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

Rodríguez-Carretero Isabel; Canet Rodolfo, Pérez-Piqueres Ana, Quiñones Ana

Centro para el Desarrollo de la Agricultura Sostenible, Instituto Valenciano de Investigaciones Agrarias (IVIA), CV-315, km 10.7, 46113 Moncada, Valencia, Spain.

*Corresponding author: rodriguez_isacar@gva.es

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 two industrial-scale composts produced from ~~RS and SS (~~PR~~RS~~/SS~~)~~ ~~at~~ and RS/SS ~~industrial scale, in comparison with compost derived from pruning residues and sewage sludge (PR/SS), which is commonly produced~~ in a commercial Mediterranean ~~composting facilities~~citrus orchard. 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. Soil organic matter, organic N, available P and K, and Zn contents generally increased following compost application, while improvements in soil biological indicators were mainly observed during the first growing season. ~~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. Moreover, successive compost applications improved several~~, enhancing~~ soil fertility indicators~~properties~~ and support~~ing~~ the partial replacement of ~~reducing dependence on~~ mineral P fertilisation under similar conditions~~ers~~.

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

1. Introduction

In recent years, the need to develop ~~efforts toward a~~ more sustainable strategies for managing organic waste and improving soil fertility has become increasingly urgent~~and environmentally responsible development model that integrates economic growth with environmental protection and social well-being have intensified~~. This transition is supported by European and national policies promoting circular economy principles and sustainable soil management, including the ~~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~~ European~~,~~ ~~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~~and Spanish~~in,~~ Real Decreto (RD) 1051/2022. Within this context, ~~increasing~~ attention has been given to the ~~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 agricultural by-products and agro-industrial residues as soil ~~amendments~~~~waste~~nutrient sources ~~materials~~.

Among these residues, ~~R~~rice straw (RS) is o~~O~~ne of the most significant agricultural residues generated in the Valencia region, where rice cultivation is mainly concentrated in the Albufera Natural Park (ANP)~~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).~~ Annual production is estimated ~~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. In addition to RS, sewage sludge (SS) from wastewater treatment plants represents another relevant organic residue with high potential for agricultural reuse. In Spain, 1.2 million t of sludge are produced annually. These residues are rich in OM and nutrients but may also contain high levels of heavy metals, pathogens, and organic pollutants (MITECO, 2024).

In this context, ~~C~~composting represents an efficient ~~option~~ strategy for ~~RS~~ valorisation of these residues, as it enables their ~~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,~~and transformation~~ing~~ ~~them~~ into agronomically valuable products ~~suitable for agricultural use~~ while reducing their potential environmental risks (López Bravo et al., 2017). In this process, ~~T~~the choice of bulking agent is a key factor in composting performance, influencing aeration, moisture regulation, and decomposition dynamics. Pruning residues (PR) are commonly used for this purpose; however, their availability may be limited and not always aligned with regional residue management strategies. In this regard, rice straw represents a promising locally available alternative as a bulking agent in composting processes.

Specifically, ~~Despite these limitations, properly stabilised composts are widely accepted for agricultural use under current regulations. In this context~~ the ~~, the~~ composting of rice straw and sewage sludge (RS-SS) constitutes a promising ~~strategy~~approach combining residues with complementary properties ~~to stabilise these residues and produce a material suitable for agricultural application~~ (Iranzo et al., 2004). Although previous studies have evaluated RS–SS composting at pilot and medium scales (Ferrer et al., 2002; Roca-Pérez et al., 2009), information under industrial-scale production conditions remains limited (Rodríguez-Carretero et al., 2023). In addition, while SS may present certain limitations, however, properly stabilised composts are widely accepted under current regulations for agricultural applications.

~~The choice of bulking agent is a key factor in composting performance, influencing aeration, moisture regulation, and decomposition dynamics. Pruning residues (PR) are commonly used for this purpose; however, their availability may be limited and not always aligned with regional residue management~~ priorities, highlighting the need to explore locally available alternatives such as RS.

Compost ~~The~~ application ~~of compost to agricultural~~can improve soil~~s enhances their~~ physical, chemical, and biological properties, enhancing ~~. It improves~~ soil structure, nutrient availability, and microbial activity (Aggelides and Londra, 2000; Bouajila and Sanaa, 2011; Pérez-Piqueres et al., 2006;~~ Bouajila and Sanaa, 2011~~). ~~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).~~ However, its agronomic performance under field conditions remains variable and is still poorly documented in perennial woody crops such as citrus,

~~Considering the global importance of citrus cultivation — Spain being~~ one of the most important fruit crops ~~leading producers and the Valencian Community the largest producer~~ in the Mediterranean region, particularly in Spain and the Valencian Community. ~~— 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~~In addition, irrigation management constitutes another key factor influencing soil processes and crop response in citrus systems. Although irrigation systems have progressively modernised towards localized irrigation, flood irrigation is still used in approximately 13% of irrigated citrus orchards in Spain [Ministerio de Agricultura, Pesca y Alimentación (MAPA) 2024]~~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 t~~The limited availability of information~~ available,~~ highlights the need to evaluate~~ing~~ sustainable fertilisation strategies, ~~—~~including organic ~~amendments~~products, ~~—~~ in these ~~is type of irrigation~~ systems~~, is particularly relevant~~.

