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ORIGINAL RESEARCH

Effects of Different Fertilizer Regimes and Irrigation Water Qualities on Soil Fertility under Lettuce Production

Thomaz Figueiredo Lobo[1], **Helio Grassi Filho**[1], **João de Andrade Bonetti** [2]

[1] São Paulo State University, UNESP. Avenida Universitária, 3780, CEP 18610-034, Botucatu, SP, Brazil.
[2] São Paulo State University, UNESP. Avenida Universitária, 3780, CEP 18610-034, Botucatu, SP, Brazil. Researcher at the Smart B100 Advanced Research Center/FAPESP.

Correspondent author: joao.bonetti@unesp.br

Abstract

Purpose: This study aimed to evaluate the effect of organic compost as a substitute for synthetic nitrogen (N) and the use of wastewater irrigation on lettuce cultivation by assessing changes in key soil fertility parameters.

Methods: A greenhouse experiment was conducted at the Soil Science Department of the School of Agricultural Sciences in Botucatu, Brazil (22°50′S, 48°22′W), on a medium-textured Rhodic Hapludox. The experimental design was completely randomized in a split-plot arrangement, with six N fertilization treatments (organic and synthetic) combined with either wastewater or freshwater irrigation, and five replicates. The N treatments were as follows: T1 – no N; T2 – 0.54 g N applied as urea, split at 7, 14, and 28 days after transplanting; T3 – 0.27 g N from organic compost and 0.27 g N from urea, split at 7, 14, and 28 days after transplanting; T4 – 0.54 g N from organic compost; T5 – 0.81 g N from organic compost; T6 – 1.08 g N from organic compost.

Results: The highest compost rate (1.08 g N, T6) significantly improved soil fertility by increasing pH, cation exchange capacity, base saturation, and the availability of macro- and micronutrients, under both freshwater and wastewater irrigation. These treatments also enhanced soil organic matter and dissolved organic carbon contents, which were positively correlated with nutrient availability.

Conclusion: The T6 treatment also produced the highest green biomass yield of lettuce compared to the exclusive use of urea, highlighting organic compost as a sustainable alternative for N fertilization.

Keywords: Lettuce, Organic matter, Wastewater, Poultry manure, Composting.

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1. Introduction

Lettuce (*Lactuca sativa* L.) is the most widely consumed leafy vegetable worldwide, mainly eaten fresh in salads (Torres et al., 2022; Tütüncü et al., 2024) owing to its nutritional importance as a source of vitamins and mineral salts. In Brazil, lettuce ranks among the top vegetables in terms of both production volume and commercial value (Torres et al., 2022). Lettuce shows a strong response to nitrogen (N) fertilization (Sylvestre et al., 2019), requires high soil moisture, and has significant production potential when grown with organic fertilizers (Hernández et al., 2016; A. F. T. Silva et al., 2017) and wastewater (V. C. F. d. Silva et al., 2023).

The combined use of organic and mineral fertilizers in vegetable production allows gradual nutrient release and improved nutrient use efficiency (Regkouzas et al., 2025; Torres et al., 2022). Organic fertilization offers several advantages, including waste recycling, greater farmer autonomy from commercial input markets, and improvements in soil quality. Lettuce plants can grow rapidly in soils rich in organic matter and reach harvest maturity quickly (Tütüncü et al., 2024). Additionally, organic fertilization not only increases yield but also enhances the qualitative traits of plants compared to those cultivated solely with mineral fertilizers, potentially improving the nutritional quality of lettuce (Regkouzas et al., 2025). The use of organic fertilizers has been shown to increase both yield and nutrient content in lettuce (Pane et al., 2014).

Organic fertilization using various organic materials such as animal manure, plant biomass mixtures, and others has been widely adopted in lettuce production to reduce the use of chemical fertilizers and improve the soil's physical, chemical, and biological properties (Regkouzas et al., 2025). Organic composts, including manure and sewage sludge, can serve as alternatives to inorganic fertilization in lettuce cultivation, achieving equal or higher yields while reducing nutrient leaching risks and improving soil chemical, physical, and microbiological properties (Hernández et al., 2016). The application of pelletized organic compost at a rate of 170 kg N ha^{-1} has been shown to increase lettuce yield, soil microbial biomass, and acid phosphatase activity (García-López & Horta, 2022).

Wastewater, which originates from domestic, commercial, or industrial sources and is often underutilized or discarded, represents a valuable alternative for agricultural use. It conserves potable water for human consumption and recovers both water and nutrients beneficial for crop growth. Wastewater offers great potential for agricultural reuse, as it provides essential nutrients, organic matter, and micronutrients to the soil, thereby enhancing crop yield and quality (Gatta et al., 2015). Moreover, wastewater positively affects soil and plant tissue properties, supplying an additional source of N and P fertilization while promoting the adoption of circular practices within the water sector (Regkouzas et al., 2025).

Despite extensive research demonstrating the individual benefits of organic fertilization and wastewater irrigation for lettuce cultivation, few studies have addressed the combined effects of these two sustainable practices on soil fertility and nutrient dynamics under tropical conditions. Wastewater supplied most of the crop's nutrient needs (≈90% N, P, K) and achieved comparable yields to groundwater irrigation, indicating its potential as a sustainable alternative nutrient source that can lessen soil nutrient gaps and environmental risks (Niquice-Janeiro et al., 2023).

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However, the combined effects of organic compost substitution for mineral N and nutrient-rich wastewater irrigation on soil fertility remain poorly understood, especially under tropical conditions. This knowledge gap limits our ability to design integrated management systems that enhance nutrient use efficiency and promote sustainable vegetable production. The objective of this study was to evaluate the effect of organic compost as a substitute for synthetic N and the use of wastewater irrigation on lettuce cultivation by assessing soil fertility parameters.

