Field application of rice straw–sewage sludge compost in Mediterranean citrus orchards: effects on soil properties, nutrient status and fruit quality

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Abstract

Intensive agricultural practices have degraded soil fertility and polluted natural resources in Spanish citrus orchards, highlighting the need for more sustainable management strategies. Composting rice straw (RS) and sewage sludge (SS)—two residues that are difficult to manage in Mediterranean regions—offers an environmentally sound alternative for residue valorisation and soil fertility restoration. This study assessed the agronomic performance of compost produced from RS and SS (RS/SS) at an industrial scale, in comparison with compost derived from pruning residues and sewage sludge (PR/SS), which is commonly produced in Mediterranean composting facilities. The effects of compost application at two rates over two consecutive years were evaluated through analyses of soil physical, chemical, and biological properties, as well as foliar nutrient concentrations, yield, and fruit quality. RS/SS compost contained higher nutrient levels, particularly P, suggesting its potential as a P-rich organic fertiliser. Compost application reduced soil pH and slightly increased electrical conductivity without exceeding critical thresholds. Active lime decreased, while organic matter, N, P, K, and Zn contents increased, accompanied by improvements in soil biological indicators. Effects on foliar nutrient status, yield, and fruit quality were limited. These results indicate that industrial-scale RS/SS compost application represents a sustainable strategy for residue valorisation and soil fertility improvement in Mediterranean citrus systems, enhancing soil properties and reducing dependence on mineral fertilisers.

Keywords: industrial composting; soil fertility; nutrient availability; fruit yield; sustainable nutrient management

1. Introduction

In recent years, efforts toward a more sustainable and environmentally responsible development model that integrates economic growth with environmental protection and social well-being have intensified. At the international level, the United Nations adopted 2030 Agenda for Sustainable Development, which provides a global roadmap for achieving the Sustainable Development Goals. In Europe, the Green Deal [European Commission (EC), 2019] aims to achieve climate neutrality and reduce pollution of water, air, and soil. This framework includes key strategies such as the Biodiversity Strategy (EC, 2020a), the Farm to Fork Strategy (EC, 2020b), the Soil Protection Strategy (EC, 2021a), and the Circular Economy Action Plan (EC, 2020c), which share common objectives related to resource efficiency, sustainable agricultural production, and reduced dependency on chemical input, while also addressing specific targets in each case. Moreover, the new Common Agricultural Policy (CAP) (EC, 2021b) integrates these principles by supporting farming practices that contribute to climate change mitigation, soil quality improvement and biodiversity conservation.

In Spain, Real Decreto (RD) 1051/2022 regulates sustainable soil nutrient management, emphasizing the need to maintain or increase organic matter (OM) to ensure soil health and productivity, through the regular application of organic inputs such as manure, compost, vermicompost, or crop residues, as well as the establishment and maintenance of plant cover—either living (spontaneous or sown) or inert, such as plant residues. Moreover, the sustainable use of mineral and next-generation fertilisers is promoted, contributing to more efficient and environmentally friendly nutrient management.

In light of this legislative framework, it is vital to implement sustainable practices that consider the valorisation of waste materials. One of the most significant residues generated in the Valencia region is rice straw (RS). Spain is one of the main rice-producing countries in Europe, with a cultivated rice area of 56,000 ha and an annual production of around 355,000 t. Around 30% of this production is concentrated in the province of Valencia [Ministerio de Agricultura, Pesca y Alimentación (MAPA), 2023], mainly within the Albufera Natural Park (ANP). Rice cultivation generates large quantities of straw after harvest, estimated at 75,000 -90,000 t per year (Ribó et al., 2017). Traditionally, this residue has been managed by open-field burning; however, the environmental impact of this practice has led to increasing restrictions, making it necessary to identify sustainable alternatives for its management and valorisation.

Composting represents an efficient option for RS valorisation, particularly when combined with other organic residues with complementary properties, such as sewage sludge (SS) from wastewater treatment plants. In Spain, 1.2 million t of sludge are produced annually (MITECO, 2024). These residues are rich in OM and nutrients but may also contain high levels of heavy metals, pathogens, and organic pollutants (MITECO, 2024). Composting allows the stabilisation of these residues, transforming them into agronomically valuable products suitable for agricultural use while reducing their potential environmental risks. (López Bravo et al., 2017).

The application of compost to agricultural soils enhances their physical, chemical, and biological properties. It improves soil structure, porosity, and water retention while reducing bulk density and penetration resistance (Aggelides and Londra, 2000). Compost provides macronutrients as nitrogen (N), phosphorus (P), and potassium (K), and micronutrients to soil and plant shoots (Roghanian et al., 2012); increases total organic carbon (TOC) and total N (Bouajila and Sanaa, 2011); and can stabilize or improves soil pH and cation exchange capacity (Adugna, 2016). In mature olive trees, it improves soil OM, N, available P, exchangeable K, and foliar nutrient concentrations (Magdich and Rouina, 2022). Additionally, compost stimulates soil microbial biomass, activity, and the diversity of soil microbial communities (Brown and Cotton 2011; García-Gil et al. 2000; Pérez-Piqueres et al., 2006).

Considering the global importance of citrus cultivation— Spain being one of the leading producers and the Valencian Community the largest producer in the Mediterranean region—it is essential to adopt sustainable strategies. Intensive farming practices have negatively impacted soil fertility and polluted natural resources, which makes the adoption of such strategies even more urgent. Among them, compost application stands out as a promising approach; however, studies assessing its effectiveness in woody crops such as citrus are still limited. Although the complementary characteristics of SS and RS make them a suitable mixture for composting (Iranzo et al., 2004), this combination has rarely been studied. Previous works have evaluated this composting process at pilot and medium scales (Ferrer et al., 2002; Roca-Pérez et al., 2009); however, research at the industrial scale remains limited (Rodríguez-Carretero et al., 2023). Beyond large-scale assessment, it is also necessary to evaluate the agronomic performance of this compost and compare it with conventional composts produced from SS and other bulking agents.