Based on these ~~former~~ considerations, ~~this study was based on the~~it was hypothesised that the successive applications of sewage sludge-based composts produced with different structuring material would ~~the innovative~~a ~~compost produced from RS and SS could improve~~contribute to the progressive improvement of soil fertility and crop performance under Mediterranean conditions while. Furthermore, compost producing rice straw as a bulking agent was expected to provide agronomic benefits comparable to those obtained with pruning residues, supporting its use as a sustainable and locally available alternative for conventional compost production.~~ constituting a sustainable alternative to conventional pruning residue-based composts.~~ ~~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 specific objectives were to (i) ~~evaluate the agronomic performance of industrial-scale sewage sludge-based composts produced with different bulking agents (RS or PR), an industrial-scale RS and SS compost in comparison with a conventional pruning residues (PR) and SS compost,~~ and (ii) ~~assess~~ evaluate both the short-term and cumulative effects of compost applications ~~their effects of these compost~~ on soil physicochemical properties, plant nutritional status, ~~fruit~~ yield, and fruit 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~~ Park 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. The physicochemical characteristics of the feedstocks used for compost production (RS, PR and SS) have been previously reported by Rodríguez-Carretero et al. (2023). 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 concentration (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 (season 1) 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.

The field trial followed a randomized complete block design with three treatments: (i) control (no compost application), (ii) single compost dose (10 t ha^{-1}), and (iii) double compost dose (20 t ha^{-1}), ~~with doses based on~~ with annual application rates established according to regional regulations (~~–~~Orden 10/2018, Valencian Community, Spain)~~.~~. ~~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~~ Each treatment~~s~~ ~~were~~ was replicated three times~~, in a randomized block design,~~ with eight trees per ~~experimental plot~~replicate, resulting in a total of nine experimental plots. These ~~Plots~~ were ~~maintained and followed throughout both growing seasons and~~ separated by buffer rows to prevent cross-interference between treatments.

Concerning compost treatments, COMP1, produced from PR and SS (PR–SS; 1:3 w:w fresh weight), was applied in S1, whereas COMP2, produced from RS and SS (RS–SS; 1:8 w:w fresh weight), was applied in S2 to the same trees that had previously received COMP1. This approach reflects a realistic agronomic practice, where compost composition varies between seasons depending on available organic residues. ~~Therefore~~Consequently, S2 represents the cumulative effect of successive compost applications (COMP1 + COMP2) under commercial orchard conditions.~~both composts COMP1 and COMP2 were applied in S1 and S2, respectively, in Juneevaluated sequentially in the same fieldcommercial orchard under comparable management and environmental conditions, rather than through a simultaneous comparison within a single growing season~~. Composts were~~as~~ surface applied in June within ~~in~~ the tree canopy projection zone using a trailer spreader attached to a tractor.

Mineral fertilisation was initially maintained in S1 to ensure adequate crop nutritional requirements under commercial management conditions (205 kg N ha^{-1}; 54 kg P_2O_5 ha^{-1}; 156 kg K_2O ha^{-1}; 0.8 kg Fe ha^{-1}; and 11 kg of organic products ha^{-1}). In S2, fertilisation rates were adjusted based on soil and foliar analysis results, reflecting the increased availability of nutrients in the soil.~~phosphorus fertiliser inputs were reduced by 10% based on soil and foliar analysis results, in line with strategies aimed at reducing~~

~~mineral fertiliser use. 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%. Due to the cumulative effects associated with compost application over time, as well as changes in mineral fertilisation management between seasons, statistical comparisons between S1 and S2 were not performed.~~ 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

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 from each growing season (S1 and S2) were analysed ~~independently because different composts were evaluated in each season and mineral fertilisation management differed between growing seasons. Therefore, statistical comparisons between seasons were not performed.~~

~~Data were subjected to~~ separately using ~~an~~analysis of variance (ANOVA) to ~~test~~ assess the effect of compost application treatments (including the different compost application rates and the non-amended control) on analysed parameters. Before ~~carrying out any~~ statistical analysis, ~~the normality of all the~~ data normality was ~~studied~~ evaluated using the Kolmogorov–Smirnov test. When the~~If the hypothesis of~~ normality assumption was ~~discarded~~ not met at the 95% confidence level, data were log-transformed ~~according to the logarithmic function~~. The variance of the transformed or non-transformed data was, subsequently, ~~partitioned~~ analysed by one-way ~~with a variance analysis (~~ANOVA using~~,~~ Statgraphics Centurion for Windows~~,~~ (Statistical Graphics Corp., The Plains, VA, USA)~~ into one source of variability~~. Treatments means ~~The significance of the comparisons made between treatments was analysed~~were compared ~~with~~ using 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, $N\text{-}NH_4^+$, and $N\text{-}NO_3^-$, 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-NH_4^+ (mg kg^{-1})	2,112	2,389	ns	Pb (mg kg^{-1})	18.1	50.9	***
N-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

Results from S1 and S2 are presented separately because the second growing season evaluated the effects of a subsequent compost application on plots previously amended with compost. Consequently, each season was analysed independently, and treatment effects are reported within each growing season. ~~Overall, soil and plant responses to compost application were more pronounced in S1 than in S2 for several parameters, particularly those related to soil biological activity. In contrast, responses in S2 were generally less marked and more variable depending on the parameter.~~

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 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).

According to the classification proposed by Legaz et al. (1995) for clay ~~The~~ soils, soil OM contents ranged from normal to very high ~~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 et al., 1995; MAPA, 2010), and no significant differences were observed between treatments in either season.

