ORIGINAL PAPER

A Novel Technology for Processing Urban Waste Compost as a Fast-Releasing Nitrogen Source to Improve Soil Properties and Broccoli and Lettuce Production

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Abstract

Purpose This study evaluated nitrogen (N) mineralization dynamics in three soils after the addition of heat-treated urban waste amendments or urban waste compost (UWC). The effects of UWC and urea on soil properties and broccoli and lettuce production were compared.

Methods The first N mineralization experiment was conducted in a factorial arrangement (4×3), as a randomized complete block design (RCBD), with three replicates. Four UWC doses: 12.5, 25.0, 37.5, and 50.0 mg dm^{-3} were applied to three soils: sandy Ustoxic Quartzipsamment (QS), intermediate-texture red Ultisol (US), and clayey red Oxisol (OS), during eight incubation periods (0, 7, 14, 28, 42, 56, 70, and 84 days). In the second experiment, the effects of UWC and urea fertilizer on soil properties were compared. The growth of broccoli and lettuce plants was evaluated (experiments 3 and 4). The treatments (Experiments 2–4) followed a factorial arrangement (4×2; RCBD; three replicates), using OS soil. Four N doses (as for experiment 1) were combined with two N sources (UWC and urea).

Results The processed UWC application proportionally increased the N mineralization rate by 72% in QS, 54% in US, and 66% in OS. Furthermore, UWC application enhanced soil properties (pH and nutrient availability), compared with urea fertilizer, and improved N uptake, resulting in higher fresh biomass production in broccoli and lettuce plants (50.0 and 37.5 mg dm^{-3}, respectively).

Conclusions Our findings suggest that heat-treated UWC is an economical, viable, and efficient fertilizer to improve soil properties and short-cycle vegetable crop productivity.

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Graphic Abstract
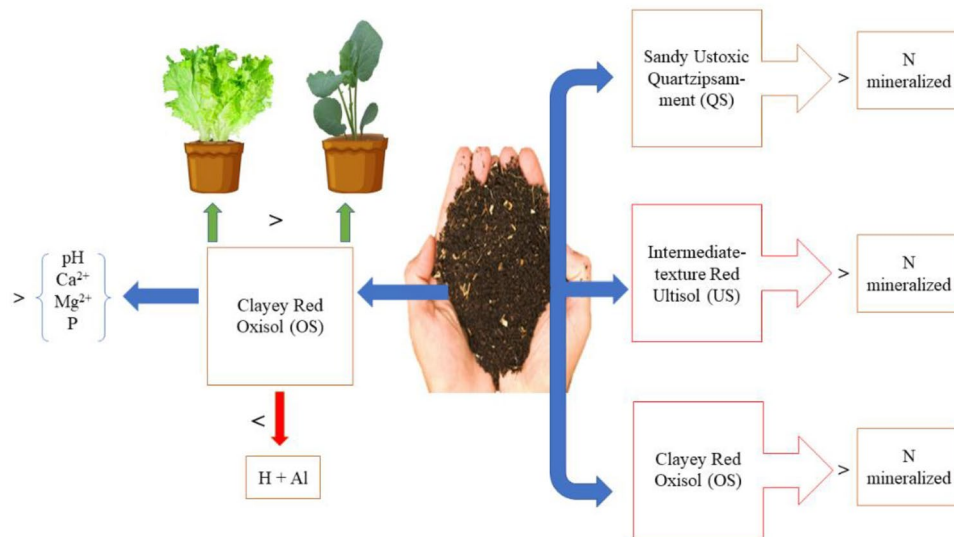
Statement of Novelty

Population growth and intensive urbanization are the leading causes of the production and accumulation of urban waste. Processing urban waste into urban waste compost (UWC) is an innovative way of recycling organic waste from cities. This study's importance, both nationally and internationally, relates to the use of novel technology to eliminate sources of soil- and water-polluting organic waste that can harm animal and human health. It also contributes to the potential reduction of the use of inorganic N sources such as urea, a non-renewable and finite resource, the production of which depends on natural gas. This study suggests that heat-treated UWC is an economical, viable, and efficient fertilizer to increase the productivity of short-cycle vegetable crops.

Introduction

Population growth and intensification of urbanization are the leading causes of increased production and urban waste accumulation [1]. Aerobic composting is an alternative approach for urban solid waste disposal, promoting degradation of the putrescible organic fraction and producing compost [2], which can be utilized in agriculture as an organic fertilizer source [3, 4]. Some research has shown the benefits of using composts and other amendments to enhance soil chemical (pH and nutrient content) and biological properties such as soil microbial populations and plant growth [5]. Nonetheless, chemical compounds found in urban waste

composts, particularly nitrogen (N), are not readily available to plants [6, 7], so it is necessary to determine the availability of this element in the soil [8].

Understanding the N cycle in soils is a basic requirement for identifying management options that couple soil cycle in space and time. This is required as N cycling affects N availability to the plant, as well as microbial activity [9]. With regard to urban waste amendment, there are few detailed studies about how this impacts N mineralization and soil properties and thus affects crop production [10]. Soil N supply from organic amendments depends on both the initial availability of inorganic N (IN) in the amendments and mineralization rate [11]. This means that organic amendments can either be a source of plant-available N or compete with plants for it. To successfully manage nutrient cycling from organic amendments, it is necessary to know their decomposition rates and their influence on N processes within the soil [5, 12].

Nitrogen mineralization is a complex biological process. The amount of N released depends on multiple factors such as the chemical composition of the organic matter (e.g., N content, C:N ratio, contents of cellulose and hemicelluloses, lignin, and polyphenols) [13, 14], and on the physical, chemical, and biological properties of soil microbes [15]. The N mineralization of urban wastes can be affected by high phosphorus (P) concentrations, heavy metals, pathogens, and other harmful substances [16, 17]. Previous studies have determined that the mineralization rate of urban waste compost (UWC) is relatively low [18]. Organic composts with high N concentrations and low C:N

ratios mineralize sufficient N to satisfy plant growth [15, 19]. Conversely, N can be immobilized in organic composts with lower N contents and higher C:N ratios [14, 15].

For effective utilization of urban waste as compost, the N mineralization rate is a suitable criterion for defining the maximum N doses to be applied under particular soil, climate, and crop conditions, in the absence of other restrictive factors. However, the interactions and effects of such factors are not yet well understood in tropical soils. This is an important matter for consideration because of the need to use high-quality organic wastes as an N source for crops. Therefore, information on the agricultural performance of UWC is important for growing vegetable crops that are widely cultivated in the green belts located around big metropolises that produce large amounts of urban solid waste. Additionally, there are recent reports that UWC increases productivity in broccoli [20], lettuce [21], and potatoes [6].