On the other hand, citrus cultivation in Spain has undergone significant modernization in recent years, particularly regarding the implementation of advanced irrigation systems such as localized irrigation. However, according to data from the MAPA, in 2024, 13% of the irrigated area in citrus orchards still relies on flood irrigation, especially in regions where traditional infrastructures remain in place. Similarly, in areas such as the Valencian Community, although localized irrigation has gained traction, flood irrigation continues to be used. Therefore, given the limited information available, evaluating sustainable

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fertilisation strategies—including organic amendments—in this type of irrigation system, is particularly relevant.

Based on the former considerations, this study was based on the hypothesis that the innovative RS–SS compost would (1) enhance soil nutrient availability and improve soil health indicators more effectively than conventional compost, (2) positively influence plant nutritional status and fruit quality, (3) provide comparable or superior crop yields relative to mineral fertilisation, and (4) contribute to the valorisation of RS, on Mediterranean citrus orchards. The objectives were to (i) evaluate the agronomic performance of an industrial-scale RS and SS compost in comparison with a conventional pruning residues (PR) and SS compost, and (ii) assess the effects of these compost on soil physicochemical properties, plant nutritional status, fruit yield, and quality, in a commercial citrus orchard under flood irrigation over two growing seasons.

2. Materials and methods

2.1. Characterisation of the composts

Experiments were conducted using two composts from "La Vintena" commercial composting facility, located in Carcaixent (39º6´32.207" N; 0º29´6.87" W), Valencia, Spain: compost 1 (COMP1) from PR and SS (ratio 1:3, w:w fresh weight), typically produced at this facility; and compost 2 (COMP2) from RS originated from commercial rice orchards in the ANP and SS (ratio 1:8, w:w fresh weight) obtained following the methodology described by Rodríguez-Carretero et al. (2023), without modifying the usual protocol followed in the facility.

Four representative samples of each compost were collected to determine their physical and chemical properties. Each sample was homogenised and divided into two subsamples. One subsample was refrigerated at 4 °C for organic, ammonium, and nitrate N determinations. The other subsample was oven-dried at 60 °C, ground using a cutting mill (SM 100, Retsch, Germany), sieved through a 0.25 mm mesh, and stored for subsequent analyses. Parameters determined were: moisture (drying at 105 °C to constant weight), pH (1:25 water extract), electrical conductivity [(EC), 1:5 water extract], total OM (TOM) and TOC (ashing at 560 °C), oxidisable organic C [(OOC), oxidisation with $K_2Cr_2O_7$], humic substances [(HS), extraction with 0.1 N $Na_2P_2O_7$ + NaOH], humic acids [(HA), precipitation of humic substances extract at pH 2], organic N (Kjeldahl method), NH_4^+-N and NO_3^--N (2 N KCl extract), macronutrients

(HCl digestion), micronutrients, and heavy metals (aqua regia digestion) following the Official Methods of the Spanish MAPA [MAPA 1994] with minor modifications.

pH was measured with a pH meter (Basic 20, Crison, Spain), EC with a conductometer (Sensor+ EC7, Hach, Spain), organic and mineral N using a 8200 Kjeltec digestor (Foss, Tecator AB, Sweden), and the total concentrations of P, K, Ca, Mg, sodium (Na), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), nickel (Ni), lead (Pb), cadmium (Cd), mercury (Hg), and Cr were measured in simultaneous inductively coupled plasma atomic emission spectrometry (iCAP-AES 6000, Thermo Scientific, UK). The C/N ratio was calculated from the TOC [TOM (%)/1.724] and total N (TN, organic-N + NH_4^+-N + NO_3^--N).

2.2. Field experiments

2.2.1. Experimental development of the field trials

Field trials were carried out over two consecutive seasons, S1 and S2 (S1: season 1 and S2: season 2) in a commercial orchard of adult “Tango” mandarins (Citrus reticulata Blanco), grafted onto a hybrid rootstock (Citrus sinensis × Poncirus trifoliata), located in Manuel (39°3'29.1" N; 0°29'17.4" W), Valencia, Spain. Trees were planted at 5 × 4 meters in clay loam soil (27.9% sand, 34.9% clay, 37.2% silt) and irrigated via surface flooding. Treatments were control (no compost application), single compost application (10 t ha^{-1}), and double compost application (20 t ha^{-1}), with doses based on Orden 10/2018. All treatments were replicated three times in a randomized block design, with eight trees per plot, separated by buffer rows to prevent cross-interference. COMP1 and COMP2 were applied in S1 and S2, respectively, in June. Compost was surface applied in the tree canopy projection zone using a trailer spreader attached to a tractor. Regardless of the organic experimental treatments, in S1, a mineral fertilisation plan was designed to meet crop requirements (205 kg N ha^{-1}; 54 kg P_2O_5 ha^{-1}; 156 kg K_2O ha^{-1}; 0.8 kg Fe ha^{-1}; 11 kg of organic products ha^{-1}). In S2, based on the results obtained from soil and foliar analyses, P fertiliser inputs were reduced by 10% as a step toward aligning with the European objective of reducing mineral fertiliser nutrient use by 20%. The irrigation water used in the field trials had the following composition: pH 8.14; electrical conductivity 1.08 dS m^{-1} (25 °C); chloride 99.0 mg L^{-1}; sulfate 299 mg L^{-1}; bicarbonate 206 mg L^{-1}; carbonate <10.0 mg L^{-1}; nitrate <10.0 mg L^{-1}; calcium 113 mg L^{-1}; magnesium 38.4 mg L^{-1}; potassium 3.06 mg L^{-1}; and sodium 59.2 mg L^{-1}.

2.2.2. Soil and plant sampling during the crop cycle

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In each season, soil, foliar and fruit sampling was performed to evaluate the effect of the different treatments. Soil sampling was carried out in March, by taking two subsamples per tree; with a cylindrical auger at a depth of 0–20 cm. Foliar samples were collected during the dormant period in December, by taking twelve leaves per tree from the spring flush, without terminal fruit, across all four cardinal orientations. Additionally, at harvest, in February, yield was recorded and six fruits per tree were collected from each replicate for fruit quality assessment.