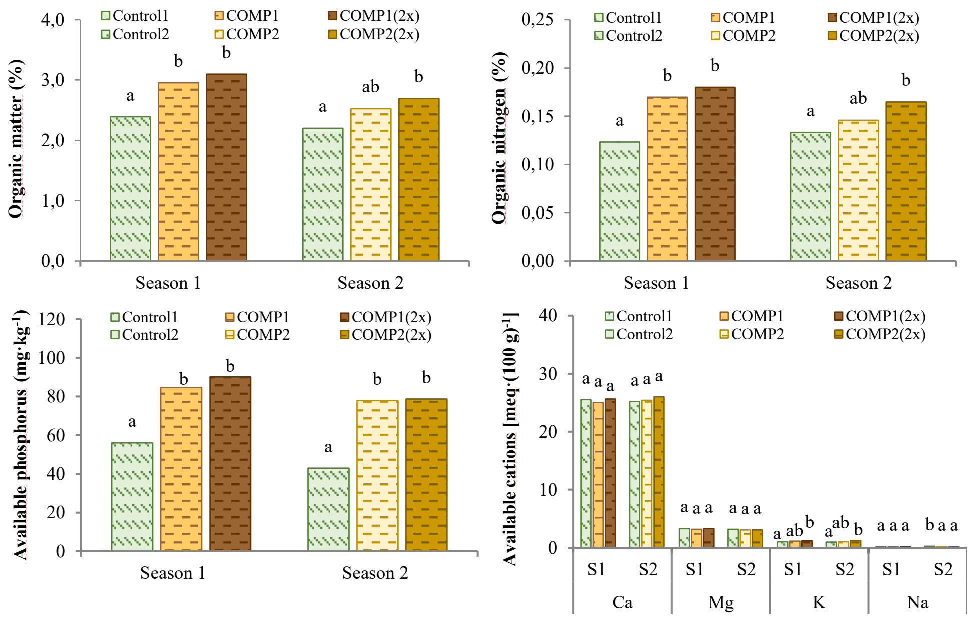

Figure 1. Concentration of organic matter, organic nitrogen, available phosphorus and cations of the soil from both seasons. COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). Different letters indicate significant differences between treatments in each season according to the Fisher's LSD test ($p 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

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, whereas no significant differences among treatments were detected in S2~~but not in S2~~ (Figure 2). In S1, microbial biomass C showed a significant increase of 65% with the double dose compared to the control soil, while dehydrogenase activity increased under both application rates.

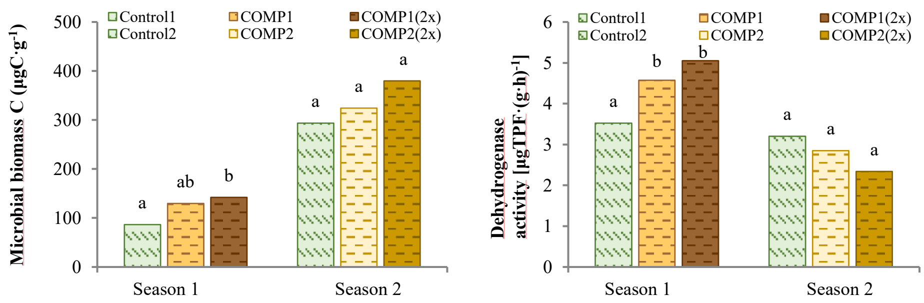

Figure 2. Soil biomass carbon and dehydrogenase activity from both seasons. COMP1: compost 1 (PR); COMP2 (RS): compost 2 (RS). Different letters indicate significant differences between treatments in each season according to the Fisher's LSD test ($p < 0.05$).

3.2.2. Plant nutrient uptake

Foliar macronutrient concentrations in ~~trees from~~ all treatments remained~~were~~ within optimal ranges across both seasons (Quiñones et al., 2012), with the exception of ~~few exceptions for~~ K ~~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. Compost 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 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

~~4.~~ 4.1. Agronomic potential of RS–SS compost under industrial-scale conditions

Compost derived from the large-scale composting of SS and RS (COMP2) exhibits considerable agronomic potential due to the complementary properties of both materials. Compared with the reference compost produced from ~~pruning residues~~PR and ~~sewage sludge~~~~SS~~sludges (COMP1)~~ (PR–SS)~~, ~~the RS–SS~~COMP2 compost exhibited similar or even higher nutrient contents, particularly in N and P, confirming its suitability as a fertilising ~~amendment~~organic product for Mediterranean agricultural systems.~~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 also ~~exhibited~~ showed 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, indicating that ~~which should be considered when establishing field~~ application rates should be carefully managed, although~~.~~ ~~Nevertheless~~ the~~,~~ improvement of soil physical properties following compost application~~ induced improvements in soil structure and permeability over time~~ may~~,~~ promote ~~facilitat~~t~~eing~~ salt leaching~~ in the long term~~ and reduce the risk of salt accumulation over the time (Aggelides and Londra, 2000; Tejada et al., 2006).

Although both composts showed similar ~~COMP1 and COMP2 did not differ in~~ TOC contents, ~~but the C/N ratio was lower in~~ COMP2 exhibited a lower C/N ratio due to its higher total N ~~value~~concentration. 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, as the P_2O_5 ~~with a~~ fertiliser unit (FU) value of COMP2 was ~~P_2O_5~~ more than twice that of COMP1 and exceeded~~, surpassing~~ the average~~s~~ values commonly reported for livestock ~~sheep, cattle, or swine~~ manures (Pomares, 2000).

Moreover, ~~D~~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), confirming the environmental suitability of the compost under the studied conditions.

4.2. Soil fertility response

Compost application improved several soil fertility indicators;~~,~~ ~~however~~with~~,~~ responses differing~~ed~~ ~~in~~between S1 and S2, highlighting the importance of temporal dynamics in the effects of organic ~~amendment~~product applications~~ effects~~.