The use of UWC can be an efficient alternative for agricultural production. To substantiate the use of UWC to improved soil and vegetable crop production, this study specifically aims to (i) quantify the effects of different UWC amendments on inorganic N, net mineralizable N, and N mineralization rates; and (ii) investigate their improvement effects on soil properties and broccoli and lettuce productivity in comparison with urea. To meet these objectives, we tested the following hypothesis: (1) N mineralization rate in UWC amendments is relatively fast, although it varies with soil type, (2) UWC application is a more efficient N source than urea due to decrease soil acidity and increases soil nutrient availability, and (3) the contribution of UWC to broccoli and lettuce production would be more strongly related to increasing N availability.

Materials and methods

Trials and Setup

Controlled experiments were conducted at the University Center of the Educational Foundation of Barretos, Barretos, Sao Paulo, Brazil. The purpose of the trials described in Sect. 2.1 was to determine the effects of UWC on N mineralization rate, soil properties, and the growth of broccoli and lettuce. The initial screenings for N mineralization of UWC in three different soils were carried out in a soil fertility laboratory (Experiment 1). The beneficial effects of UWC on soil properties compared to urea fertilizer were validated in OS soil (Experiment 2). Finally, the agricultural effect of UWC on the growth and nutritional quality of greenhouse-grown lettuce and broccoli plants was determined in comparison to the urea fertilizer (Experiments 3 and 4).

Soil Collection and Chemical and Physical Characteristics

The soils used had different textures, according to the FAO criteria [22]: (1) clayey red Oxisol (OS), equivalent to eutrudox; (2) intermediate-textured red Ultisol (US); and a Sandy Ustoxic Quartzipsamment soil (QS), equivalent to hapludult, according to the IUSS Working Group WRB [22], respectively. The OS and US soils were collected in Barretos, São Paulo, Brazil: RO in a native pastured-forest area, and RU in a pastured area, whereas the QS soil was sampled in Jaboticabal, SP, Brazil, in a pastured area. Approximately 50 kg of each soil was collected from the 0–0.2 m layer. Soil samples were air-dried, sieved (4 mm), and stored in a well-ventilated storage room. Subsamples were collected for chemical analysis (pH, H + Al, P, Ca, and Mg) using the methods described by Raij et al. [23], and the physical (particle size) analysis was performed following the methodology described by Embrapa [24]; these data are provided in Table S1.

Description, Composition, and Classification of Heat-Treated Urban Waste Compost

The urban waste compost used in this study was derived from the organic fraction of domestic garbage collected in the city of Araraquara, São Paulo, Brazil. The urban waste composting process involves three main steps. It begins with rough screening of the waste to remove non-organic materials (e.g., plastic and glass), and retain only the organic part. Thereafter, the material is moistened with water to 55% humidity to stimulate the decomposition phase. The third phase is performed in a yard where organic waste is deposited on wooden pallets in windrows to enable static aerobic decomposition to occur.

The aeration technique employed consists of passive aeration using perforated plastic tubes below each windrow, without any type of compressor. A constant renewal of hot to cold air promotes aeration of the entire mass contained in each windrow. The windrows are moistened with leachate, promoting the reintegration of leachate into the process. The temperature and pH value of the compost during composting started at 60 °C and 5.0, respectively, and reached 35 °C and 8.5, respectively. After stabilization of the organic matter, the material deposited in the windrows is removed and sieved (< 15 mm). Then, the UWC is dried in ovens at temperatures of 65 to 70 °C for 3 days, following which the compost is powdered (< 0.6 mm) to obtain a final homogeneous product.

The chemical characteristics of UWC were determined using the methodology of Abreu et al. [25] according to the presence of toxic elements (e.g., heavy metals). The environmental aspects related to the reuse of residues in agriculture are provided in Table S2. The UWC was classified as a class-C

simple organic fertilizer, according to the Normative Instruction No. 25, 2009, of the Brazilian legislation, and by this same legislation, the particle size showed the following characteristics: 0.04% retained on the NBR #10 sieve mesh size, 26.51% on the NBR #20 sieve, 60.25% on the NBR #50 sieve, and 13.20% retained on the NBR #50 sieve. The gravimetric moisture of the compost was 4% [26].

Incubation Experiments

Determination of Nitrogen Mineralization Rate

Experiment 1

This experiment was carried out under laboratory conditions to evaluate the N mineralization in three different soils (QS, US, and OS) fertilized with different amendments of UWC during an incubation period of 84 days. Determination of N mineralization rate was performed according to the methodology proposed by Coscione and Andrade [27]. Four UWC doses (12.5, 25.0, 37.5, and 50.0 mg dm^{-3}) were mixed with the three soil samples (QS, US, and OS) and placed in 0.25-dm^3 polyethylene bottles. Each bottle contained 100 g of soil mixed with the corresponding compost dose. All soil and UWC dose combinations were prepared in triplicate. During the 12 weeks of incubation, the samples were analyzed at the following times: 0, 7, 14, 28, 42, 56, 70, and 84 days. The moisture of the samples was adjusted to 70% of soil water-holding capacity by adding deionized water. The temperature was controlled to 25–28 °C and monitored daily after the first sample was weighed. The trial was a factorial (4×3) randomized complete block design (RCBD) with three replications.

To determine mineral N (MN), 3 g of soil mixture was extracted in 15 mL 1 M KCl with 1 h of shaking. The soil mixture was filtered through Whatman 41 filter paper (MN 616; Whatman International, Maidstone, UK), and the extract was stored at −18 °C until analysis. The IN concentration of each soil sample was then analyzed by flow injection analysis (FIA, Foss Tecator; FOSS Analytical, São Paulo, Brazil) [28] and was calculated based on the dry soil weight after 0, 7, 14, 28, 42, 56, 60, and 84 days of the incubation period.

Removal of mineral N from the soil solution by denitrification or immobilization was not considered, and only net N mineralization (NNM) was estimated. The NNM of each soil mixture sample was calculated as the fit of several kinetic models to the evolution of soil mineral N. The NNM was described by a zero-order kinetic model as follows:

$$N(t) = N_0 + k \times t \tag{1}$$

where $N(t)$ is the amount of MN at time t (days), N_0 is the initial amount of mineral N (µg N g^{-1} soil), and k$_0$ is the zero-order N mineralization rate (µg g^{-1} day^{-1} N).