2. Materials and Methods

A greenhouse experiment was conducted in a greenhouse at the Soil Science Department of the School of Agricultural Sciences, Botucatu, Brazil (22°50′S, 48°22′W, 815 m altitude). The region has a subtropical climate. The mean annual air temperature is 19.4 °C and average annual precipitation is 1.525 mm. The soil used was a medium-textured Rhodic Hapludox, and its chemical properties are provided in Supplementary Table 1.

The experimental design was completely randomized in a split-plot arrangement with six N fertilization treatments (organic and synthetic) and two irrigation types (wastewater and freshwater), with five replicates. The N treatments per plant were as follows: i) T1 – without N; ii) T2 – 0.54 g N applied as urea, split at 7, 14, and 28 days after transplanting (Trani et al., 2012); iii) T3 – 0.27 g N from organic compost (98 g of compost) and 0.27 g N from urea, split at 7, 14, and 28 days after transplanting; iv) T4 – 0.54 g N from organic compost (196 g of compost); v) T5 – 0.81 g N from organic compost (294 g of compost); and vi) T6 – 1.08 g N from organic compost (392 g of compost).

Pots with a capacity of 7 L, measuring 22 cm in height and 27 cm in diameter, were used. Sixty days prior to the start of the experiment, soil liming was performed using 12.25 g of dolomitic limestone totaling per pot with a PRNT of 90% to raise base saturation (V%) to 80% (Trani et al., 2022). After the incubation period, phosphorus (P) and potassium (K) fertilizers were applied and homogeneously incorporated into the soil. Phosphorus was applied at 150 ppm, corresponding to 9.8 g of single superphosphate (18 g kg^{-1} P_2O_5) per pot. Potassium was applied at 50 ppm, corresponding to 0.5 g of potassium chloride (60 g kg^{-1} K_2O) per pot. This P and K correction was performed only during the first year of cultivation. N fertilization formed the basis of the experimental treatments and was applied using either mineral (urea) or organic fertilizer.

Organic compost was applied before each planting cycle. For the first cycle, it was incorporated into the soil, while for cycles 1–4 it was applied on the soil surface. No compost was applied in cycles 5 and 6. The experiment lasted approximately 212 days, comprising six growth cycles of 32, 46, 31, 35, 36, and 32 days, respectively.

The organic compost consisted of a mixture of poultry manure and eucalyptus bark, with an initial C/N ratio of 33:1. The composted materials included eucalyptus bark shredded to 2.5 cm with the following chemical characteristics: 0.8% N and 41% C; and poultry manure with 2.1% N and 19% C (Teixeira et al., 2017). The first compost batch was composed of 77% eucalyptus bark and 23% poultry manure by weight. The composting process included seven turnings: the first to homogenize the materials, and the remaining six for aeration. Temperature peaked at 68°C on the seventh day of composting. Water was added to adjust

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moisture levels due to the low initial humidity of the materials. After 100 days of composting, the material was used for the first and second lettuce cultivation cycles.

The second compost batch was prepared similarly, except for the addition of 2% single superphosphate to reduce NH_4 volatilization. This compost was used in the third and fourth lettuce cycles. The compost application rate was calculated based on the required amount of N, assuming a 20% N mineralization rate. Compost analysis is presented in Supplementary Table 1.

A total of six cultivation cycles were conducted, with fertilization applied only until the fourth cycle. The lettuce cultivars used were 'Lucy Brown' (1st, 2nd, 3rd, 5th, and 6th cycles) and 'Raider Plus' (4th cycle). Seedlings were transplanted at a depth of 5 cm in the center of each pot. Irrigation was supplied using either freshwater or domestic wastewater, based on the evaporation rates from a Class A evaporation pan located on-site. The nutrient composition of the wastewater is shown in Supplementary Table 1.

2.1 Soil and plant evaluations

Five subsamples were collected from the 0–20 cm layer of each pot to capture spatial variability and reduce sampling bias. The samples were air-dried, sieved, and used for subsequent soil analyses. Soil fertility was assessed at the end of the sixth lettuce cultivation cycle (Raij et al., 2001). The following parameters were evaluated: soil pH ($CaCl_2$), soil organic matter (SOM), available phosphorus (resin-extractable P), exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), potential acidity ($H^+ + Al^{3+}$), sulfur (S), and micronutrients (B, Cu, Fe, Mn, Zn), according to the methods described by Raij et al. (2001).

Soil pH was measured in a 0.01 mol L^{-1} $CaCl_2$ solution using a 1:2.5 soil-to-solution ratio. Potential acidity ($H^+ + Al^{3+}$) was calculated using the following equation: $H+Al=e^{(10.665-(1.1483SMP))}/10$, where pH_SMP refers to the pH of a soil suspension with SMP buffer solution. Exchangeable Al^{3+}, Ca^{2+}, and Mg^{2+} were extracted using 1 mol L^{-1} KCl. Aluminum was determined by titration with 0.0125 mol L^{-1} NaOH, while Ca^{2+} and Mg^{2+} were quantified by atomic absorption spectrophotometry. Soil organic carbon was extracted using sodium dichromate and quantified via photocolorimetry (Raij et al., 2001). The conversion from soil organic carbon (SOC) to soil organic matter (SOM) was performed using the Van Bemmelen factor (SOM = SOC × 1.724; Van Bemmelen, 1890). Available phosphorus (P) was determined by extraction with anion-exchange resin, following the method described by Raij et al. (2001). In this procedure, soil samples were equilibrated with resin strips in a 1:10 soil-to-solution ratio using deionized water and 0.5 mol L^{-1} $NaHCO_3$ as the eluent; the P desorbed from the resin was then quantified colorimetrically using the molybdenum blue method. Available sulfur (S) was extracted using a 0.01 mol L^{-1} calcium phosphate solution [$Ca(H_2PO_4)_2$]. The S concentration in the extract was then determined turbidimetrically by measuring the barium sulfate ($BaSO_4$) suspension formed after the addition of barium chloride, with readings performed at 420 nm. From the analytical results, the following indices were calculated: Sum of bases ($SB = Ca^{2+} + Mg^{2+} + K^+$); Total cation exchange capacity ($CEC = SB + H^+ + Al^{3+}$); and Base saturation ($V\% = 100 \times SB/CEC$). Green biomass was determined by harvesting and weighing the aboveground fresh plant material.