~~increasing nutrient availability and several soil health indicators.~~ Soil moisture ~~parameter is~~was not significantly affected in either season, suggesting that~~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 consecutive years of application ~~are~~ were insufficient to induce noticeable changes in soil ~~structure~~ water retention capacity, despite the recognise contribution of organic applications to soil physical properties associated with ~~and bulk density, which are~~both ~~closely linked to soil porosity and~~ water ~~retention~~ storage and availability~~capacity~~ (Bronick and Lal, 2005).

In contrast, soil pH showed a clearer temporal response. Significant decreases were mainly observed in S2, particularly under the double-dose treatment, suggesting a cumulative effect associated with repeated organic matter inputs and mineralisation processes. ~~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~~ after the application of RS-~~ and~~ SS compost to citrus trees grown in clay soil, ~~likewise~~ also observing a more pronounced pH decline (from 8 to 7) with increasing compost rates (0 to 6% w/w). T~~Furthermore, t~~he slightly acidic pH of the RS-SS compost ~~used in S2 could~~may have further ~~also~~ contributed to this trend~~decrease in soil pH~~.

~~As observed in soil moisture,~~ Soil ~~E~~electrical conductivity~~C~~ ~~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~~ increased~~s~~ ~~observed at the higher~~after compost application in S1, especially under the higher application rate, and this trend persisted in S2 following the second compost application.~~rate, regardless of the structuring material used (PR or RS)~~. This ~~indicates~~suggest that, within the ~~studied timeframe~~duration of the study, the beneficial effects of compost on soil physical properties ~~structural improvements~~ were insufficient to offset salt inputs ~~derived~~resulting ~~-~~from successive compost application. ~~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).~~ Moreover, ~~T~~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 compost ~~them~~ biennially could be advisable under long-term management scenarios. Proper irrigation management could also help ~~contribute to~~ reduce~~ing~~ EC through ~~values by facilitating~~ salt leaching and ~~the redistribution of~~ cation~~s~~ redistribution ~~between the soil solution and the exchange complex~~ (Madejón et al., 2003), particularly considering ~~. Moreover,~~ the positive effects of OM ~~application~~ on soil ~~structure~~ physical properties and permeability ~~is well documented~~ (Lakhdar et al., 2009).

Regarding C~~The total c~~arbonate concentrations were~~as~~ high in S1 and S2, 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 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, although total carbonate concentrations increased in S2 under the double-dose treatment, active lime decreased slightly.~~the double compost dose applied in S2 reduced active lime concentrations, thereby enhancing nutrient bioavailability.~~ This suggests enhanced ~~reduction may be attributed to the dissolution of~~ carbonate~~s~~ solubilisation driven by organic acid~~s,~~ release ~~d~~ during the decomposition of organic matter, potentially increasing ~~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~~ As for s~~S~~oil OM~~, and consequently of OC~~ concentrations ~~,~~ increased following compost application in both seasons. However, the response was ~~double compost dose did~~ not proportional to compost dose, suggesting that higher application rates do not necessarily result in greater stabilised organic carbon accumulation. Moreover, the decrease in OM observed in the control soil in S2 indicates that mineralisation exceeded organic matter inputs in non-amended plots, reinforcing the importance of repeated organic amendments to maintain soil carbon levels under Mediterranean conditions. Furthermore, the overall decrease in OM observed between seasons across all treatments suggests that, in addition to compost management, differences in environmental conditions between seasons, variations in mineralisation rates, and the inherent variability associated with field soil sampling may also have contributed to the observed trend. ~~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.~~

4.3. Nutrient availability

Compost application increased soil organic N and plant-available P and K in both seasons, although treatment responses were not always consistent across the study period.~~the magnitude and agronomic relevance of these responses differed between seasons~~. ~~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~~. ~~T~~Furthermore, t~~he C/N ratios ~~obtained ~~across all treatments and ~~in both ~~seasons remained ~~were mostly ~~within the ~~optimal ~~range ~~of 10–12 ~~considered optimal (10-12), indicating adequate conditions for ~~to ensure proper ~~N release (MAPA, 2010).

A~~aPlant a~~vailable P in soil ~~concentrations ~~increased with both compost doses ~~compared to the control plots ~~in both seasons, in agreement with previous studies conducted in citrus systems~~. These increases align with previous findings on compost application in citrus crops~~ (Madejón et 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. Based on these results and the adequate foliar P concentrations observed in S1, mineral P fertilisation was reduced by 10% in S2~~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)~~. Despite this reduction, foliar P concentrations remained within the optimal range (Quiñones et al., 2012), suggesting that compost-derived P may contribute to reducing mineral P fertilisation requirements under similar conditions.~~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).~~

A~~Just as P, plant available~~Soil K availability enhanced ~~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 decreased after compost application, especially in S2~~concentrations, which was statistically significant in S2~~. Although this effect could be attributed to an improvement in soil ~~structure~~physical properties, and consequently, enhanced salt leaching, the EC results do not support this hypothesis.

T~~he t~~otal metals concentrations ~~of metals~~ (Fe, Cu, Mn, Zn, Ni, Pb, and Cr) ~~were mostly~~remained 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.