The mineralized N of the UWC doses was calculated as described previously by Mohanty et al. [29]. The percentage of total N mineralized (%TNM) from each UWC dose at the end of the incubation time (84 days) was calculated as described by Azeez and Van Averbeke [30], as follows:

$$\%TNM = \left(\frac{NM(doses) - NM(control)}{totalNapplied} \right) \times 100 \tag{2}$$

where NM is mineralized N and N is the total N applied in the UWC doses.

Determination of Soil Properties after Urban Waste Compost and Urea Treatments

Experiment 2

This experiment was carried out under laboratory conditions to evaluate soil properties and fertility in an OS soil fertilized with UWC or urea and incubated for 30 days. Pots were used in this experiment and were distributed in a factorial arrangement (4×2) in an RCBD, with four replications. Four N doses (12.5, 25.0, 37.5, and 50.0 mg dm^{-3}) and two different N sources (UWC and urea) were applied. Each experimental unit consisted of 0.25-dm^3 polyethylene pots filled with the OS soil. Phosphorus and potassium were equilibrated and applied to all the treatments, according to the chemical soil analysis results (Table S1), and following the recommendations of Trani and Raij [31]. This was accomplished by mixing 5 g of a 0–25–25 compound fertilizer with the soil in each pot.

After 30 days of incubation, six randomized soil subsamples were collected from each pot, air-dried, and analyzed for the following soil parameters: pH, total acidity (H + Al), exchangeable calcium (Ca), magnesium (Mg), and P resin. After drying, the samples were defragmented and passed through a 2-mm mesh, homogenized, and stored in a refrigerator for chemical analysis, following the methodology described by Raij et al. [23]. The soil pH was measured in CaCl$_2$ using a pH meter. Total acidity (H + Al) was determined in a calcium acetate solution. The P resin and exchangeable bases, extracted with ion exchange resin, were quantified using the colorimetric method and a standard curve previously obtained using a visible spectrophotometer (SP-1105; Ningbo Hinotek Technology, Shanghai, China). Exchangeable Ca^{2+} and Mg^{2+} were extracted in 1 M ammonium acetate saline solution at pH 7.0 and quantified using an atomic absorption spectrophotometer (Varian® SpectrAA, 50 B; Varian Medical Systems Australasia, Belrose, NSW, Australia).

Determination of Soil Properties after UWC and Urea Treatments

Experiments 3 and 4

Broccoli (*Brassica oleracea* L. cv. 'Avenger') and lettuce (*Lactuca sativa* L. cv. 'Amelia') crops were grown in a glass greenhouse under natural light conditions, with day/night temperatures of 24 °C/18 °C (± 3.5 °C), a 10 h day/14 h night photoperiod, and 70–75% relative humidity. Seeds of both plant species were sown in 128 cell polystyrene trays containing a vermiculite mixture (3:1) and were irrigated three times per day for 15 days using deionized water. Thereafter, seedlings of both plant species were transplanted to 8-dm^3 polyethylene pots filled with the OS soil, with three seedlings per pot. Ten days after transplanting (DAT), plants were thinned to one per pot to evaluate growth. Two pot experiments were carried out, and eight treatments were arranged factorially (2 × 4) in an RCBD, with four replicates (*n* = 4) for each experiment, giving a total of 64 pots (32 for each crop). The two N sources (UWC and urea) were applied to pots in four different doses: 12.5, 25.0, 37.5, and 50.0 mg dm^{-3}.

Lettuce shoots were harvested after 30 DAT, while the broccoli was harvested after 90 DAT. The plant stems were cut at soil level to evaluate the fresh biomass, and the samples were then dried in a forced-air oven (Tecnal® TE 394-3; Tecnal Scientific Equipment, Piracicaba, Brazil) at 65 °C until a constant mass was obtained. The dried shoots were then pulverized using a Wiley mill equipped with a stainless-steel chamber and blades (Marconi® MA 360; Marconi Equipment Laboratories Ltd., Piracicaba, Brazil). The total N concentration was determined using the Kjeldahl method [32]. Based on the concentrations of N in the aerial parts of both plant species and their respective values of dry biomass, the N accumulations of these elements were calculated (mg per plant).

Data Analysis

Data were analyzed using the Shapiro–Wilk test, assuming normality, and using the Fisher tests, assuming variance homogeneity ($P < 0.05$). When F values were significant ($P < 0.05$), the data were subjected to regression analysis, and equations were adjusted using the linear and polynomial models of the SigmaPlot 14.0 statistical package (Systat Software Inc., USA). Mean values were compared using Tukey's HSD test ($P < 0.05$). For data interpretation, the equations with significance ($P < 0.05$) and the highest coefficients of determination (R^2) were selected.

Results

Changes in Inorganic Nitrogen Production Related to Different Urban Waste Compost Amendments

The ANOVA revealed a significant interaction between soils and UWC doses on inorganic N content (INC) during the 84-day incubation period ($P < 0.0001$; Table 1). The INC showed a linear increase with incubation time in the three soils used, related to the increasing UWC doses. The highest dose of UWC (50 mg dm^{-3}) at all incubation times provided a higher INC than the other UWC doses (12.5, 25.0, and 37.5 mg dm^{-3}). The OS soil accumulated more INC and showed a significant difference ($P < 0.0013$) in comparison to the QS and US soils; however, the US soil was superior to the QS soil (Table 1).

Changes in Net Nitrogen Mineralized in Response to Different UWC Amendments

We found significant interactions between soils and UWC doses on NNM during the 84-day incubation period (Table 2). The amount of NNM increased linearly as UWC doses increased in the three soils used. The NNM content was higher at the highest UWC dose (50 mg dm^{-3}) than the other UWC treatments. The OS soil showed higher amounts of NNM compared with the other soils, whereas the US soil was superior to the QS soil (Table 2).

Changes in Total Nitrogen Mineralization Rate in Response to Different UWC Amendments

The UWC application at the highest dose increased the potentially mineralizable N (N_0) in the three soils used. These increases were 18, 47, and 27% in the QS, US, and OS soils, respectively (Table 3). In addition, NM was positively correlated (as a power function) with soil type, as occurred in the QS ($R^2 = 0.71$ to 0.81), US ($R^2 = 0.70$ to 0.89), and OS ($R^2 = 0.80$ to 0.89) soils, in relation to the amount of UWC applied (Table 3).