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2.2 Statistical analysis

The data were subjected to analysis of variance (ANOVA), and when significant effects were observed, treatment means were compared using Fisher's Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$), with statistical computations performed using SISVAR software version 5.6 (Ferreira, 2011). Additionally, Pearson's correlation analysis was carried out to examine the relationships between SOM and soil fertility attributes.

3. Results and discussion

The analysis of soil chemical attributes revealed significant differences among the treatments and irrigation water types (Table 1). In general, treatments T3 to T6 promoted improved soil fertility conditions compared to T1 and T2, regardless of the irrigation water source. Soil pH varied significantly across treatments and was highest in T5 and T6, both with freshwater (6.7) and wastewater (6.66), indicating a positive effect of these amendments on soil acidity neutralization. In contrast, treatment T2 exhibited the lowest pH values (4.4–4.5), which were associated with higher concentrations of exchangeable Al^{3+} and potential acidity (H+Al), reflecting increased soil acidity and aluminum toxicity.

Exchangeable aluminum (Al^{3+}) was reduced to zero in most treatments except for T2, which maintained high concentrations (1.7 to 2.1 $cmol_c\ dm^{-3}$), indicating its inefficiency in correcting soil acidity. Consequently, potential acidity (H+Al) was also higher in this treatment, impairing the effective cation exchange capacity (CEC) and nutrient availability (Table 1).

Cation exchange capacity increased progressively from T1 to T6, reaching the highest values in T6 (450.9 $cmol_c\ dm^{-3}$ with freshwater and 453.4 $cmol_c\ dm^{-3}$ with wastewater), indicating an accumulation of exchangeable bases (Table 1). This was also reflected in higher base saturation (V%) and sum of bases (SB), particularly in treatments T5 and T6. Magnesium (Mg^{2+}) content followed this trend and was significantly higher in these same treatments.

Regarding micronutrients, the levels of Cu, Zn, Mn, and Fe were higher in treatments with greater organic inputs (T3 to T6), suggesting that these elements benefited from the improved chemical conditions in the soil. Notably, T6 recorded the highest Zn (19.6–20.4 mg kg^{-1}) and Cu (1.48–1.72 mg kg^{-1}) values (Table 1). Irrigation with wastewater had similar effects to freshwater in most parameters, with slightly higher concentrations of nutrients such as Cu and Zn reflected in the average values per water type (Table 1).

The improvement in soil fertility, particularly at the highest dose of 108 g (Table 1), is directly related to the nutrient-rich organic compost used (Table 1) and its carbon content (Fig. 1). Changes in soil acidity dynamics influenced the overall nutrient distribution, leading to increases in both macro- and micronutrients (Table 1). For phosphorus (P), all treatments involving organic compost, including T3 (50% urea and 50% organic compost), outperformed mineral chemical fertilization with urea and the unfertilized control. Fertilization with cattle and chicken manure has proven more effective than mineral fertilization for producing leafy green lettuce, primarily due to the residual effects of phosphorus in the soil (Ribeiro et al., 2019). Additionally, the combined application of chemical and organic fertilizers improves soil fertility, enhances the structure of the microbial community, and promotes increased yield and quality of lettuce (Jin et al., 2022).

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The higher acidity, with an average pH of 4.45 for both freshwater and wastewater irrigation, and elevated aluminum concentration observed in the urea treatment were expected due to nitrification, which releases H^+ ions, and leaching of base cations from the soil (Brady & Weil, 2013). The higher acidity, with an average pH of 4.45 for both freshwater and wastewater irrigation, and elevated aluminum concentration observed in the urea treatment were expected due to nitrification, which releases H^+ ions, and leaching of base cations from the soil (Awaad et al., 2016), which aligns with our findings.

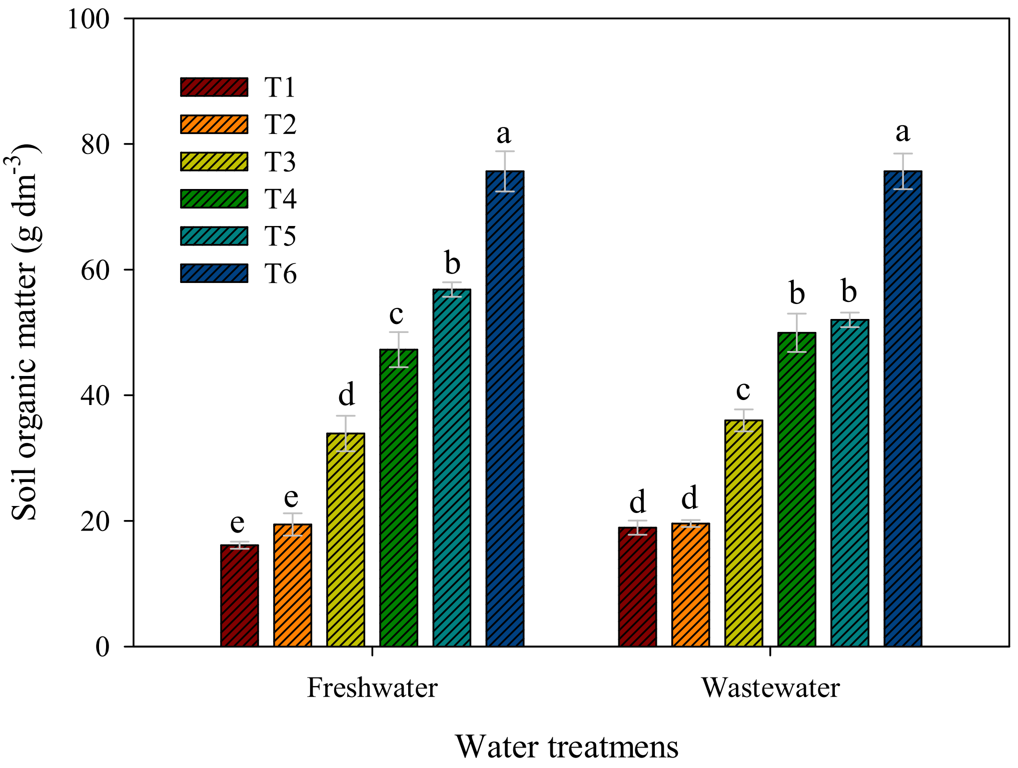

Figure 1. Soil organic matter after application of organic compost and urea doses as nitrogen sources in lettuce cultivation irrigated with freshwater and wastewater