2.2.3. Sample Processing

Soil samples were homogenised and subdivided into three fractions. One fraction was used for moisture content determination. A second was sealed in a plastic bag and stored at 4 °C for microbial biomass C and dehydrogenase activity analyses. The remaining fraction was air-dried for subsequent physicochemical analyses. Dried samples were ground using a ball mill (OABM 255, Orto Alresa, Spain) and passed through a 2 mm sieve. Foliar samples were washed with deionised water and a non-ionic detergent, dried in a forced-air oven (JP Selecta) at 65 °C until constant weight, and ground using a water-refrigerated mill (M 20, IKA, Germany) to a particle size of <0.3 mm.

2.2.4. Analytical Determinations

Soil analyses included texture (Bouyoucos hydrometer), moisture content (drying at 105 °C to constant weight), pH (1:2.5 water extract), total carbonates and active lime (Bernard calcimeter), oxidisable OM (OOM) and OOC (oxidisation with $K_2Cr_2O_7$), organic N (Kjeldahl method), C/N ratio, available P (Olsen P, sodium bicarbonate extraction), available cations (ammonium acetate extraction), micronutrients and heavy metals (aqua regia digestion), and EC (in saturation extract), following the Official Methods of the Spanish Ministry of Agriculture, Food and Fisheries [MAPA 1994] with minor modifications. Microbial biomass C and dehydrogenase activity were determined according to Vance et al. (1987) and Casida et al. (1964), respectively. The C/N ratio was calculated from the OOC (%) [OOM (%)/1.724] and organic N (%). Concentrations of available cations and metals were determined by flame atomic absorption spectrophotometry (FAAS, AAnalyst 200, Perkin Elmer, USA), while micronutrients and heavy metals were measured by ICP-OES (Thermo Scientific). Microbial biomass C content was determined using a TOC Analyser (TOC-VCSN, Shimadzu, Japan); and Olsen P was measured with a UV-VIS spectrophotometer (UV-1800, Shimadzu, Japan).

In the foliar material, total N (Kjeldahl method); micronutrients and macronutrients were determined following the methodology described by Morales et al. (2022); with analysis by ICP-OES (Thermo

Scientific). In the fruits, physical and chemical parameters were measured. Physical parameters included fruit weight, number of fruits per tree, diameter, colour index (CI), peel thickness, and weight of peel plus pulp and juice. Chemical properties included total soluble solids (TSS), titratable acidity (TA, titration with 0.1 N NaOH solution), and maturity index (MI, calculated as TSS/TA), according to the methodology described by González-Sicilia (1968) with slight modifications. Juice was extracted using an electric juice extractor (Model 4, Lomi®, Spain) and filtered. Fruit diameter and peel thickness were measured using a digital calliper (CD-15D, Mitutoyo, Japan). CI was determined with a colourimeter (CR-300, Konica Minolta, Japan), and TSS in juice was measured with a digital refractometer (PR-32, Atago, Japan). CI was determined as per Jiménez-Cuesta et al. (1981).

2.2.5. Statistical analyses

Data were subjected to an ANOVA to test the effect of treatments on analysed parameters. Before carrying out any statistical analysis, the normality of all the data was studied using the Kolmogorov–Smirnov test. If the hypothesis of normality was discarded at the 95% confidence level, data were transformed according to the logarithmic function. The variance of the transformed or non-transformed data was partitioned with a variance analysis (ANOVA, Statgraphics Centurion for Windows, Statistical Graphics Corp., The Plains, VA, USA) into one source of variability. The significance of the comparisons made between treatments was analysed with Fisher's least significance difference (LSD) test at $p < 0.05$.

3. Results

3.1. Characterisation of composts

The main physicochemical and chemical properties of COMP1 and COMP2 are presented in Table 1. COMP1 had lower moisture content than COMP2, but both complied with the legal limit of 40% (RD 999/2017). pH values also differed, being 7.16 in COMP1 and 6.71 in COMP2. On the other hand, regardless of the structural material used, the composts did not differ in EC, with high values in both cases. TOM exceeded the minimum required threshold established by legislation (35%; RD 999/2017) in both composts. No significant differences were observed in TOM, and therefore in TOC, despite the use of different bulking agents and varying sludge proportions. However, the OOC content was significantly higher in COMP1, as were the concentrations of HS, HA, and FA.

On the other hand, COMP2 presented a significantly higher total N concentration, mainly due to the greater amount of organic N, since mineral N, N-NH_4^+, and N-NO_3^-, showed very similar values in both composts. The C/N ratio differed significantly between composts ($p < 0.001$), with lower values in COMP2 (10.3) compared to COMP1 (13.8), due to the higher total N concentration in COMP2. Both composts met the legal requirement established for use as fertilising products (C/N ratio < 20; RD 999/2017). Regarding macronutrient content, significant differences were observed between COMP1 and COMP2, with higher concentrations of P_2O_5, K_2O, and MgO in COMP2, and lower contents of CaO and Na_2O. Similarly, micronutrient and heavy metal concentrations were generally higher in COMP2 than in COMP1, with the exception of Cu. According to RD 506/2013, COMP1 could be classified as a Class B fertilising product, but COMP2 slightly exceeded the maximum permitted Zn concentration (500 mg kg^{-1}) for inclusion in this category. However, this compost complies with the limits established by the more recent Spanish legislation (RD 1051/2022).

Table 1. Composition of the obtained composts

Parameter[1]	COMP1[2]	COMP2[2]	SA[3]	Parameter[1]	COMP1[2]	COMP2[2]	SA[3]
Moisture (%)	23.5	35.5	***	P_2O_5 (%)	2.03	4.41	***
pH (1:25)	7.16	6.71	**	K_2O (%)	0.743	1.40	***
EC (1:5) (dS m^{-1})	14.5	14.6	ns	CaO (%)	11.5	8.36	***
TOM (%)	53.0	51.6	ns	MgO (%)	0.910	1.14	*
TOC (%)	30.7	30.0	ns	Na_2O (%)	0.990	0.563	***
OOC (%)	29.9	20.9	***	Fe (mg kg^{-1})	15,163	34,122	***
HS (%)	18.1	9.93	***	Cu (mg kg^{-1})	168	105	***
HA (%)	8.53	2.93	**	Mn (mg kg^{-1})	98.5	177	***
FA (%)	9.55	7.02	*	Zn (mg kg^{-1})	241	588	***
Organic N (%)	1.98	2.64	***	Ni (mg kg^{-1})	32.4	40.6	***
$N\text{-}NH_4^+$ (mg kg^{-1})	2,112	2,389	ns	Pb (mg kg^{-1})	18.1	50.9	***
$N\text{-}NO_3^-$ (mg kg^{-1})	507	455	ns	Cd (mg kg^{-1})	0.589	1.84	***
Total N (%)	2.24	2.93	***	Cr (mg kg^{-1})	37.5	54.0	***