The cumulative NM in the 84-day incubation period was higher for the OS soil (194.6 ± 0.6 µg N g^{-1} soil), followed by the US (167.3 ± 0.4 µg N g − 1 soil), and QS (150.5 ± 0.6 µg N g − 1 soil) soils. The percentage of TNM increased as the UWC dose increased in the three soils. The high UWC doses increased the TNM by 72%, 54%, and 66% in the QS, US, and OS soils, respectively. The TNM varied from 42% to 89% after 84 days of incubation, depending on the applied UWC dose and soil type (Table 3).

Table 1 Nitrogen mineralization, reflected as total inorganic N content (μg N g⁻¹ soil), in response to the application of urban waste compost (UWC) amendments

Soils	UWC (mg dm⁻³)	Incubation time (days) (μg N g⁻¹ soil)							
		0	7	14	28	42	56	70	84
QS		20.7±0.05eC	25.9±0.4dB	27.0±0.1eC	29.1±0.5dC	30.1±0.2dC	30.2±0.3eC	31.1±0.3eC	33.1±0.2eC
	12.5	31.5±0.4dC	33.6±0.5cC	35.1±0.1dC	39.1±0.2cC	44.3±0.1cC	46.2±0.4dC	50.1±0.2dC	63.4±0.5dC
	25.0	33.3±0.5cC	38.8±0.2bC	45.0±0.2cC	56.0±0.4bC	56.9±0.1bC	56.4±0.7cC	57.0±0.2cC	73.0±0.2cB
	37.5	35.8±0.7bC	38.9±0.3bC	55.1±0.2bC	57.1±0.5abC	57.0±0.1bC	59.0±0.4bC	60.1±0.1bC	75.2±0.3bC
	50.0	38.3±0.7aC	40.5±0.5aC	60.2±0.1aC	60.3±0.3aC	58.1±0.2aC	77.1±0.3aC	78.2±0.1aC	88.1±0.2aC
US	0.0	42.7±0.4cB	52.5±0.5*d*A	47.0±0.2*e*B	39.7±0.7*d*B	43.0±0.1*e*B	48.1±0.3*e*B	65.0±0.4*e*B	58.2±0.1*e*B
	12.5	44.7±0.5abB	53.6±0.5*d*B	48.2±0.2*d*B	52.1±0.1*c*B	57.1±0.1*d*B	66.0±0.3*d*B	69.0±0.2*d*B	68.2±0.1*d*B
	25.0	45.4±0.6aB	57.3±0.5*c*B	55.0±0.2*c*B	66.4±0.1*b*B	60.1±0.1*c*B	72.1±0.2*c*B	79.1±0.2*c*B	73.1±0.3*c*B
	37.5	43.7±0.6bcB	70.7±0.6*b*A	67.1±0.2*b*B	69.0±0.2*b*B	63.2±0.1*b*B	82.2±0.3*b*B	85.2±0.2*b*B	87.3±0.1*b*B
	50.0	42.7±0.5cB	77.8±0.6*a*A	76.1±0.2*a*B	73.3±0.3*a*B	67.1±0.1*a*B	85.1±0.3*a*B	89.1±0.1*a*B	97.1±0.2*a*B
OS	0.0	50.1±0.6eA	53.7±0.6eA	57.0±0.3**d**A	57.1±0.4eA	85.0±0.1eA	104.0±0.6eA	112.1±0.1eA	110.3±0.2eA
	12.5	53.6±0.6dA	56.3±0.5dA	84.1±0.6**c**A	79.0±0.7**d**A	88.1±0.1**d**A	107.1±0.3**d**A	115.3±0.2**d**A	124.2±0.1**d**A
	25.0	55.5±0.6cA	59.7±0.6cA	90.8±0.8**b**A	85.1±0.5**c**A	95.0±0.2**c**A	111.2±0.2**c**A	124.2±0.3**c**A	131.2±0.1**c**A
	37.5	58.3±0.7bA	62.7±0.5**b**B	103.1±0.1**a**A	100.2±0.6**b**A	100.2±0.1**b**A	114.2±0.2**b**A	128.1±0.4**b**A	138.1±0.2**b**A
	50.0	63.3±0.6A	67.3±0.5**a**B	103.2±0.1A	104.1±0.4**a**A	110.1±0.1**a**A	126.1±0.3**a**A	136.2±0.3**a**A	157.8±0.5**a**A
F test	S	6347.1**	11542.2**	22456.6**	936.2**	673694.8**	50428.9**	301743.9**	249483.3**
	D	396.8**	1589.2**	79591.1**	2468.8**	66880.8**	5656.1**	22359.6**	36534.0**
	S×D	118.4**	227.1**	1141.3**	41.0**	3403.3**	384.9**	1210.0**	1087.0**

Three soils were treated with different UWC doses during an 84-day incubation experiment

Values are means of four replicates ± standard deviation (SD). Heat-treated urban waste compost (UWC); initial inorganic N content (0 [IINC]) sandy Ustoxic Quartzipsamment (QS), intermediate-texture Red Ultisol soil (US), clayey Red Oxisol soil (OS). Different normal lowercase letters (e.g., a, b, c) indicate significant differences among UWC doses in the QS soil; different italic lowercase letters (e.g., *a, b, c*) indicate significant differences among UWC doses in the US soil; different bold lowercase letters (e.g., **a, b, c**) indicate significant differences among UWC doses in the OS soil, and different uppercase letters (e.g., A, B, C) indicate significant differences among the three types of soil at the same UWC doses, according to the Tukey test. (F values and ** $P < 0.01$ from the ANOVA)

Changes in Soil Properties in Response to Urban Waste Compost and Urea Treatments

The data illustrated in Fig. 1 clearly show that pH values and Ca, Mg, and P concentrations had a significant linear response to the increase in UWC doses (Fig. 1a–e); however, the concentration of H + Al showed a significantly decreased quadratic response (Fig. 1b). Conversely, the application of urea decreased linearly pH values, whereas the H + Al increased linearly (Fig. 1b) and did not significantly affect Ca, Mg and P concentrations (Fig. 1c–e). At all doses of N, except at 12.5 mg dm⁻³, the use of UWC provided higher values for pH and Ca, Mg, and P concentrations (Fig. 1a–e) and lower concentrations of H + Al (Fig. 1b) compared to the urea fertilizer.