SOM levels were highest following the application of 0.108 g of organic compost (T6) under both wastewater and freshwater irrigation (Fig. 1). N fertilization with 0.54 g of urea (T2) did not differ significantly from the control treatment without N application (T1) regarding SOM content (Fig. 1) and available phosphorus (Fig. 2), and was lower than treatments receiving organic compost. Potassium (K) levels were greater in treatments with organic compost application (T4, T5, and T6), while the remaining treatments were similar to the control (T1) under both freshwater and wastewater irrigation (Fig. 2).

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Table 1. Soil fertility after application of organic compost and urea doses as nitrogen sources, irrigated with freshwater and wastewater.

Freshwater											
Trat.	pH	Al^{3+}	H+Al	Mg	SB	CEC	S	B	Cu	Fe	Mn	Zn
	CaCl	$mmol_c\ dm^{-3}$ --					mg dm^{-3}--					
T1	$5.5^{\pm 0.11}$c	$0.0^{\pm 0.00}$b	$24.1^{\pm 1.19}$b	$18.1^{\pm 1.25}$d	$66.4^{\pm 4.61}$ e	$90.5^{\pm 3.68}$e	$85.6^{\pm 11.00}$b	$0.17^{\pm 0.01}$d	$0.9^{\pm 0.05}$d	$16.4^{\pm 0.94}$c	$0.7^{\pm 0.14}$b	$0.9^{\pm 0.23}$d
T2	$4.4^{\pm 0.09}$d	$1.7^{\pm 0.51}$a	$52.0^{\pm 3.98}$a	$14.8^{\pm 0.84}$d	$60.4^{\pm 5.04}$ e	$112.4^{\pm 4.46}$e	$103.9^{\pm 4.77}$ab	$0.23^{\pm 0.01}$d	$1.0^{\pm 0.03}$d	$26.9^{\pm 0.98}$a	$2.0^{\pm 0.18}$b	$1.1^{\pm 0.09}$d
T3	$6.3^{\pm 0.16}$b	$0.0^{\pm 0.00}$b	$10.8^{\pm 0.41}$c	$27.2^{\pm 1.2}$c	$222.5^{\pm 20.45}$d	$233.3^{\pm 20.47}$d	$115.9^{\pm 20.69}$ab	$0.46^{\pm 0.03}$c	$1.2^{\pm 0.06}$c	$13.8^{\pm 1.38}$e	$5.5^{\pm 0.48}$a	$7.6^{\pm 1.09}$c
T4	$6.5^{\pm 0.08}$ab	$0.0^{\pm 0.00}$b	$10.3^{\pm 0.38}$c	$32.8^{\pm 1.3}$b	$296.1^{\pm 20.00}$c	$306.4^{\pm 20.00}$c	$98.7^{\pm 7.04}$ab	$0.77^{\pm 0.05}$b	$1.4^{\pm 0.06}$b	$15.5^{\pm 0.60}$cd	$5.5^{\pm 0.40}$a	$12.3^{\pm 0.33}$b
T5	$6.7^{\pm 0.08}$a	$0.0^{\pm 0.00}$b	$10.7^{\pm 0.37}$c	$37.8^{\pm 2.14}$b	$375.9^{\pm 29.45}$b	$386.7^{\pm 29.27}$b	$129.0^{\pm 19.20}$a	$0.85^{\pm 0.14}$b	$1.3^{\pm 0.12}$b	$15.2^{\pm 1.42}$cd	$5.4^{\pm 0.88}$a	$12.7^{\pm 1.75}$b
T6	$6.7^{\pm 0.02}$a	$0.0^{\pm 0.00}$b	$11.5^{\pm 0.56}$c	$48.9^{\pm 1.36}$a	$439.4^{\pm 5.83}$a	$450.9^{\pm 5.79}$ a	$128.1^{\pm 19.77}$a	$1.48^{\pm 0.08}$a	$1.8^{\pm 0.05}$a	$20.7^{\pm 1.04}$b	$6.4^{\pm 0.15}$a	$19.6^{\pm 0.86}$a
	6.04^{ns}	0.28^{ns}	19.93^{ns}	29.95^{ns}	243.48^{ns}	263.41^{ns}	110.24^{ns}	0.66 B	1.27^{ns}	18.10^{ns}	4.29 B	9.06^{ns}
Wastewater												
T1	$5.5^{\pm 0.12}$c	$0.1^{\pm 0.05}$b	$32.8^{\pm 1.99}$b	$13.3^{\pm 0.09}$d	$65.5^{\pm 9.62}$e	$98.3^{\pm 8.89}$e	$74.0^{\pm 8.33}$c	$0.32^{\pm 0.02}$d	$0.8^{\pm 0.02}$d	$16.7^{\pm 1.44}$b	$1.7^{\pm 0.29}$b	$1.2^{\pm 0.28}$d
T2	$4.5^{\pm 0.13}$d	$2.1^{\pm 0.78}$a	$55.7^{\pm 6.75}$a	$10.0^{\pm 0.82}$d	$53.73^{\pm 4.32}$ e	$109.4^{\pm 4.23}$e	$89.2^{\pm 10.76}$c	$0.37^{\pm 0.04}$d	$0.9^{\pm 0.06}$d	$27.2^{\pm 1.59}$a	$2.3^{\pm 0.22}$b	$1.3^{\pm 0.19}$d
T3	$6.3^{\pm 0.07}$b	$0.0^{\pm 0.00}$b	$12.8^{\pm 0.18}$c	$21.9^{\pm 1.31}$c	$220.9^{\pm 16.57}$d	$233.8^{\pm 16.63}$d	$105.0^{\pm 4.55}$b	$0.58^{\pm 0.03}$c	$1.18^{\pm 0.10}$ c	$12.77^{\pm 0.72}$b	$6.6^{\pm 0.55}$a	$8.14^{\pm 0.37}$c
T4	$6.6^{\pm 0.08}$ab	$0.0^{\pm 0.00}$b	$11.2^{\pm 0.30}$c	$33.0^{\pm 1.35}$b	$331.4^{\pm 9.21}$c	$342.7^{\pm 9.19}$c	$107.4^{\pm 4.22}$b	$0.93^{\pm 0.04}$b	$1.44^{\pm 0.04}$b	$15.55^{\pm 0.83}$b	$6.3^{\pm 0.26}$a	$13.5^{\pm 0.45}$b
T5	$6.7^{\pm 0.05}$a	$0.0^{\pm 0.00}$b	$11.4^{\pm 0.47}$c	$34.8^{\pm 1.03}$b	$375.6^{\pm 11.32}$b	$387.0^{\pm 11.32}$b	$103.1^{\pm 6.18}$ b	$1.04^{\pm 0.09}$b	$1.5^{\pm 0.02}$b	$14.8^{\pm 0.64}$b	$5.9^{\pm 0.25}$a	$14.9^{\pm 0.51}$b
T6	$6.66^{\pm 0.02}$a	$0.0^{\pm 0.00}$ b	$13.4^{\pm 0.70}$ c	$44.2^{\pm 1.52}$a	$439.9^{\pm 18.96}$a	$453.4^{\pm 19.34}$a	$113.3^{\pm 2.47}$a	$1.72^{\pm 0.05}$a	$1.8^{\pm 0.03}$a	$19.5^{\pm 0.50}$b	$6.9^{\pm 0.45}$a	$20.4^{\pm 0.41}$a
	6.04	0.36	22.92	26.25	247.88	270.80	98.71	0.83 A	1.29	17.78	4.94 A	9.94