4.4. Biological activity

Microbial biomass C and dehydrogenase activity are widely used ~~biochemical~~ indicators of the ~~quantity~~ size and activity of ~~living~~ soil ~~microorganisms~~microbial communities ~~present in the soil~~. Agricultural practices that ~~increase~~ stimulate microbial biomass and ~~stimulate~~ enzymatic activity can promote ~~a~~ ~~greater~~ OM mineralisation ~~of OM~~, improve soil quality, and enhance plant ~~resistance~~ resilience to biotic and abiotic stresses~~against pests and diseases~~ (Erhart and Hartl, 2010). In the present~~our~~ study, compost addition ~~led to higher~~increased microbial biomass C and dehydrogenase activity in S1, ~~but~~ whereas ~~there were~~ no significant treatments effects were detected~~differences~~ in S2. A possible explanation for this contrasting response is that, despite their similar total OM and TOC contents, the composts differed significantly in the composition of their organic fraction, particularly in oxidisable organic carbon (OOC) and organic N contents. Oxidisable organic carbon represents a more readily available substrate for soil microorganisms than total OM. Therefore, the higher OOC content of the compost applied in S1 may have stimulated microbial growth and activity to a greater extent, contributing to the stronger microbial response observed during this season (S1). ~~These contrasting responses between seasons highlight the strong temporal variability of soil biochemical indicators~~. ~~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 absence of significant differences in S2 does not necessarily indicate reduced~~Furthermore, ~~-~~microbial activity indicators are highly sensitive to environmental conditions , ~~but rather suggests that microbial responses to organic amendments are strongly influenced by edaphoclimatic conditions and sampling time~~including~~. S~~soil moisture, temperature, and substrate ~~dynamics~~availability at the time of sampling which may also have contributed to the variability observed between seasons ~~may substantially affect these parameters, which partly explains the variability reported in the literature~~. Consequently, the absence of significant treatments effects in S2 does not necessarily indicate a reduction in microbial activity but rather highlights the influence of multiple factors regulating soil microbial dynamics. Similar variability has been widely reported in the literature, where the effects of organic amendments on microbial biomass and enzymatic activity depend not only on the quantity but also on the quality of the organic substrates applied and the prevailing environmental conditions. ~~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 repeated ~~three years of applying olive mill wastewater sludge~~ compost application. ~~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, Albiach (1997) ~~other studies~~ found no significant effects on microbial biomass C or dehydrogenase activity following the application of different organic products under Mediterranean conditions ~~— 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)~~. These contrasting findings illustrate the high variability commonly reported for soil biological indicators and support the view that their response depends not only on the characteristics of the organic amendments applied but also on the environmental conditions prevailing at the time of sampling. ~~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 dates, ideally covering different crop phenological stages ~~of the crop~~, to ~~better~~ improve the interpretation of soil biochemical parameters.

4.5. Plant nutrition, yield and agronomic implications

~~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).~~ Despite improvements in several soil fertility indicators, ~~However, in the present~~

~~study, the changes observed in soil characteristics were not reflected on~~ foliar macronutrient ~~foliar~~ contents remained largely unaffected by ~~. 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,~~ This suggests that ~~the~~ mineral fertilisation, which was applied ~~provided~~ equally across ~~for all the~~ treatments (except ~~in~~ for P FUs in S2), ~~,~~ ~~could have been~~was 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.~~ Similar results have been reported in olive and citrus orchards under Mediterranean conditions, where repeated applications of organic amendments did not significantly affect foliar macronutrient concentrations (Canali et al., 2012; Fernández-Hernández et al., 2014). ~~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). These results suggest that compost-derived P may contribute to reducing mineral P fertilisation requirements under similar conditions. 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 ~~reported ~~an ~~increased foliar ~~in ~~Zn concentrations ~~in trees treated with~~following compost ~~derived from citrus by-products, poultry manure, or livestock waste compost compared to trees treated with mineral fertilisation~~application, whereas ~~. 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~~responses depending on the type of compost applied.

~~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 ~~products 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 the present study, no agronomically relevant effects on yield or fruit quality were observed. This may be partly explained by the fact that crop nutritional requirements were adequately met in all treatments, as indicated by foliar analyses. Under these conditions, improvements in soil fertility associated with compost application were not translated into additional gains in productivity or fruit quality during the study period. ~~addition, as mineral fertilisation was largely maintained throughout the experiment, with only a partial reduction in P fertiliser units (FUs) in S2. Consequently, crop plant nutritional requirements were likely met regardless of treatment, as supportedindicated by foliar analysis results, which may explain the limited response observed in yield and fruit quality parameters~~. 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~~ increased ~~in~~ yields in ~~(kg tree^{-1}) of~~ Valencia oranges trees when ~~combining~~ organic and mineral fertilisation were combined, compared with ~~to the~~ exclusive ~~application of 100%~~ mineral fertilisation~~ers~~. These contrasting findings suggest that crop responses to organic ~~amendments~~products are highly site-specific and may only become evident after prolonged application periods. ~~Under the conditions of the present study, the main effects of compost application were observed on soil fertility indicators rather than on crop productivity or fruit quality.~~ Nevertheless, since the experiment was conducted under flood irrigation conditions, caution should be exercised when extrapolating these findings to drip-irrigated citrus orchards, where soil water distribution and nutrient dynamics may differ.

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.~~

~~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.~~

The compost produced from rice straw and sewage sludge showed a favourable nutrient composition, particularly with respect to phosphorus content, confirming its potential as an alternative organic fertiliser and a sustainable strategy for rice straw valorisation. Moreover, its agronomic quality and regulatory compliance support its use as a viable alternative to conventional sewage sludge composts produced with pruning residues.

Successive compost applications enhanced several soil fertility indicators, including soil OM, organic N and the availability of P and K. Improvements in soil biological indicators were detected during the first growing season, although responses varied over time, highlighting the temporal variability of soil microbial processes.

Despite these positive effects on soil fertility, compost application had limited effects on plant nutritional status, yield, and fruit quality under the conditions of the present study.

Overall, these findings highlight the potential of industrial-scale composting of rice straw and sewage sludge as a circular and sustainable strategy to improve soil fertility while valorising agricultural residues. Further long-term studies under different irrigation systems are needed to evaluate the persistence of the observed soil responses, the cumulative effects of successive compost applications, and the potential to optimise compost use in combination with reduced mineral fertilisation strategies in different citrus production systems.