Changes in Lettuce and Broccoli Production in Response to Urban Waste Compost and Urea Treatments

Increased doses of UWC and urea applied to the soil resulted in a linear increase in the concentrations of N in broccoli and lettuce plants (Fig. 2a, b). In both cultures, the application of UWC promoted a higher concentration of N in the leaves compared to the foliar N concentrations associated with the urea applications, except at a dose of 25 mg dm⁻³ of N, which showed no difference between the sources of N (Fig. 2a, b). In contrast, for the 12.5 mg dm⁻³ dose, urea produced higher concentrations of N in the broccoli plants than produced by the UWC (Fig. 2a). In both cultivated species, there was an increase in N accumulation with linear adjustment as a function of N doses and the forms of UWC and urea (Fig. 2c, d). In broccoli plants, the two highest doses of UWC resulted in greater N accumulation compared to urea, and the opposite occurred at the lowest dose of N (Fig. 2c). However, in lettuce plants, the application of N in the form of UWC, relative to the urea, provided greater N accumulation in all studied N doses (Fig. 2d).

The application of N doses as two N sources promoted a linear increase in the production of the fresh mass of broccoli plants (Fig. 3a). The application of UWC only, at the two highest N doses, resulted in greater production of fresh mass from the broccoli plants compared to the application of urea (Fig. 3a). In lettuce plants, the application of both sources of N promoted increments with quadratic adjustment in the production of fresh mass, reaching the maximum

Table 2 Net nitrogen mineralized (NNM) (μg N g^{-1} soil day^{-1}) in three soils treated with urban waste compost (UWC) doses during an 84-day incubation experiment

| Soils	UWC (mg dm^{-3})	Incubation time (days) (μg N g^{-1} soil)						
		7	14	28	42	56	70	84
QS	12.5	6.0±0.1dB	8.0±0.3dB	13.0±0.3dB	18.9±0.2dB	22.1±0.3dC	26.4±0.5dC	41.1±0.6dC
	25.0	7.0±0.2cC	20.1±0.1cB	23.1±0.4cB	29.0±0.3cB	29.1±0.1cC	31.0±0.2cC	51.0±0.3cC
	37.5	9.1±0.2bC	26.0±0.1bB	28.1±0.4bB	30.7±0.4bC	33.0±0.1bC	35.0±0.2bC	56.1±0.2bB
	50.0	12.1±0.1aC	30.1±0.4aB	31.5±0.4aC	33.1±0.3aC	36.1±0.5aC	40.2±0.8aC	62.1±0.3aC
US	12.5	4.0±0.5dC	7.0±0.1dC	12.0±0.1dC	18.0±0.1dC	26.0±0.3dB	38.1±0.1dB	46.1±0.4dB
	25.0	15.1±0.4*c*B	16.0±0.2*c*C	19.0±0.8*c*C	22.0±0.3*c*C	35.1±0.3*c*B	40.0±0.2*c*B	53.0±0.2*c*B
	37.5	18.0±0.2 *b*B	22.1±0.1 *b*C	28.0±0.1 *b*B	38.1±0.8 *b*B	50.0±0.3 *b*B	50.1±0.4 *b*B	56.2±0.4 *b*B
	50.0	23.1±0.1*a*A	24.1±0.5*a*C	38.1±0.2 *a*B	44.1±0.2 *a*B	58.1±0.2 *a*B	61.0±0.1 *a*B	64.1±0.2 *a*B
OS	12.5	9.0±0.5**d**B	32.1±0.1**d**A	37.0±0.6**c**A	60.1±01**d**A	107.0±0.2**d**A	123.2±0.1**d**A	130.1±0.2**d**A
	25.0	11.0±0.3**c**B	37.1±0.1**c**A	43.0±0.4**b**A	73.0±0.1**c**A	110.1±0.2**c**A	127.0±0.2**c**A	136.0±0.3**c**A
	37.5	12.1±0.1**b**B	44.1±0.2**b**A	47.0±0.2**a**A	80.0±0.1 **b**A	113.0±0.4 **b**A	131.1±0.5 **b**A	140.1±0.3 **b**A
	50.0	14.2±0.6**a**B	52.1±0.4**a**A	53.1±0.5**a**A	93.0±0.2**a**A	117.1±0.2**a**A	135.1±0.4**a**A	154.1±0.3**a**A
F test	D	1573.5**	5587.8**	3627.2**	9327.9**	7384.3**	3317.5**	5817.7**
	S	1240.8**	17068.3**	9509.5**	84337.7**	284534.6**	221409.5**	252519.9**
	D×S	342.5**	111.2**	125.4**	739.2**	1127.6**	249.3**	118.8**

Values are means of fourth replicates ± S.D. Heat-treated urban waste compost (UWC), sandy Ustoxic Quartzipsamment (QS), intermediate-texture Red Ultisol soil (US), clayey Red Oxisol soil (OS). Different normal lowercase letters (e.g. a, b, c) indicate significant differences among UWC doses under QS soil; different italic lowercase letter (e.g. *a*, *b*, *c*) indicate significant differences among UWC doses under US soil, different bold lowercase letter (e.g. **a**, **b**, **c**) indicate significant differences among UWC doses under OS soil and different uppercase letters (e.g. A, B, C) indicate significant differences among the three types of soil at the same UWC doses, according to the Tukey test. (F values and ** $P < 0.01$ from the ANOVA)

Table 3 Nitrogen mineralization rate in three soils treated with different urban waste compost (UWC) doses after 84-day incubation experiment

Soils	UWC (mg dm^{-3})	N_0 (μg N g^{-1})	R^2	NMR (μg N g^{-1})	TNM (%)
US	12.5	32.4±0.3dC	0.75	129.6±1.1dC	56.1±0.3dA
	25.0	34.6±0.3cC	0.81	139.4±0.5cC	62.7±0.7cB
	37.5	39.5±0.4bC	0.78	141.3±0.7bC	82.1±0.3bA
	50.0	43.6±0.3aC	0.80	150.5±0.6aC	89.3±0.6aA
RS	12.5	45.4±0.3*d*B	0.70	136.3±0.6*d*B	42.3±0.3*d*C
	25.0	49.4±0.3*c*B	0.83	149.4±0.4*c*B	51.2±0.2*c*C
	37.5	59.4±0.4*b*B	0.83	155.1±0.6*b*B	52.3±0.5*b*C
	50.0	65.4±0.2*a*B	0.89	167.3±0.4*a*B	71.3±0.4*a*C
OS	12.5	74.3±0.9**b**A	0.80	170.8±0.6**d**A	53.3±0.3**d**B
	25.0	75.5±0.3**b**A	0.81	176.1±0.2**c**A	64.3±0.5**c**A
	37.5	84.5±0.7**a**A	0.83	180.4±0.4**b**A	71.3±0.3**b**B
	50.0	85.2±0.5**a**A	0.89	194.6±0.6**a**A	80.5±0.2**a**B
F test	D	1164.5**		2419.1**	13320.8**
	S	16170.0**		12642.3**	7441.4**
	D×S	51.9**		56.8**	257.6**