SB: Sum of bases; CEC: Cation exchange capacity; V%: Base saturation. Lowercase letters compare nitrogen treatment. Uppercase letters compare irrigation types.

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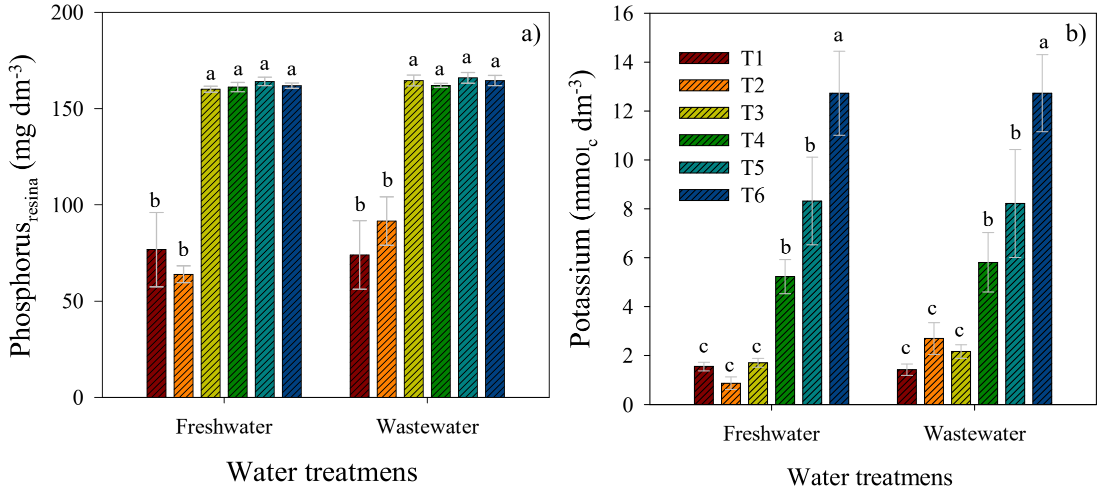

Figure 2. Resin-extractable phosphorus (a) and potassium (b) after application of organic compost and urea doses as nitrogen sources in lettuce cultivation irrigated with freshwater and wastewater

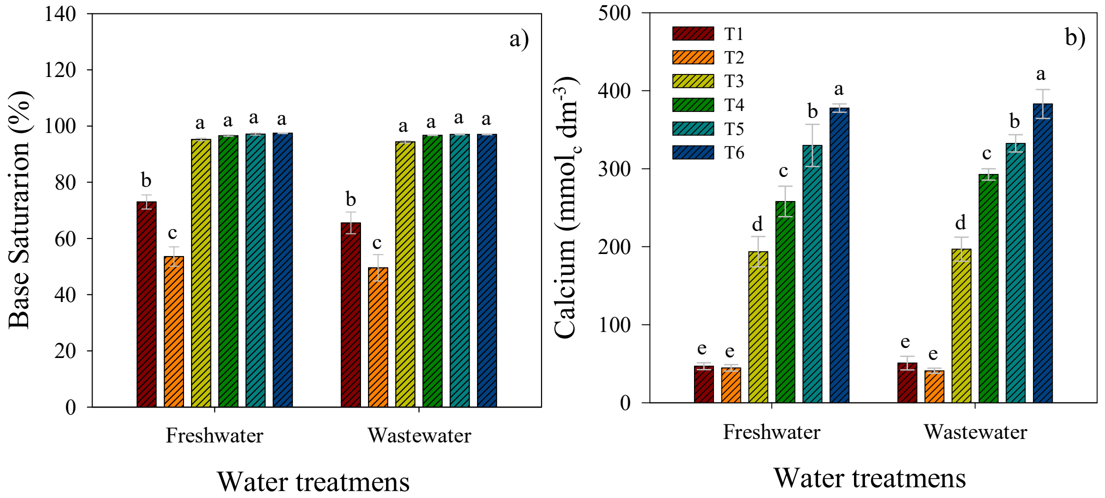

Figure 3. Base saturation (a) and calcium (Ca) (b) after application of organic compost and urea doses as nitrogen sources in lettuce cultivation irrigated with freshwater and wastewater

Organic compost treatment (T3, T4, T5, and T6) increased base saturation compared to the absence of N fertilization and exclusive urea fertilization (T1 and T2) under both freshwater and wastewater irrigation (Fig. 3). Calcium (Ca) levels were higher in treatments with organic compost application (T3, T4, T5, and T6), while urea use (T2) was similar to the control (T1; Fig. 3) under both irrigation types.

