was comparatively elevated, ranging from 31.4 to 61.8 mg kg^{-1}. These initial values are conducive to optimal crop growth, as nitrate is directly available for assimilation by the crop. However, following the first crop cycle (T2), a substantial decline in nitrate concentration was observed in all treatments, ranging from 2.0 to 9.2 mg kg^{-1} soil. This decline is attributed to the plant uptake for its own growth [41]. At the end of the experiment, following the second crop cycle, nitrate concentrations remained low, ranging from 2.7 to 8.8 mg kg^{-1} soil, with treatment E showing the highest value.



(**a**)



(**b**)



(**c**)

Figure 4. Evolution of the N forms throughout the two growing seasons of lettuce. (**a**) Beginning of growing cycle 1; (**b**) end of growing cycle 1 and beginning of growing cycle 2; (**c**) end of growing cycle 2. B: control treatment; E: goat–rabbit manure; CM1 and CM2: urban composts from community composting; CM3 and CM4: urban composts from decentralized composting plants; IN: inorganic fertilizer; TKN: total Kjeldahl N. Values with different letters in the same day of measurement in each treatment indicate statistical differences between treatments by Tukey test ($p > 0.05$).

4. Conclusions

Municipal waste composts from decentralized composting scenarios, such as community composting and decentralized urban small-scale composting plants, constitute a suitable and sustainable alternative to inorganic fertilization for lettuce production, in general obtaining similar lettuce yields. Furthermore, these treatments also showed a positive dual effect on both the crop production and quality. In contrast to the inorganic fertilization, compost application contributed to improvements in soil properties, showing benefits with increases in the organic matter and nutrient contents. Consequently, the use of compost from decentralized urban composting and community composting emerges as a viable alternative to chemical fertilizers, thereby reducing agricultural costs and enhancing the circularity and sustainability of agricultural environments.

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