Values are means of fourth replicates ± S.D. Heat-treated urban waste compost (UWC), sandy Ustoxic Quartzipsamment (QS), intermediate-texture Red Ultisol soil (US), clayey Red Oxisol soil (OS). Different normal lowercase letters (e.g. a, b, c) indicate significant differences among UWC doses under QS soil; different italic lowercase letter (e.g. a, b, c) indicate significant differences among UWC doses under US soil, different bold lowercase letter (e.g. a, b, c) indicate significant differences among UWC doses under OS soil and different uppercase letters (e.g. A, B, C) indicate significant differences among the three types of soil at the same UWC doses, according to the Tukey test. F values and **$P < 0.01$ from the ANOVA). Initial amount of mineral N (N_0), coefficient of determination (R^2), N mineralization rate (NMR), percentage N mineralization after 84 days (TNM)

Fig. 1 Soil pH (**a**) and H + Al (**b**) values, and concentrations of Ca (**c**), Mg (**d**), and P (**e**), as a function of N doses (12.5, 25.0, 37.5, and 50.0 mg dm^{-3}) and the N sources (UWC and urea) applied. Values are given as the mean of four replications ± standard deviation (Mean ± SD; $n = 4$). Different lowercase letters indicate significant differences between the different sources of N at the same doses of N according to the Tukey test ($P < 0.05$). (F values, *$P < 0.05$, and **$P < 0.01$ from the ANOVA)

Discussion
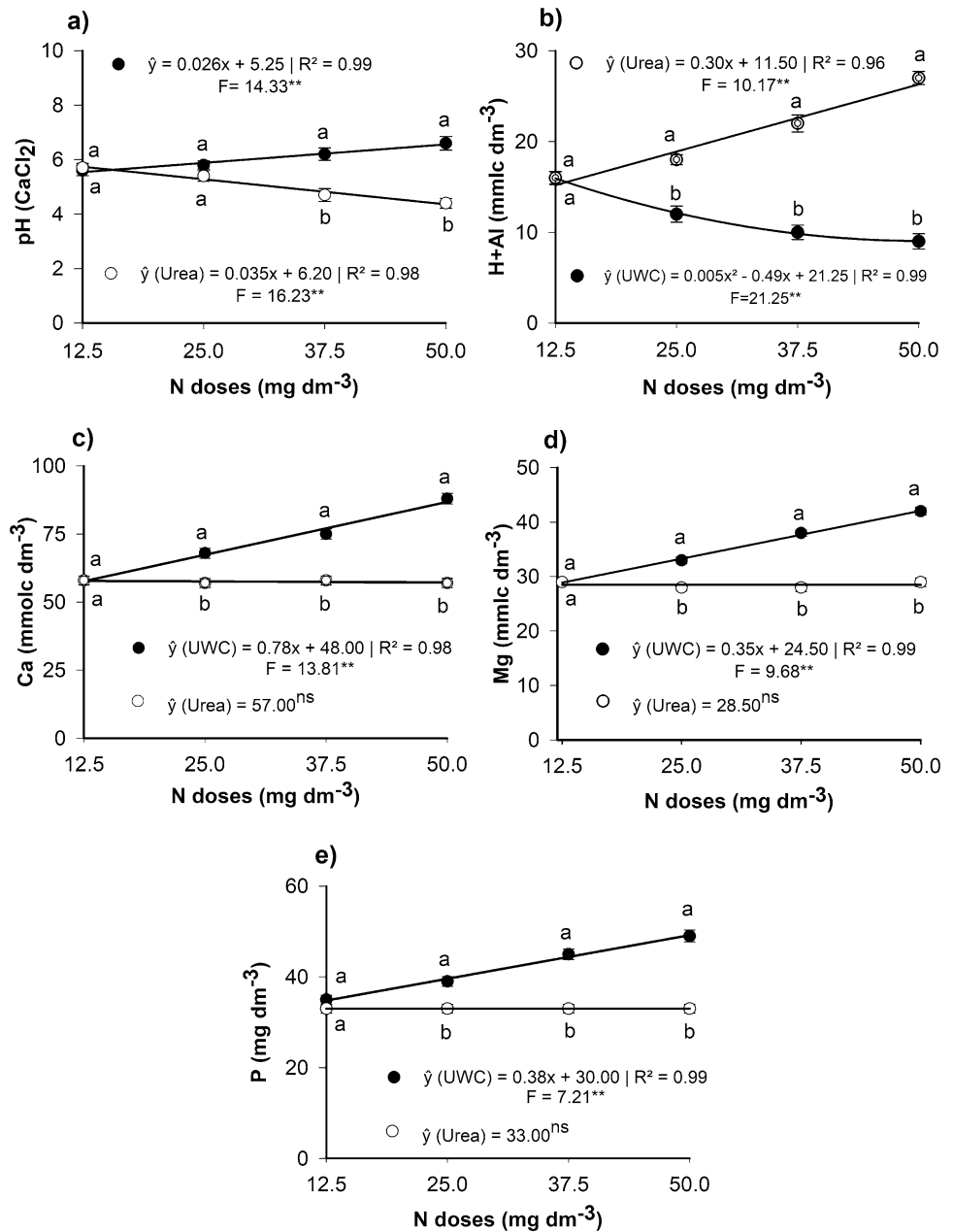
In the present study, we found that the application of UWC as an alternative N fertilizer was reinforced by the fact that its application to the soil increased the INC, NMR, NM, and TNM with incubation time but varied among UWC point at N doses equal to 37.5 and 25 mg dm^{-3} for UWC and urea, respectively (Fig. 3b). The use of UWC, in comparison with urea application only, for the two highest doses of N employed, resulted in greater production of the fresh mass of lettuce plants (Fig. 3b).

doses and soil types (Tables 1, 2, and 3). In this study, the amount of total mineralized N (TMN) released from UWC varied widely with its amendment doses and soil types and increased with the incubation period (Table 1). The maximum total amount of mineralized N released was recorded at 84 days of incubation and, at the highest dose of UWC (50.0 mg dm^{-3}), resulted in 88.1, 97.1, and 157.8 μg N g^{-1} soil in the QS, US, and OS soils, respectively. These values fall within the range reported by other researchers [19, 33]. Variation in the TMN released may be explained by differences in the soils used, and the amount of UWC applied. Similar findings were observed in previous studies when UWC was applied to the soils [1, 11, 33]. The current study's