Statements & Declarations

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Competing Interests

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

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References

~~Abd El-Mageed, T. A., Semida, W. M., and Abd El-Wahed, M. H.: Effect of mulching on plant water status, soil salinity and yield of squash under summer–fall deficit irrigation in salt affected soil, Agricultural Water Management, 173, 1–12, 2016.~~

Abouziena, H. F., Hafez, O. M., El-Metwally, I. M., Sharma, S. D., and Singh, M.: Comparison of weed suppression and mandarin fruit yield and quality obtained with organic mulches, synthetic mulches, cultivation, and glyphosate, HortScience, 43, 795–799, 2008.

~~Adugna, G.: A review on impact of compost on soil properties, water use and crop productivity, Academic Research Journal of Agricultural Science Research, 4, 93–104, 2016.~~

Aggelides, S. M. and Londra, P. A.: Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil, Bioresource Technology, 71, 253–259, 2000.

~~Aguilar, J. M., Albiach, R., Soriano, M. D., Estela, M., Tarazona, F., and Pomares, F.: Efectos derivados de la aportación de los restos de poda en las propiedades del suelo y estado nutricional del arbolado en una parcela de cítricos, in: X Congreso de la Sociedad Española de Agricultura Ecológica, Spain, 850–862, 2012.~~

Albiach, R.: Estudio de varios índices de actividad biológica del suelo en relación a diferentes aportaciones de enmiendas orgánicas, PhD thesis, Universitat de València, Spain, 1997.

~~Alexandre, C. A., Bajouco, R., Leal, J. D., Peça, J. O., and Dias, A. B.: Effects on soil chemical properties and carbon stock two years after compost application in a hedgerow olive grove, Agronomy, 13, 1933, 2023.~~

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., and Thami Alami, I.: Composting parameters and compost quality: a literature review, Organic Agriculture, 8, 141–158, 2018.

Bhuyan, M. H. M. B., Sarker, J., Rahman, S., Fujita, M., and Hasanuzzaman, M.: Evaluation of integrated nutrient management for mandarin orange production in hot humid region of Bangladesh,American Journal of Experimental Agriculture, 10, 1–10, 2016.

Bouajila, K. and Sanaa, M.: Effects of organic amendments on soil physico-chemical and biological properties, Journal of Materials and Environmental Science, 2, 485–490, 2011.

Bronick, C. J. and Lal, R.: Soil structure and management: a review, Geoderma, 124, 3–22, 2005.

~~Brown, S. and Cotton, M.: Changes in soil properties and carbon content following compost application: results of on-farm sampling, Compost Science & Utilization, 19, 87–96, 2011.~~

Canali, S., Roccuzzo, G., Tittarelli, F., Ciaccia, C., Fiorella, S., and Intrigliolo, F.: Organic citrus: soil fertility and plant nutrition management, in: Advances in Citrus Nutrition, 353–368, 2012.

~~Canet, R., Pomares, F., Estela, M., and Tarazona, F.: Efecto de diferentes enmiendas orgánicas en las propiedades del suelo de un huerto de cítricos, Agrochimica, 42, 41–49, 1998.~~

Casida, J. E., Klein, D. A., and Santoro, T.: Soil dehydrogenase activity, Soil Science, 98, 371–376, 1964.

~~Chalker-Scott, L.: Impact of mulches on landscape plants and the environment – a review, Journal of Environmental Horticulture, 25, 239–249, 2007.~~

~~Chandra, S., Singh, R. D., Bhatnagar, V. K., and Bisht, J. K.: Effect of mulch and irrigation on tuber size, canopy temperature, water use and yield of potato, Indian Journal of Agronomy, 47, 443–448, 2002.~~

~~Conselleria de Agricultura, Desarrollo Rural, Emergencia Climática y Transición Ecológica: Decreto 81/2022, de 10 de junio, del Consell, por el que se amplían los municipios designados como zonas vulnerables a la contaminación de las aguas por nitratos procedentes de fuentes agrarias, Spain, 2022.~~

Conselleria de Agricultura, Medio Ambiente, Cambio Climático y Desarrollo Rural, 2018: Orden 10/2018, de 27 de febrero, sobre la utilización de materias fertilizantes nitrogenadas en las explotaciones agrarias de la Comunitat Valenciana, Spain, 2018.

Dadrasnia, A., de Bona Muñoz, I., Yáñez, E. H., Lamkaddam, I. U., Mora, M., Ponsá, S., Ahmed, M., Argelaguet, L. L., Williams, P. M., and Oatley-Radcliffe, D. L.: Sustainable nutrient recovery from animal manure: a review of current best practice technology and the potential for freeze concentration, Journal of Cleaner Production, 315, 128106, 2021.

Diacono, M. and Montemurro, F.: Long-term effects of organic amendments on soil fertility: a review, Agronomy for Sustainable Development, 30, 401–422, 2010.

~~Eissa, M. A. and Helail, B. M.: A comparative study on some weed control treatments in Balady lime nursery, Annals of Agricultural Science, 35, 935–947, 1997.~~

Erhart, E. and Hartl, W.: Compost use in organic farming, in: Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming, 311–345, 2010.

European Commission (EC): The European Green Deal, available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en, last access: 3 Nov 2025, 2019~~)~~.