The increase in SOM content (Fig. 1) was proportional to the doses of organic compost applied, indicating the compost's potential as a carbon source (average of 25.5 g kg^{-1} for the four applied cycles; Supplementary Table 1). Higher levels of phosphorus (P) (Fig. 2), base saturation (Fig. 3; treatments T3, T4, T5, and T6), potassium (K) (Fig. 2), and calcium (Ca) (Fig. 3; treatments T4, T5, and T6) further demonstrate that the organic compost is nutrient-rich, with P and K contents of 3.25 g kg^{-1} and 1.25 g kg^{-1}, respectively (Supplementary Table 1). Lettuce

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fertilization using chicken manure resulted in higher soil pH, P, and K levels, while cattle manure contributed to greater magnesium (Mg), organic carbon, and organic matter contents (Ribeiro et al., 2019). Combined chemical and organic fertilizers enhanced soil fertility, microbial structure, and improved lettuce yield and quality (Jin et al., 2022).

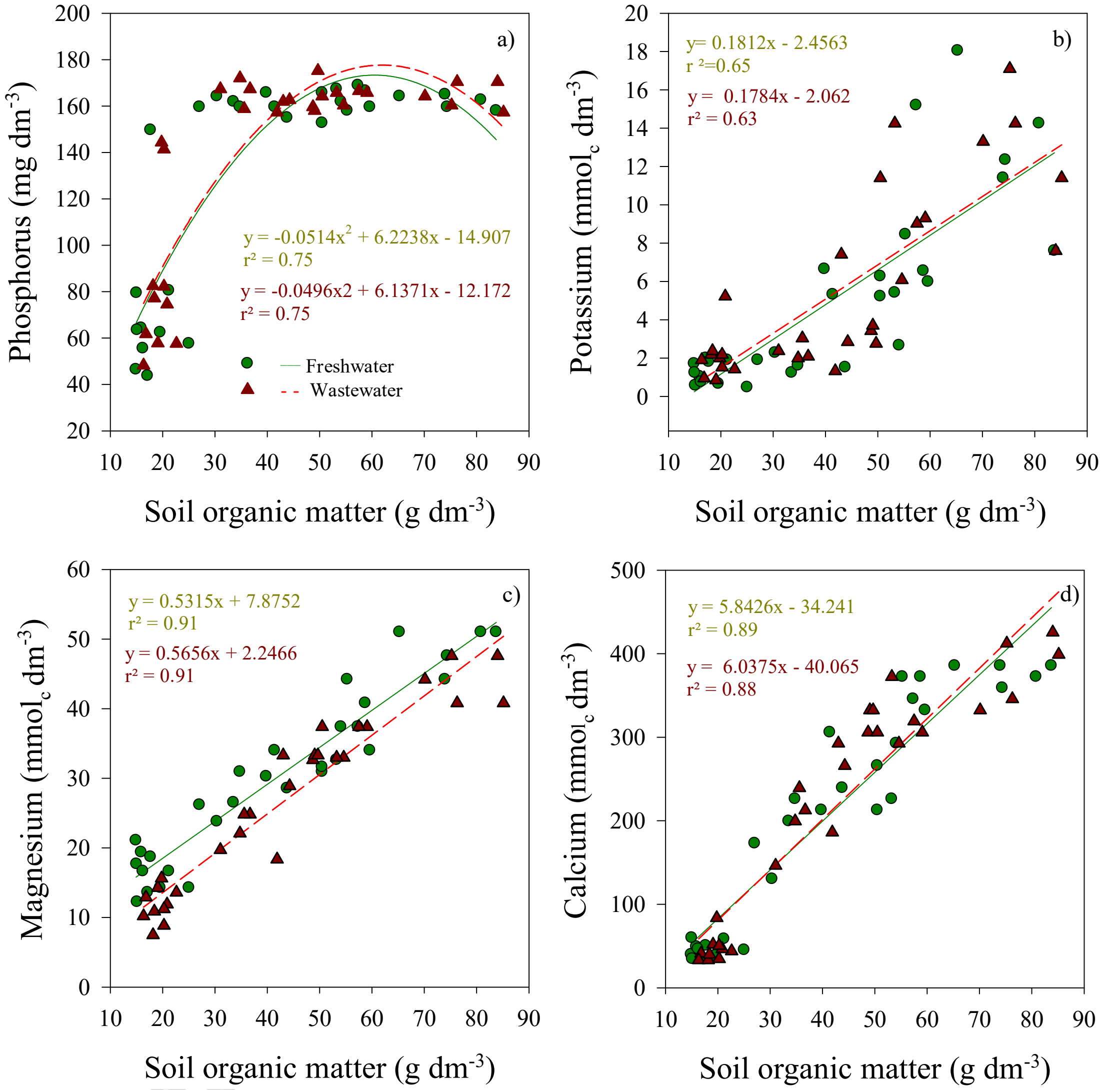

Figure 4. Regression of organic matter with macronutrients phosphorus (a), potassium (b), magnesium (c), and calcium (d) after application of organic compost and urea doses as nitrogen sources in lettuce cultivation irrigated with freshwater and wastewater

Strong correlations were observed between SOM content and macronutrients (Fig. 4). Phosphorus (P) exhibited a polynomial correlation ($r^2 = 0.75$ for both freshwater and wastewater irrigation). Potassium (K) showed a linear correlation with SOM ($r^2 = 0.65$ for freshwater and $r^2 = 0.63$ for wastewater), as did magnesium (Mg) ($r^2 = 0.91$ for both irrigation types) and calcium (Ca) ($r^2 = 0.89$ for freshwater and $r^2 = 0.88$ for wastewater).