*[1]EC: electrical conductivity at 25 °C; TOM: total organic matter; TOC: total organic carbon; OOC: oxidisable organic carbon; HS: humic substances; HA: humic acids; FA: fulvic acids. All data are expressed on a dry weight basis. [2]COMP1: compost 1 (PR); COMP2: compost 2 (RS). [3]SA: statistical analysis of the effect of the bulking agent in the compost on the analysed parameters. ns: not significant; * significant at $p < 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.001$ (Fisher´s LSD).*

3.2. Effect of compost application on citrus nutrition

3.2.1. Soil fertility

Compost application did not result in significant differences in soil moisture content in either season, regardless of the dose applied, when compared to the control soil (Table 2). The high soil pH, typical of agricultural soils in the citrus-growing regions of eastern Spain, was significantly reduced in the second

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year following the application of the double dose of COMP2 (Table 2). Regarding salinity, estimated through soil EC, significantly higher values were recorded with the double compost application in both seasons, with increases of 21% and 105% in S1 and S2, respectively, compared to the control soil (Table 2).

Table 2. Moisture, pH, electrical conductivity, and concentration of total carbonates and active lime in the soil from both seasons

Season	Treatment[1]	Moisture (%)	pH (1:2.5)	EC[2] (dS m^{-1})	Total carbonates (%)	Active lime (%)
1	Control	16.9a[3]	8.63a	0.685a	33.4a	9.15a
	COMP1	17.1a	8.56a	0.784ab	36.3a	9.10a
	COMP1 (2x)	17.6a	8.53a	0.832b	37.6a	8.93a
	SA[4]	ns	ns	*	ns	ns
2	Control	14.9a	8.78b	0.652a	28.3a	10.0b
	COMP2	15.9a	8.60ab	0.976ab	28.2a	10.2b
	COMP2 (2x)	16.7a	8.46a	1.340b	30.3b	9.23a
	SA	ns	*	*	*	**

*[1]COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). [2]EC: electrical conductivity at 25 °C. [3]Different letters within a column indicate significant differences between treatments in each season according to the Fisher´s LSD test ($p < 0.05$). [4]SA: statistical analysis; ns: not significant for $p > 0.05$; * significant at $p < 0.05$ (Fisher's LSD test).*

The total carbonate concentration in the soil exceeded 21% (Table 2), a percentage considered high for citrus orchards according to Legaz et al. (1995). At such levels, it is also important to assess active lime content, as both parameters can affect tree development (Garrido, 1993). In S1, compost application did not lead to significant differences in either total carbonates or active lime (Table 2). In contrast, in S2, a significantly higher concentration of total carbonates and a significantly lower concentration of active lime were observed with the double compost dose compared to the remaining treatments (Control and COMP1).

The soil presented optimal OM values for citrus cultivation in both seasons (Legaz et al., 1995) (Figure 1). Compost application resulted in a significant increase in OM in S1 with both doses, and only with the double dose in S2, even though COMP1 and COMP2 did not show significant differences in their OM content. It is worth noting that OM concentration decreased between the two seasons across all treatments.

Regarding organic N concentration, in S1 the control soil showed slightly low values; however, compost application increased this parameter to levels within the normal range (0.13–0.18%) (Legaz et al., 1995). In S2, both the control and treated soils were within the normal range. As observed for OM, compost application led to a significant increase in S1 at both doses, and in S2 only with the double dose (Figure 1). The C/N ratio values obtained in all treatments, in both seasons, were within the normal range (Legaz

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et al., 1995; MAPA, 2010), and no significant differences were observed between treatments in either season.

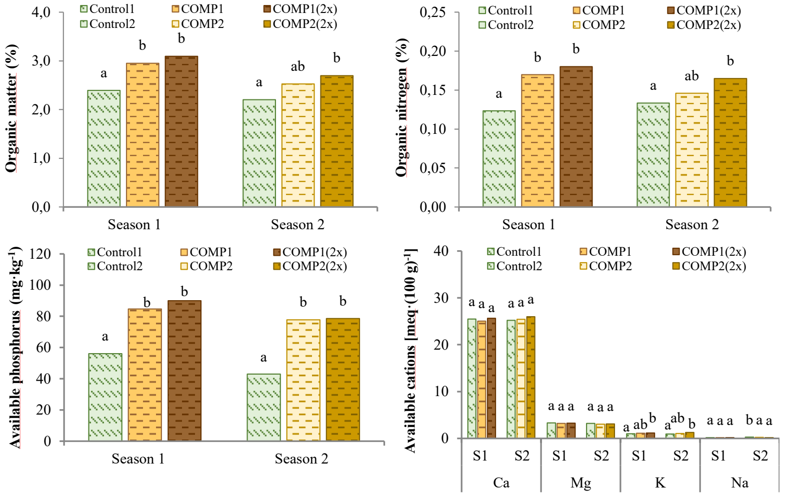

Figure 1. Concentration of organic matter, organic nitrogen, available phosphorus and cations of the soil from both seasons. COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). Different letters indicate significant differences between treatments in each season according to the Fisher's LSD test ($p < 0.05$).

The level of available P in the control soil was high in S1 and normal in S2; however, compost application increased these values to very high levels in S1 and high levels in S2 (Legaz et al., 1995). In both seasons, this application resulted in a significantly higher concentration of available P, regardless of the dose (Figure 1).

Among the assimilable cations (Figure 1), Ca concentration was very high across all treatments and both seasons, whereas Mg levels were within normal ranges throughout. The control soil and the soil receiving the single compost dose exhibited normal levels of available K; however, this level was high with the double compost dose in both seasons, according to Legaz et al. (1995). With respect to the effect of compost application on the concentration of assimilable cations, significant differences between treatments were only observed in K and Na concentrations (Figure 1). Compost application increased K concentration in both seasons, although the increase was only significant with the double dose, which led to an increase of 17% and 29% in S1 and S2, respectively, compared to the control soil. Regarding Na, in S2, soils with compost application at both doses presented a significantly lower concentration that the non-amended soil.