~~European Commission (EC): EU Biodiversity Strategy for 2030, available at: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_es, last access 3 Nov 2025, 2020a.~~

~~European Commission (EC): Farm to Fork Strategy, available at: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en, last access: 3 Nov 2025, 2020b.~~

~~European Commission (EC): Circular Economy Action Plan, available at: https://ec.europa.eu/commission/presscorner/detail/es/ip_20_420, last access: 3 Nov 2025, 2020c.~~

~~European Commission (EC): EU Soil Strategy for 2030, available at: https://eur-lex.europa.eu/legal-content/ES/ALL/?uri=CELEX:52021DC0699, last access: 3 Nov 2025, 2021a.~~

~~European Commission (EC): Common Agricultural Policy, available at: https://agriculture.ec.europa.eu/common-agricultural-policy_en, last access: 3 Nov 2025, 2021b.~~

European Commission: Commission Delegated Regulation (EU) 2021/1890 of 2 August 2021 amending Implementing Regulation (EU) No 543/2011 as regards marketing standards in the fruit and vegetables sector, *Official Journal of the European Union*, L 384, 23–83, 2021.

Fernández-Hernández, A., Roig, A., Serramiá, N., Civantos, C. G. O., and Sánchez-Monedero, M. A.: Application of compost of two-phase olive mill waste on olive grove: effects on soil, olive fruit and olive oil quality, Waste Management, 34, 1139–1147, 2014.

Ferrer, E., Canet, R., Pomares, F., and Moreno, R.: Effects of inoculation and urea addition on the composting of sewage sludge and rice straw, WIT Transactions on Ecology and the Environment, 56, 297–303, 2002.

Fikry, A. M., Sayed-Ahmed, A., Mohsen, F. S., and Ibrahim, M. M.: Effect of nitrogen fertilization through inorganic, organic and biofertilizers sources on growth, yield and nutritional status in murcott tangerine trees, Plant Archives, 20, 1–10, 2020.

~~García-Gil, J. C., Plaza, C., Soler-Rovira, P., and Polo, A.: Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass, Soil Biology & Biochemistry, 32, 1907–1913, 2000.~~

Garrido Valero, M. S.: Interpretación de análisis de suelos, Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain, 1993.

González-Sicilia, E.: El cultivo de los agrios, Ediciones Bello, Valencia, Spain, 1968.

Iranzo, M., Cañizares, J. V., Roca-Pérez, L., Sainz-Pardo, I., Mormeneo, S., and Boluda, R.: Characteristics of rice straw and sewage sludge as composting materials in Valencia (Spain), Bioresource Technology, 95, 107–112, https://doi.org/10.1016/j.biortech.2003.08.001, 2004.

Jiménez-Cuesta, M., Cuquerella, J., and Martínez-Jávega, J. M.: Determination of a colour index for citrus de-greening, Proceedings of the International Society of Citriculture, 4, 750–753, 1981.

Juárez Sanz, M., Sánchez Andreu, J., and Sánchez Sánchez, A.: Química del suelo y medio ambiente, Publicaciones Universidad de Alicante, Alicante, Spain, 2006.

Kumar, P. S., Choudhary, V. K., Kanwat, M., and Sangeetha, A.: Influence of different nutrient sources on growth, yield and quality of Khasi mandarin, Journal of Applied Horticulture, 15, 220–223, 2013.

Lakhdar, A., Rabhi, M., Ghnaya, T., Montemurro, F., Jedidi, N., and Abdelly, C.: Effectiveness of compost use in salt-affected soil, Journal of Hazardous Materials, 171, 29–37, 2009.

Legaz, F., Serna, M. D., Ferrer, P., Cebolla, V., and Primo-Millo, E.: Análisis de hojas, suelos y aguas para el diagnóstico nutricional de plantaciones de cítricos, Generalitat Valenciana, Spain, 1995.

~~López Bravo, E., Rivera, A., Herrera Suárez, M., González Cueto, O., and García de la Figal Costales, A.: Propiedades de un compost obtenido a partir de residuos de la producción de azúcar de caña, Centro Agrícola, 44, 49–55, 2017.~~

Ma, W., Tang, S., Dengzeng, Z., Zhang, D., Zhang, T., and Ma, X.: Root exudates contribute to belowground ecosystem hotspots: a review, Frontiers in Microbiology, 13, 937940, 2022.

Madejón, E., Burgos, P., López, R., and Cabrera, F.: Agricultural use of three organic residues: effect on orange production and on soil properties in Huelva (SW Spain), Nutrient Cycling in Agroecosystems, 65, 281–288, 2003.

Magdich, S. and Rouina, B.: Impact of compost agronomic application on soil chemical properties and olive tree growth parameters, Journal of Agriculture and Agronomy, 1, 42–54, 2022.

~~Martínez-Alcántara, B., Martínez-Cuenca, M. R., Bermejo, A., Legaz, F., and Quiñones, A.: Liquid organic fertilizers for sustainable agriculture: nutrient uptake of organic versus mineral fertilizers in citrus trees, PLoS ONE, 11, e0161619, 2016.~~

Ministerio de Agricultura, Pesca y Alimentación: Real Decreto 1310/1990, de 29 de octubre, por el que se regula la utilización de los lodos de depuración en el sector agrario, Boletín Oficial del Estado, 262, 32339–32340, 1990.

Ministerio de Agricultura, Pesca y Alimentación (MAPA): Métodos oficiales de análisis de suelos y aguas para el riego. In: Plantas, Productos Orgánicos Fertilizantes, Suelos, Aguas, Productos Fitosanitarios, Fertilizantes Inorgánicos, Vol. 3, p. 662, Madrid, Spain, 1994.

Ministerio de Agricultura, Pesca y Alimentación (MAPA): Guía práctica de la fertilización racional de los cultivos en España. Sebastián Ruano Criado (coord.), Parte I, España, 2010.