Fig. 2 Leaf nitrogen concentration in the aerial parts of broccoli (**a**) and lettuce plants (**b**). Nitrogen accumulation in broccoli (**c**) and lettuce plants (**d**) as a function of N doses (12.5, 25.0, 37.5, and 50.0 mg dm^{-3}) and the N sources (UWC and urea) applied. Mean ± S.D.; $n = 4$. Different lowercase letters indicate significant differences between the different sources of N at the same N doses, according to Tukey's test ($P < 0.05$). (F values from the ANOVA: *$P < 0.05$; **$P < 0.01$)
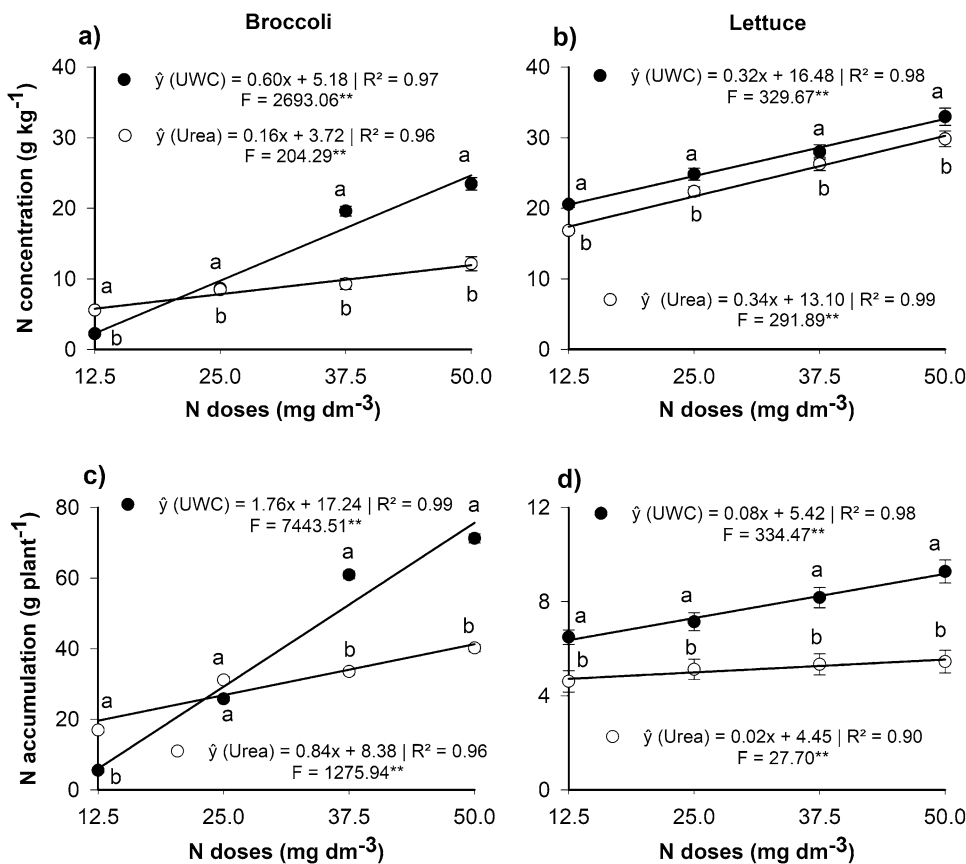
Fig. 3 Fresh biomass production in broccoli (**a**) and lettuce plants (**b**) as a function of the N doses (12.5, 25.0, 37.5, and 50.0 mg dm^{-3}) and N sources (UWC and urea) applied. Mean ± S.D.; $n = 4$. Different lowercase letters indicate significant differences between the different sources of N at the same N doses, according to the Tukey test ($P < 0.05$). (F values, *$P < 0.05$, and **$P < 0.01$ from ANOVA)
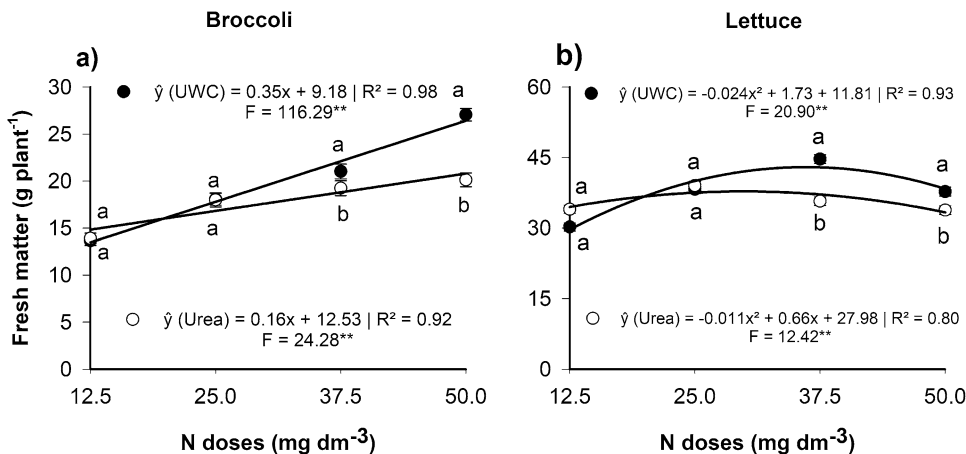
findings indicated that the higher rates of UWC application caused greater TMN release, suggesting that the UWC used in this study contained a large amount of mineral N and released higher levels of N.

In the current study, the high NNM observed for UWC in the OS soil (154.1 μg N g^{-1} soil) may have been due to the low C:N ratio (23) and high N content in the UWC (Table S2). The low relationship between C and N agrees with previous observations that the amount of N released increased [13, 14]. In other reports, NM in soil containing UWC ranged from 53 [34] to 54% [14] of the total N applied, which is in line with the previous findings of Fascella et al. [16], who reported that the N mineralization of urban wastes could be affected by high P concentrations. In addition, Masunga et al. [14] reported that organic compost with higher N contents and lower C:N ratios mineralizes enough N to increase plant growth and production. In this study, the NM was positively correlated as a power function with soil type, as occurred in the QS ($R^2 = 0.71$ to 0.81), the US ($R^2 = 0.70$ to 0.89), and the OS ($R^2 = 0.80$ to 0.89), with the

amount of UWC applied. These findings imply that UWC presumably increased microorganisms' activities in the soil, which helped accelerate N mineralization.