The total concentrations of heavy metals in the soil (Cu, Zn, Ni, Pb, Cd, and Cr) remained within the permissible limits established by RD 1310/1990 and RD 1051/2022 across all treatments (Table 3). The application of compost at double rates significantly increased soil Zn concentrations in both seasons, by 18.1% and 16.6%, respectively.

Table 3. Concentration of total heavy metal in the soil from both seasons

Season	Treatment[1]	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})
1	Control	9,486a[2]	18.1a	107a	42.3a	12.6	20.4a	1.00a	18.1a
	COMP1	9,527a	21.1a	108a	45.7ab	12.9	21.0a	1.03a	17.5a
	COMP1 (2x)	9,306a	20.8a	107a	50.1b	12.9	20.8a	1.02a	17.6a
	SA[3]	ns	ns	ns	*	ns	ns	ns	ns
2	Control	10,230a	20.9a	167a	45.5a	11.3a	21.3a	1.03a	18.4a
	COMP2	10,403a	21.2a	168a	47.8ab	11.3a	23.1a	1.10a	18.3a
	COMP2 (2x)	10,229a	22.5a	167a	52.6b	11.2a	23.5a	1.12a	18.2a
	SA	ns	ns	ns	**	ns	ns	ns	ns

*[1]COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). [2]Different letters within a column indicate significant differences between treatments in each season according to the Fisher's LSD test ($p < 0.05$). [3]SA: statistical analysis; ns: not significant for $p > 0.05$; * significant at $p < 0.05$; ** $p < 0.01$ (Fisher's LSD test).*

Finally, microbial biomass C and dehydrogenase activity increased significantly with compost application in S1 but not in S2 (Figure 2). In S1, microbial C showed a significant increase of 65% with the double dose compared to the control soil, while dehydrogenase activity increased under both application rates.

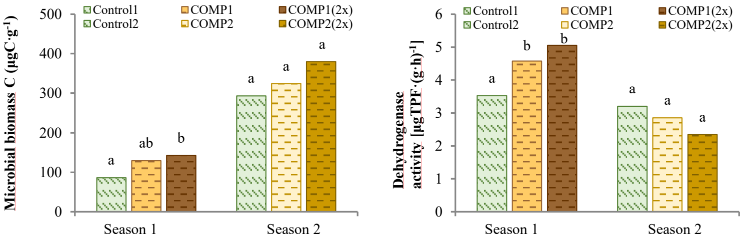

Figure 2. Soil biomass carbon and dehydrogenase activity from both seasons. COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). Different letters indicate significant differences between treatments in each season according to the Fisher's LSD test ($p < 0.05$).

3.2.2. Plant nutrient uptake

Foliar macronutrient concentrations in trees from all treatments were within optimal ranges (Quiñones et al., 2012), except for K in the leaves of control trees and those treated with COMP2 in S2 (Table 5). Regarding micronutrients, foliar concentrations of Fe, B and Mo were within optimal levels for citrus. Foliar Cu levels were optimal in S1 but high in S2, whereas Mn showed the opposite trend, with low concentrations in S1 and optimal levels in S2. Zinc concentrations remained below optimal levels in all treatments and seasons. ompost application significantly increased foliar Zn only in S1 (Table 5).

Table 5. Foliar concentration of macronutrients and micronutrients from both growing seasons.

Season	Treatment[1]	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	S (%)
1	Control	2.50a[2] (O)[3]	0.123a (O)	0.690a (O)	4.64a (O)	0.297a (O)	0.0212a	0.211a (O)
	COMP1	2.40a (O)	0.116a (O)	0.942a (O)	4.66a (O)	0.298a (O)	0.0356a	0.209a (O)
	COMP1 (2x)	2.44a (O)	0.116a (O)	0.724a (O)	4.86a (O)	0.302a (O)	0.0320a	0.200a (O)
	SA[4]	ns	ns	ns	ns	ns	ns	ns
2	Control	2.40a (O)	0.119a (O)	0.653a (L)	5.15a (O)	0.353a (O)	0.0329a	0.220a (O)
	COMP2	2.47a (O)	0.126a (O)	0.681a (L)	4.94a (O)	0.352a (O)	0.0265a	0.226a (O)
	COMP2 (2x)	2.56a (O)	0.129a (O)	0.842a (O)	4.66a (O)	0.345a (O)	0.0325a	0.228a (O)
	SA	ns	ns	ns	ns	ns	ns	ns

Season	Treatment	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	B (mg kg^{-1})	Cu (mg kg^{-1})	Mo (mg kg^{-1})
1	Control	60.3a (O)	16.4a (L)	15.5a (L)	46.5a (O)	5.69a (O)	0.110a (O)
	COMP1	75.9a (O)	24.3b (L)	17.5a (L)	52.7a (O)	6.83a (O)	0.0704a (O)
	COMP1 (2x)	63.3a (O)	24.2b (L)	16.1a (L)	51.1a (O)	7.26a (O)	0.100a (O)
	SA	ns	*	ns	ns	ns	ns
2	Control	85.5a (O)	20.8a (L)	32.2a (O)	78.2a (O)	17.7a (H)	0.0888a (O)
	COMP2	75.3a (O)	18.9a (L)	31.6a (O)	71.7a (O)	21.3a (H)	0.0953a (O)
	COMP2 (2x)	86.6a (O)	22.0a (L)	35.6a (O)	73.5a (O)	18.4a (H)	0.0898a (O)
	SA	ns	ns	ns	ns	ns	ns

*[1]COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). [2]Different letters within a column indicate significant differences between treatments in each season according to the Fisher's LSD test ($p < 0.05$). [3]In parentheses: nutritional diagnosis- low (L); optimal (O). [4]SA: statistical analysis; ns: not significant ($p > 0.05$ Fisher's LSD test); * significant at $p < 0.05$ (Fisher's LSD test).*

3.2.3. Fruit yield and quality

Citrus yield and physical and chemical quality parameters of fruit are presented in Table 6.