Ministerio de Agricultura, Pesca y Alimentación (MAPA): Regadíos en España 2024. Gobierno de España, Madrid, available at: https://www.mapa.gob.es/temas/regadio2024, last accessed: 10 Nov 2025, 2024.

~~Ministerio de Agricultura, Pesca y Alimentación (MAPA): Anuario de Estadística 2023. Gobierno de España, Madrid, available at: https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuariodeestadistica/2023/default.aspx, last accessed: 10 Nov 2025, 2023.~~

Ministerio de la Presidencia: Real Decreto 506/2013, de 28 de junio, sobre productos fertilizantes, Boletín Oficial del Estado, 164, 51119–51207, 2013.

Ministerio de la Presidencia y para las Administraciones Territoriales: Real Decreto 999/2017, de 24 de noviembre, por el que se modifica el Real Decreto 506/2013, de 28 de junio, sobre productos fertilizantes, Boletín Oficial del Estado, 296, 119396–119450, 2017.

Ministerio de la Presidencia, Relaciones con las Cortes y Memoria Democrática: Real Decreto 1051/2022, de 27 de diciembre, por el que se establecen normas para la nutrición sostenible en los suelos agrarios, Boletín Oficial del Estado, 312, 188873–188916, 2022.

Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO): Lodos de depuración de aguas residuales, available at: https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/lodos-depuradora.html , last access: 10 Nov 2025.

Morales, J., Rodríguez-Carretero, I., Martínez-Alcántara, B., Canet, R., and Quiñones, A.: DRIS norms and sufficiency ranges for persimmon 'Rojo Brillante' grown under Mediterranean conditions, Agronomy, 12, 1269, 2022.

~~Ochoa, V., Hinojosa, B., Gómez-Muñoz, B., and García-Ruiz, R.: Actividades enzimáticas como indicadores de calidad del suelo en agroecosistemas ecológicos, Iniciación a la Investigación, 2, 1–10, 2007.~~

Pérez-Piqueres, A., Edel-Hermann, V., Alabouvette, C., and Steinberg, C.: Response of soil microbial communities to compost amendments, Soil Biology & Biochemistry, 38, 460–470, 2006.

~~Pomares, F. and Albiach, R.: Valoración de los residuos orgánicos como fuente de materia orgánica y nutrientes, in: Congrés Citrícola, 83–100, 2008.~~

Pomares, F., Estela, M., Tarazona, F., Sala, M. O., and Canet, R.: Estado de contaminación por metales pesados en suelos de cítricos con cultivo ecológico, in: Congreso SEAE, 247–252, 1998.

Pomares, F.: La salinidad del suelo en los cítricos, Generalitat Valenciana, Spain, 1986.

Pomares, F.: La fertilización orgánica, in: Curso de fertirrigación de cítricos, 93–115, 2000.

Quiñones, A., Martínez-Alcántara, B., Primo-Millo, E., and Legaz, F.: Fertigation: concept and application in citrus, in: Advances in Citrus Nutrition, 281–301, 2012.

~~Rahman, M. J., Uddin, M. S., Bagum, S. A., Mondol, A. T. M. A. I., and Zaman, M. M.: Effect of mulches on the growth and yield of tomato under rainfed conditions in coastal Bangladesh, International Journal of Sustainable Crop Production, 1, 6–10, 2006.~~

Rayne, N. and Aula, L.: Livestock manure and the impacts on soil health: a review, Soil Systems, 4, 64, 2020.

~~Ribó, M., Albiach, R., Gómez, A., Pomares, F., Canet, R., and Estela, M.: Efectos de la fertilización orgánica en las propiedades químicas y biológicas de suelos hortícolas, in: Congreso SEAE, 1–10, 2004.~~

Ribó, M., Albiach, R., Pomares, F., and Canet, R.: Alternativas de gestión de la paja de arroz en la Albufera de Valencia, Vida Rural, 430, 56–60, 2017.

Roca-Pérez, L., Martínez, C., Marcilla, P., and Boluda, R.: Composting rice straw with sewage sludge and compost effects on the soil–plant system, Chemosphere, 75, 781–787, 2009.

Rodríguez-Carretero, I., Canet, R., Quiñones, A., and Pérez-Piqueres, A.: Industrial-scale composting of rice straw and sewage sludge, Agronomy, 13, 2295, 2023.

~~Roghanian, S., Hosseini, H. M., Savaghebi, G., Halajian, L., Jamei, M., and Etesami, H.: Effects of composted municipal waste and its leachate on soil chemical properties and corn responses, Waste Management & Research, 30, 800–814, https://doi.org/10.1177/0734242X12443597, 2012.~~

Roose, M. and Williams, T.: U.S. Patent Application No. 11/220,875, 2007.

Tejada, M., Garcia, C., Gonzalez, J. L., and Hernandez, M. T.: Use of organic amendment as a strategy for saline soil remediation: influence on physical, chemical and biological soil properties, Soil Biology & Biochemistry, 38, 1413–1421, 2006.

~~United Nations: 2030 Agenda for Sustainable Development, available at: https://www.un.org/sustainabledevelopment/, last access: 3 Nov 2025, 2015.~~

Vance, E. D., Brookes, P. C., and Jenkinson, D. S.: An extraction method for measuring soil microbial biomass C, Soil Biology & Biochemistry, 19, 703–707, 1987.

~~Zuazo, V. H. D. and Pleguezuelo, C. R. R.: Soil erosion and runoff prevention by plant covers: a review, Sustainable Agriculture, 30, 785–811, 2009.~~

~~**Statements & Declarations**~~

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~~**Competing Interests**~~

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

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