Previous studies have determined that the N mineralization rate of UWC is relatively low [18]. A possible explanation for such variation in N mineralization may be that it is related to differences in the chemical and physical properties of the soils used (Supplementary Table S1) as well as the UWC properties (Table S2) and amounts used. Similar trends were observed with the addition of organic amendments to soils [14, 35]. The trend we observed with an increase in N mineralization in the soil with the application of UWC and the incubation time has been reported earlier in the literature [36, 37]. Our findings indicate that using UWC amendments as an alternative N source in soils, especially those containing high clay content, potentially leads to an increase in sustainable agricultural practices and a decrease in environmental contamination.

In the current study, it was evident that the higher UWC doses resulted in a greater percentage of TNM in the three soils used, with the OS showing a higher TNM in comparison to the other soils (Table 3), presumably due to greater OM content as well as higher P, K, and Ca concentrations. In addition to a greater sum of bases and cation exchange capacity, (Supplementary Table S1), this soil also has a higher clay content (Table S1). The impact of clay content on has been observed previously by other authors [13, 38]. Similarly, Hassink et al. [39] have reported that soils with high clay content have higher bacterial biomass, which helps to increase the N production and release compared to soils with a sandy texture. Higher heavy metal contents can affect the N mineralization of UWC [16, 17]; however, the UWC used in this study showed lower toxic metal contents (Supplementary Table S2).

Our study showed that urea application increased the acidity of the soils (Fig. 1a, b). Such effects of urea application on soil acidification are well known [40–42]. In contrast, the application of UWC decreased soil acidity, most likely by increasing the pH value and decreasing the concentration of H + Al (Fig. 1a, b). This benefit of UWC amendments could be due to this compound's high pH value (pH 9.6). Furthermore, the increase in soil pH we observed could have been due to an increase in the concentration of OH^-, which can occur when oxygen in the soil solution acts as a receptor for electrons from the microbial oxidation of carbon [43, 44], proton consumption capacity (H^+), and complexation of H^+ and Al^{3+} by the organic charge of the compound [45]. These results agree with previous findings that UWC applications decrease soil acidity [46, 47].

In this study, the increase in soil pH associated with the application of UWC was directly proportional to an increase in the concentrations of Ca, Mg, and P, and these findings corroborated those of previous studies [12, 45].

The increase in the soil Ca, Mg, and P concentrations that was associated with the highest doses of UWC compared with urea could be explained by the presence of these nutrients in the organic fraction of the UWC that were liberated during its decomposition process. Similar results have been observed for other UWCs [10, 48]. In addition, the increase in P concentration with the application of UWC was possibly due to the increase in the soil pH values. An increase in soil pH increases the concentration and activity of OH^- ions in the soil solution, decreasing the precipitation of low solubility P-Fe and P-Al. There is also the generation of negative charges in clays and organic matter, causing repulsion between the phosphate and the adsorbent surface, thereby increasing P availability in the soil solution [49]. These findings directly support our results, which showed the improvement of soil chemical properties with the addition of UWC, as has been widely reported [10, 48, 50].

In the current study, UWC amendments increased the fresh mass production of both plant species compared to urea, especially at the highest doses of the organic compounds (Fig. 3a, b). These results could be related to the fast N mineralization of the UWC (Tables 1, 2, and 3) and also to the decrease in the H + Al of the soil and the increase in the levels of nutrients such as Ca, Mg, and P (Fig. 1c–e). Therefore, the UWC appears to be an important N source for vegetable production, which increases N uptake (Fig. 2c, d), given the fast N release to the soil by the UWC, as was verified in the incubation experiment in our study.

The UWC application is likely to have favored plant production by increasing N uptake and accumulation, processes that perform vital biological functions in plant growth [47]. This could be one reason for the positive effects of UWC application on plant yields. Similar results have been obtained previously by Naderi et al. [10], who found that UWC increased the concentration and accumulation of N in wheat plants compared with urea applications. Our results are in line with other reports that UWC improves plant growth and productivity in different plant species such as spinach [51], pepper [11], potato [6], onion [52], rice, and wheat [48].

In these studies, however, the effects of UWC on N mineralization and changes in soil chemical attributes were not evidenced. Consequently, these results imply that the scientific basis of these studies reported in the literature is compromised, and it is not possible to answer the primary agronomic question of whether organic compost could replace urea and guarantee good vegetable productivity. Additionally, Parameter values for calculation of the N mineralization rate (Supplementary Table S2), which indicates that it could be used as potential organic amendments to enhance soil properties and crop productivity and lead to decreasing environmental contamination.

In summary, N mineralization was clearly influenced by the amount of UWC, incubation period, C:N ratio, and soil type. This research reinforces the importance of applying recycled urban waste to agricultural soils as a sustainable form of N fertilization to preserve the environment. In addition, this compound could substitute for urea as a finite-use fertilizer because urea production depends on energy (natural gas) from petroleum, a non-renewable product. Research on the efficacy of UWC as a fertilizer is important in relation to food security and environmental benefits; however, UWC studies should be expanded to incorporate other soils and crops. In further research based on this study, UWC should be tested in a field experiment to verify the laboratory incubation and greenhouse experiments results.

Conclusions

The results of this research highlight that the N content of the processed UWC proportionally increases the amount of N released, suggesting that the amount of UWC should be matched to the needs of the crop. The UWC amendments were more efficient than urea in improving the clayey red Oxisol soil properties and broccoli and lettuce plant productivity, and this occurred when providing UWC amendments at 50 and 37.5 mg dm^{-3}, respectively. Therefore, these findings imply that processed UWC as an N source in agricultural systems is more environmentally friendly than urea or other mineral compounds. Thus, UWC, which has a known composition and releases nutrients predictably, improves vegetable productivity.

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Author Contributions Conceived and designed the experiments: FON, RMP, HAS, and MGA. Performed the lab experiment: FON, HAS, and MGA. Performed the greenhouse experiments: FON, MGA, ACH, LFP and LASND. Analyzed the data: FON, RMP, HAS, and ACH. All authors discussed the conceptual model and contributed to data interpretation and the writing of the paper.

Data Availability The following information was supplied regarding data availability: Dates of Physicochemical characteristics of the studied soils and heat-treated urban waste compost, and the parameter values for calculation of the N mineralization rate are provided in the Supplemental Files.

Declarations

Conflicts of interest The authors declare there are no competing interests.

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