Table 6. Citrus yield, physical and chemical quality parameters of fruit at harvest from both growing seasons

Season	Treatment[1]	Yield (kg tree^{-1})	Fruit weight (g)	Nº fruits tree^{-1}	Fruit diameter (cm)	Colour index	Peel thickness (mm)
1	Control	54.2a[2]	84.1a	668a	5.93a	20.0a	2.93a
	COMP1	47.8a	90.4a	534a	5.97a	19.3a	2.93a
	COMP1 (2x)	57.4a	83.8a	699a	5.75a	18.3a	2.99a
	SA[3]	ns	ns	ns	ns	ns	ns
2	Control	55.2a	92.7ab	617a	6.13ab	8.77a	2.69a
	COMP2	55.3a	106b	521a	6.48b	9.01a	3.00a
	COMP2 (2x)	39.8a	83.0a	477a	5.82a	8.12a	2.63a
	SA	ns	ns	ns	ns	ns	ns

Season	Treatment	Peel+pulp weight (%)	Juice weight (%)	Soluble solids (^{0}Brix)	Acidity (g L^{-1})	Maturity index
1	Control	42.0a	58.0a	14.2a	1.12a	12.8a
	COMP1	45.8a	54.2a	14.1a	1.14a	12.4a
	COMP1 (2x)	46.4a	53.6a	12.9a	1.01a	12.7a
	SA	ns	ns	ns	ns	ns
2	Control	51.0a	49.0a	14.3a	1.49a	9.80a
	COMP2	51.0a	49.0a	13.5a	1.32a	10.2a
	COMP2 (2x)	49.1a	50.9a	13.8a	1.48a	9.39a
	SA	ns	ns	ns	ns	ns

[1]COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). [2]Different letters within a column indicate significant differences between treatments in each season according to the Fisher´s LSD test ($p < 0.05$). [3]SA: statistical analysis; ns: not significant ($p > 0.05$, Fisher's LSD test).

Across both growing seasons and all treatments, mandarin fruit weight, TSS and juice acidity were within the ranges established for the cultivar (USPP17863). Furthermore, in both seasons, the fruits met the size

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and maturity requirements according to the EU Citrus Quality Standards for the marketing of mandarins and their hybrids (Regulation EU No. 1890/2021), as fruit diameter exceeded 45 mm, minimum juice content surpassed 33%, and the MI of the fruits exceeded the minimum value of 7.5.

No significant differences were observed in yield or in the physical and chemical quality parameters between the control trees and those receiving compost in either growing season. Although some differences in fruit weight and diameter were observed in S2 depending on compost dose, these variations were not agronomically relevant.

4. Discussion

Compost derived from the large-scale composting of SS and RS exhibits considerable agronomic potential due to the complementary properties of both materials. According to our results, the RS-SS compost is an interesting source of nutrients, displaying characteristics comparable to, and in some aspects even superior to, the compost derived from PR and SS traditionally produced at industrial Mediterranean facilities. COMP2 exhibited a slightly acidic pH (6.71), lower than the optimal range reported for SS–plant residue composts (7.1 and 7.5) (Azim et al., 2018). This lower pH may be advantageous in alkaline Mediterranean soils, as it can enhance nutrient solubility and availability. Both composts showed high EC values, which should be considered when establishing field application rates. Nevertheless, compost-induced improvements in soil structure may enhance water infiltration and permeability, facilitating salt leaching in the long term (Aggelides and Londra, 2000; Tejada et al., 2006).

COMP1 and COMP2 did not differ in TOC content, but the C/N ratio was lower in COMP2 due to its higher total N value. Indeed, the larger proportion of SS relative to the bulking agent used in this compost resulted in an N content exceeding that of most manures (Dadrasnia et al., 2021; Rayne et al., 2020), highlighting its promising potential as a N fertiliser. P concentration was also particularly noteworthy, with a fertiliser unit (FU) value of P_2O_5 more than twice that of COMP1, surpassing the averages reported for sheep, cattle, or swine manure (Pomares, 2000). Despite the higher micronutrient and metal contents associated with SS, COMP2 was generally richer in micronutrients than COMP1 and complied with the limits established by Spanish legislation (RD 1051/2022).

Compost application improved soil fertility, increasing nutrient availability and several soil health indicators Soil moisture parameter is not directly related to fertility, but it can be influenced by the application of organic amendments, as they may improve soil structure, reduce salinity problems, increase crop yields, and decrease input use (Abd El-Mageed et al., 2016; Chalker-Scott, 2007; Chandra et al., 2002; Rahman et al., 2006). In the study plot, organic treatments did not affect this parameter, regardless of the compost dose applied. This may be because two years of application are insufficient to induce noticeable changes in soil structure and bulk density, which are closely linked to soil porosity and water retention capacity (Bronick and Lal, 2005).

The cumulative effect of two consecutive years of OM application at double doses reduced soil pH, probably due to the production of NH_4^+, CO_2, and organic acids, during the mineralisation of OM by microbial communities (Magdich and Rouina, 2022). Roca-Pérez et al. (2009) reported a similar effect following the application of RS and SS compost to citrus trees grown in clay soil, likewise observing a more pronounced pH decline (8 to 7) with increasing compost rates (0 to 6% w/w). Furthermore, the slightly acidic pH of the RS-SS compost used in S2 could have also contributed to this decrease in soil pH.

As observed in soil moisture, EC did not improve with compost addition, supporting the idea that two years of application are insufficient to produce noticeable changes in soil structure, and consequently, to promote salt leaching. Since the first year, compost application enhanced soil salinity, with more pronounced increases observed at the higher compost application rate, regardless of the structuring material used (PR or RS). The increase in soil salinity following compost application in citrus orchards has been previously reported by other authors. Roca-Pérez et al. (2009) observed similar results after applying compost derived from SS and RS to a clay soil. This rise in EC could be associated with the soluble ions present in the organic materials and with ions released during the biodegradation of OM (Ribó et al., 2004). The EC values obtained did not exceed the limit of 4 dS m^{-1}, established to classify a soil as saline, nor did they surpass the threshold of 1.7 dS m^{-1}, above which citrus yield begins to decline (Juárez et al., 2006; Pomares, 1986). However, it would be advisable to consider reducing the annual application rates or applying them biennially. Proper irrigation management could also contribute to reducing EC values by facilitating salt leaching and the redistribution of cations between the soil solution and the exchange complex (Madejón et al., 2003). Moreover, the positive effect of OM application on soil structure and permeability is well documented (Lakhdar et al., 2009).