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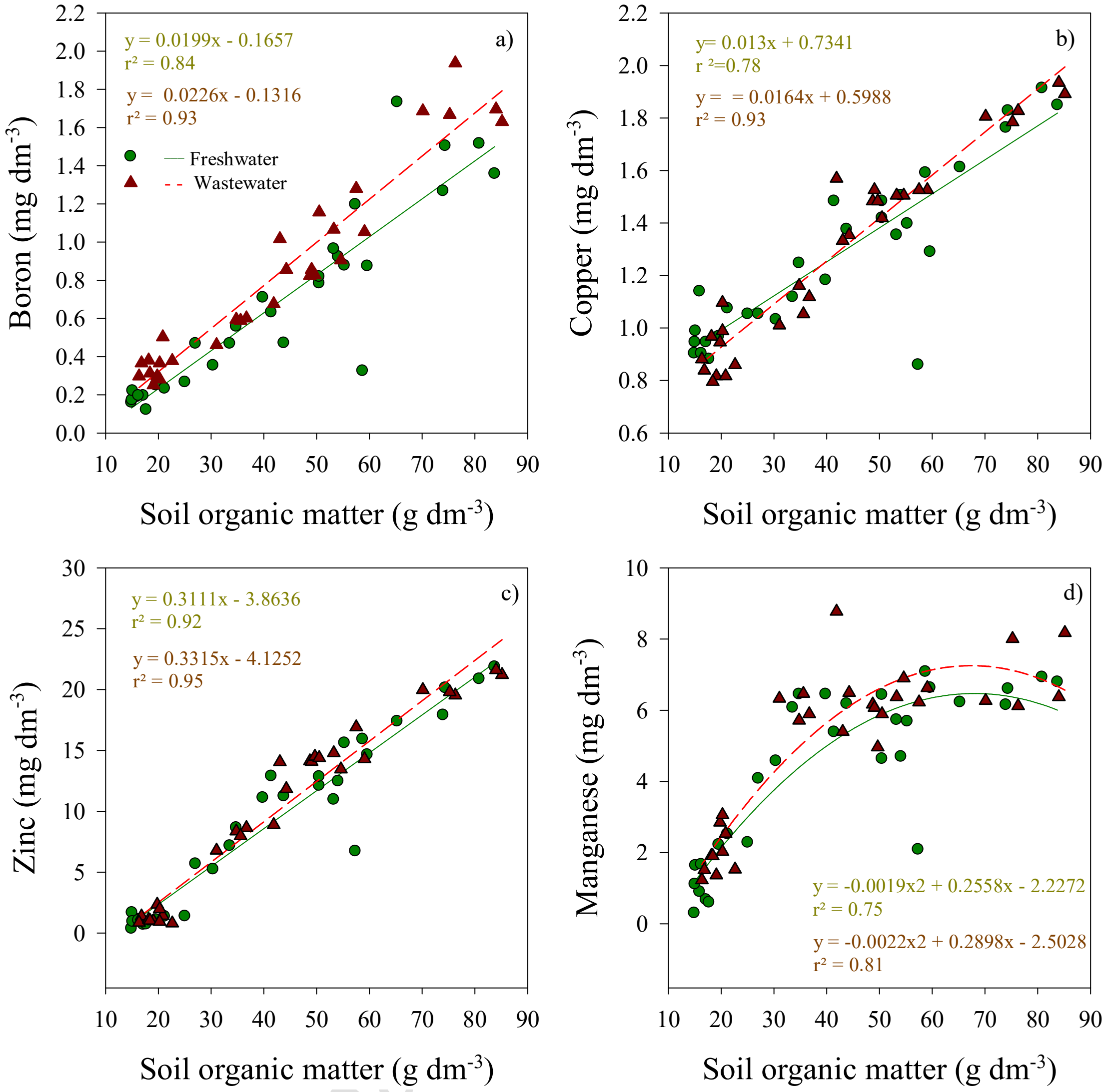

Figure 5. Regression of organic matter with micronutrients boron (a), copper (b), zinc (c), and manganese (d) after application of organic compost and urea doses as nitrogen sources in lettuce cultivation irrigated with freshwater and wastewater

Strong correlations were observed between SOM content and micronutrients (Fig. 5). Boron (B) content showed a linear correlation with SOM ($r^2 = 0.84$ for freshwater and $r^2 = 0.93$ for wastewater irrigation), as did copper (Cu) ($r^2 = 0.78$ for freshwater and $r^2 = 0.93$ for wastewater) and zinc (Zn) ($r^2 = 0.92$ for freshwater and $r^2 = 0.95$ for wastewater). Manganese (Mn) exhibited a polynomial correlation with SOM ($r^2 = 0.75$ for freshwater and $r^2 = 0.81$ for wastewater), for both irrigation types.

The strong relationships, both linear and polynomial, observed between SOM and macronutrient (Fig. 4) and micronutrient contents (Fig. 5) highlight the key role of SOM in nutrient interactions within the soil. The addition of organic fertilizers can enhance nutrient concentrations in the soil (Tütüncü et al., 2024), by increasing carbon content and promoting nutrient retention (Brady & Weil, 2013).

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The higher average fresh biomass yield of lettuce following compost application (T3, T4, T5, and T6) corroborates the observed improvements in soil fertility (Table 1; Figs 1, 2, and 3). Soil-incorporated organic fertilization enhances lettuce yield, with compost doses between 6–9 kg m^{-2} being most effective (Santos et al., 2021).