The total carbonate concentration was high, as is commonly observed in most soils of the Valencian Community. In S2, the carbonate levels increased under the double compost application. When carbonate concentrations are elevated, the assessment of active lime is essential, as values exceeding 10% can

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induce P deficiency and chlorosis in crops due to the impaired uptake of P and micronutrients (Fe, Mn, Zn and Cu), which remain in unavailable forms (Garrido, 1993; MAPA, 2010). In the evaluated plot, active lime values remained below this threshold. Interestingly, the double compost dose applied in S2 reduced active lime concentrations, thereby enhancing nutrient bioavailability. This reduction may be attributed to the dissolution of carbonates by organic acids, released during the decomposition of organic matter, a process that can promote carbonate solubilisation and improve nutrient availability (Ma et al., 2022).

The increase in soil OM through the application of organic products is one of the main benefits reported in the literature (Aguilar et al., 2012; Madejón et al., 2003; Martínez-Alcántara et al., 2016). In the present study, the concentration of OM, and consequently of OC, increased following compost application. However, the double compost dose did not produce a greater increase than the single dose, indicating that higher application rates do not necessarily promote a larger accumulation of stabilized OM in the soil. It is also worth noting that despite compost addition, annual OM losses due to mineralization were not fully compensated, as reflected by the decrease in OM content observed in the non-amended soil in S2. This suggests that the mineralization rate exceeded the OM input, which supports the appropriateness of the applied doses and the decision to carry out a second application. By contrast, Albiach (1997) reported a cumulative effect on soil OM after the consecutive application of different organic amendments (sheep manure, SS, and MSW compost) over two years in a 'Valencia Late' orange orchard.

The differences between treatments in terms of organic N were similar to those observed in OM concentration, with increases following compost application. Madejón et al. (2003) also reported an increase in soil N concentration after the application of both organic and mineral fertilisers over three years in a 'Valencia' orange orchard, using composted olive mill sludge at rates comparable to the double dose applied, as well as with higher doses of MSW compost, in comparison with soils fertilised solely with mineral inputs. Similarly, Roca-Pérez et al. (2009) observed increased soil N concentrations following the application of compost made from SS and RS in citrus orchards cultivated on clay soils in the Valencia region. Furthermore, the C/N ratios obtained across all treatments and in both seasons were mostly within the optimal range of 10 -12 considered adequate to ensure proper N release (MAPA, 2010).

Plant-available P concentrations increased with both compost doses compared to the control plots in both seasons. These increases align with previous findings on compost application in citrus crops (Madejón et

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al., 2003; Roca-Pérez et al., 2009). Despite the alkaline pH and high carbonate content of the evaluated soil, the organic amendment successfully enhanced P availability, reaching high to very high values. This outcome, together with the optimal foliar P levels observed in S1, was considered when calculating phosphorus fertilisation requirements in S2, leading to a 10% reduction in mineral P inputs, in accordance with current frameworks for sustainable soil nutrition (RD 1051/2022). Reducing mineral P inputs can prevent nutritional imbalances, as P may exert antagonistic effects on the uptake of certain micronutrients such as Cu and Zn, and, more importantly, reduce the risk of environmental pollution (Pomares and Albiach, 2008).

Just as P, plant-available K concentration increased with compost application in both seasons compared to the control soils, although in this case only under the double dose. These results align with previous studies that reported higher available K concentrations after compost addition to agricultural soils (Fernández-Hernández et al., 2014; Madejón et al., 2003; Magdich and Rouina, 2022). Because this effect was only observed under the double dose and given the optimal foliar K levels recorded in S1, no reductions in mineral K fertilisation were made. This decision proved correct, as foliar K concentrations were low in S2.

In contrast to the increases observed in soil-available K and P, the compost application resulted in a reduction in plant-available Na concentrations, which was statistically significant in S2. Although this effect could be attributed to an improvement in soil structure, and consequently, enhanced salt leaching, the EC results do not support this hypothesis.

The total concentrations of metals (Fe, Cu, Mn, Zn, Ni, Pb, and Cr) were mostly within the ranges reported by Pomares et al. (1998) in a study conducted on conventionally managed citrus soils in the Valencian Community. Soils that received the double compost exhibited significantly higher Zn concentrations than the other treatments. However, all metals concentrations remained below the maximum limits established by RD 1310/1990, in force during the experimental period, and the stricter thresholds defined by the current RD 1051/2022, indicating that compost application did not entail a risk of exceeding regulatory thresholds.

Microbial biomass C and dehydrogenase activity are biochemical indicators of the quantity and activity of living microorganisms present in the soil. Agricultural practices that increase microbial biomass and stimulate enzymatic activity promote a greater mineralisation of OM, improve soil quality, and enhance plant resistance against pests and diseases (Erhart and Hartl, 2010). In our study, compost addition led to

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higher microbial biomass C and dehydrogenase activity, compared to the control soil, in S1, but there were no significant differences in S2. An increase in soil OM is generally associated with enhanced microbial growth; however, it is not the total amount of OM that determines this response, but rather the fraction that is available to microorganisms. Thus, although compost application significantly increased SOM levels in both seasons, the composts differed in their content of OOM, which may explain the seasonal variation in microbial responses.

The literature shows variable results regarding the impact of organic product application on microbial quantity and activity. Madejón et al. (2003) observed an enhanced dehydrogenase activity after three years of applying olive mill wastewater sludge compost combined with mineral fertilisation in a 'Valencia' orange plot, compared to soil treated solely with mineral fertilisers, using 20 t $ha^{-1}y^{-1}$. However, other studies found no significant effects on microbial biomass C or dehydrogenase activity following the application of different organic products—sheep manure (12 t ha^{-1}), SS (12 and 24 t ha^{-1}), and MSW compost (12 and 24 t ha^{-1})—combined with mineral fertilisation in 'Valencia late' orange orchards in the province of Valencia (Albiach, 1997). It is important to highlight that, since these biochemical parameters refer to living microorganisms, they are strongly influenced by the edaphoclimatic conditions at the time of sampling. Therefore, absolute values or definitive adequate ranges cannot be established. Proper interpretation requires the comparison with a control sample under the same conditions as the treatments. Therefore, future studies should consider multiple samplings, ideally covering different phenological stages of the crop, to better interpret biochemical parameters.

The application of organic amendments can improve important aspects of soil health such as structure, water retention capacity, OM content, nutrient availability, salinity, and biological activity (Aggelides and Londra, 2000; Aguilar et al., 2012; Brown and Cotton, 2011; Zuazo and Pleguezuelo, 2009), resulting in an increasing nutrient uptake by plants (Eissa and Helail, 1997; Magdich and Rouina, 2022; Martínez-Alcántara et al., 2016). However, in the present study, the changes observed in soil characteristics were not reflected on macronutrient foliar contents. Indeed, after two years of compost application, and despite the improvement of different soil characteristics, such as the increase in organic N and available K contents, foliar macronutrient concentrations did not significantly differ from not amended soils. Soil analyses were conducted four months after foliar analyses, which took place at the beginning of winter dormancy, so changes in the soil might not have been persistent enough to be reflected in foliar nutrient content. To our knowledge, there are no studies that directly compared the effects of organic amendments on soil nutrient levels with foliar nutrient responses, which could have helped to interpret these results. On the other hand, the mineral fertilisation provided, equal for all the treatments except in P FUs, could have been sufficient to meet the plants' nutritional requirements, so that significant changes in foliar macronutrient contents were not produced. In the literature, this absence of effect after compost amendment has also been reported by other authors. For example, Fernández-Hernández et al. (2014) found no significant differences in foliar concentrations of N and Ca in olive trees grown in calcareous soils in southern Spain after six consecutive years of applying 7 t ha^{-1} of three different types of compost (fresh olive mill residues and sheep manure; dry olive mill residues and sheep manure; and fresh olive mill residues, sheep manure, and olive tree pruning), compared to mineral fertilisation. Other studies have reported variable effects; for instance, Canali et al. (2012) observed no significant differences in foliar concentrations of N, K, and Ca in Valencia late orange trees after repeated applications of organic fertilisers (citrus by-product compost, poultry manure, and livestock waste compost), compared to control trees treated with mineral fertilisers, although a reduction in Mg concentration was noted.

Based on the results of soil and foliar analyses, and considering the high P content of COMP2, mineral P fertiliser inputs were reduced by 10% in S2. Despite this reduction, foliar P concentrations remained within the optimal range (Quiñones et al., 2012). Moreover, trees grown in compost-amended soils showed no significant differences compared to those in non-amended soils, suggesting that a more sustainable nutrient management approach is feasible.

Foliar micronutrient concentrations were influenced by compost amendment only in the case of Zn, for which significantly higher values were observed in S1 with both compost application rates. This increase is consistent with the results of the soil analysis from the same season, in which the plots receiving compost exhibited the highest total Zn concentrations in the soil. Other authors have also reported increases in foliar Zn concentration following the application of organic products. For instance, Canali et al. (2012) observed an increase in Zn concentration in trees treated with compost derived from citrus by-products, poultry manure, or livestock waste compost compared to trees treated with mineral fertilisation. However, Fernández-Hernández et al. (2014), in an olive trial in which different types of compost made from olive mill residues (fresh and dry) were applied, combined with various structuring agents (olive pruning and sheep manure) in different proportions, observed variable effects on foliar Zn concentration depending on the compost applied.

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Regarding the remaining micronutrients, no significant differences were observed between treatments, as was also the case at the soil level. Fernández-Hernández et al. (2014) also reported no significant differences in foliar Mn, Cu, and B concentrations following the application of olive mill residue compost and organic materials in olives compared to mineral fertilisation. Similarly, Canali et al. (2012) found no differences in foliar Mn concentrations in trees treated with compost from citrus by-products, poultry manure, and livestock waste compost. Foliar concentrations of Mn and Zn were generally low in the studied plot (Quiñones et al., 2012). The fertilisation plan implemented in the plot only included the application of Fe chelates, which likely contributed to these low values. While long-term organic amendments could potentially fulfil the requirements for these elements, micronutrient supplementation should be considered during the initial years following application.

Compost application did not result in agronomically relevant changes in yield or in the physicochemical characteristics of the fruit. Although the application of organic amendments can enhance these parameters (Abouziena et al., 2008; Bhuyan et al., 2016; Fikry et al., 2020; Kumar et al., 2013; Madejón et al., 2003), their effects depend on multiple factors, including initial soil fertility, crop nutrient demand, climatic conditions, and the number of years of application (Diacono and Montemurro, 2010). The interaction between these variables can influence both the magnitude and the timing of the crop response to organic fertilisation, particularly in long-lived woody species. In addition, as mineral fertilisation was largely maintained—with only a partial reduction in P fertiliser units (FUs) in S2—plant nutritional requirements were likely met, as indicated by foliar analysis results. In the literature, studies on citrus on the effects of organic fertilisation on citrus yield and fruit quality showed variable results. For example, in a long-term study by Canali et al. (2012) comparing organic and mineral fertilisation in Valencia late oranges, no significant differences were found in yield, fruit weight, or rind thickness after 12 years of application. Conversely, Madejón et al. (2003) reported an increase in yield (kg tree^{-1}) of Valencia oranges when combining organic and mineral fertilisation, compared to the exclusive application of 100% mineral fertilisers.

5. Conclusions

RS/ SS compost showed higher nutrient concentrations than the PR/ SS compost, usually produced in Mediterranean facilities, making it a promising phosphorus-rich organic fertiliser for citrus orchards.

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Compost amendments enhanced soil fertility and improved soil health indicators such as microbial biomass C and dehydrogenase activity. However, the effects of compost on nutrient uptake, yield, and fruit quality were limited.

Overall, these findings highlight the potential of industrial composting as a sustainable strategy to improve soil fertility while valorising agricultural residues. Further research is warranted to optimize compost application rates in combination with reduced mineral fertilisation, aiming for a more sustainable and environmentally responsible citrus production system.

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Statements & Declarations

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The authors have no relevant financial or non-financial interests to disclose.

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