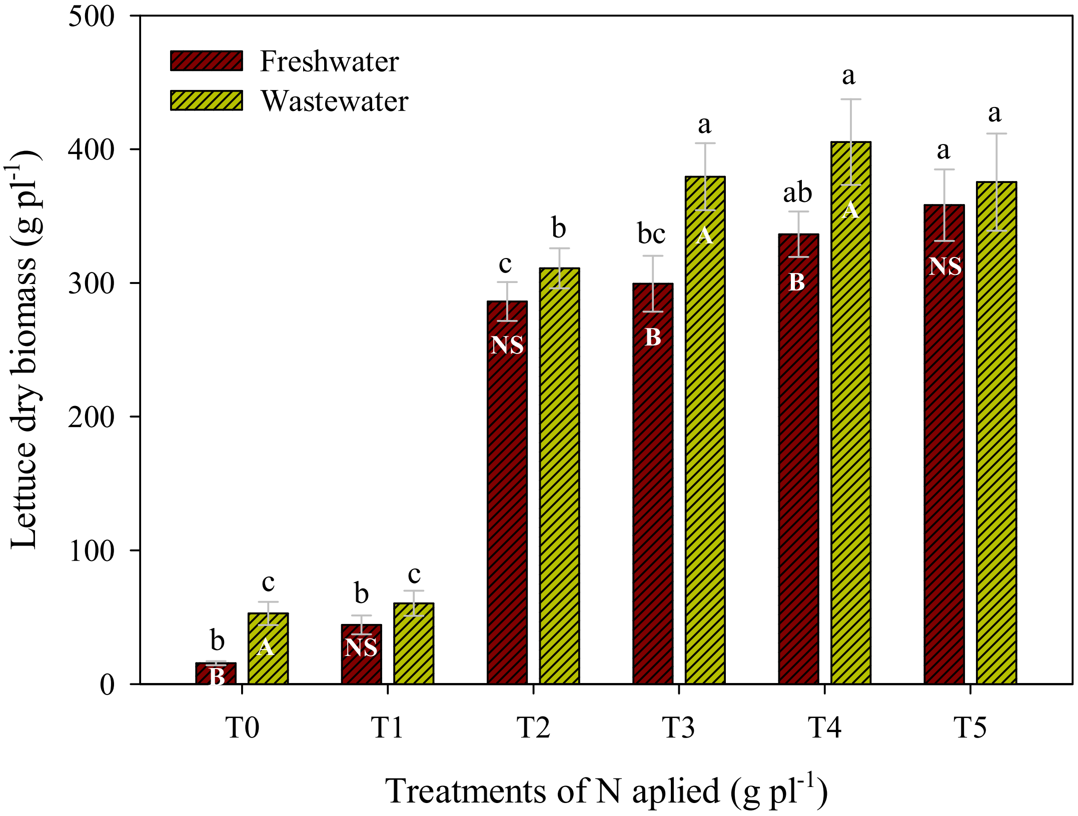

Figure 6. Average lettuce biomass productivity over six cultivation cycles with application of organic compost and urea doses as nitrogen sources, irrigated with freshwater and wastewater Lowercase letters indicate comparisons among nitrogen dose treatments, while uppercase letters indicate comparisons between freshwater and wastewater irrigation

In the comparison of treatments under both freshwater and wastewater irrigation, treatments T3, T4, T5, and T6 significantly increased the average fresh biomass productivity of lettuce compared to the unfertilized control and the urea-fertilized treatment (T1 and T2; Fig. 6). When comparing irrigation types, significant differences were observed between freshwater and wastewater in T1, T2, T3, and T4 (Fig. 6).

Wastewater irrigation increased lettuce productivity even in the absence of mineral N and at intermediate compost doses, indicating a synergistic effect between nutrient-rich irrigation and organic inputs (Fig. 6). The combined use of wastewater and organic compost, particularly at higher doses, can reduce dependence on synthetic fertilizers while improving soil fertility, nutrient availability, and crop productivity in a more sustainable manner. The combined use of biogenic materials (biochar) and treated wastewater irrigation improved soil quality and lettuce crop performance (Regkouzas et al., 2025). Additionally, the application of organic compost tea increased commercial lettuce yields by 24%, likely due to beneficial effects on plant physiological and nutritional status, as evidenced by higher leaf chlorophyll content measured throughout the cultivation cycles (Pane et al., 2014).

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The observed improvements in soil fertility and lettuce yield under wastewater irrigation and organic compost application indicate that these practices can enhance nutrient availability and reduce the dependence on synthetic fertilizers. However, long-term use of nutrient-rich wastewater may also alter soil chemical balance and increase the risk of heavy metal accumulation or pathogen persistence, as reported in previous studies (Mañas et al., 2009). Therefore, controlled irrigation, regular monitoring of soil and water quality, and balanced integration of organic and mineral fertilizers are essential for maintaining soil health and sustainable productivity.

4. Conclusion

Compost application, particularly 1.08 g of N per plant, significantly improved soil chemical properties, including increased soil pH, base sum, cation exchange capacity, and availability of macro- and micronutrients (Mg, S, B, Cu, Mn, Zn), under both freshwater and wastewater irrigation. In contrast, urea-based treatments led to higher levels of Al^{3+}, $H^+ + Al$, and Fe, indicating potential adverse effects on soil quality. Compost application also enhanced soil organic matter, which was positively correlated with key nutrient availability (Ca, Mg, K, B, Cu, Zn), with strong determination coefficients ($r^2 > 0.75$). In lettuce cultivation, compost treatments (T3–T6) consistently increased green biomass yield compared to unfertilized and urea-only treatments, regardless of the type of irrigation water. These findings highlight the agronomic and environmental benefits of organic compost as a sustainable alternative to urea, enhancing both crop productivity and soil quality. This underscores the importance of integrated nutrient management strategies that incorporate organic sources, particularly under wastewater irrigation systems.

Author Contribution

TFL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - review & editing. HGF: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization. JAB: Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

Data is available on request.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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