



Circular valorisation of olive pruning wastes into biochar: The role of pyrolysis temperature in nutrient availability and soil improvement

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ABSTRACT

This research provides novel insights into the potential agronomic use of biochars derived from olive tree pruning wastes. Biochars were produced at three temperatures (350, 500, and 700 °C) through slow pyrolysis and widely characterized and used as amendments to a Mediterranean nutrient-deficient soil to assess the influence of pyrolysis temperature on nutrient availability and agronomic properties. Their effects on turfgrass growth, nutrient uptake, soil chemical, biological, and hydrophysical properties were evaluated. Experimental results demonstrated that all biochars have potential for use as soil amendments; however, their physicochemical properties and fertilizing capacity are strongly dependent on the pyrolysis temperature. Biochars show a heterogeneous structure with the presence of large cavities produced during pyrolysis process and some of the mineral matter is segregated from the carbon structure. Biochar produced at 700 °C has a greater porosity according to a better water holding capacity that enhances plant water uptake. Accordingly, dry turfgrass biomass yield was higher in soil amended with biochar produced at 350 °C, whereas soil amended with biochar prepared at 700 °C showed greater fresh weight, indicating improved water retention and uptake. Although the biochars contained considerable amounts of nutrients, not all were taken up by the plants. Soil amendment with biochar increased K, Fe, and P concentrations in turfgrass tissue, while Ca, Mg, and Na contents were not significantly affected. Overall, these findings highlight a sustainable circular economy approach by transforming agricultural wastes into valuable soil amendments for nutrient-deficient ecosystems.

1. Introduction

Biochar is the solid carbonaceous material obtained from biomass pyrolysis that has long been recognized as an effective way to enhance soil productivity (Lehmann and Joseph, 2009; Amalina et al., 2022). It is established that biochar use as soil amendment improves physical and chemical soil properties, nutrient availability, water retention capacity, microbial activity and plant growth (Ighalo et al., 2025; Lehmann et al., 2011). Furthermore, potential advantages of biochar for soil include the reduction of greenhouse gas emissions due to carbon storage in stable organic structures (Afshar and Mofatteh, 2024). Additionally, due to its high stability biochar can retain various nutritive elements for extended periods and may potentially act as a slow-release fertilizers (Gascó et al., 2012; Niazi et al., 2023).

Nevertheless, some reports caution that biochar application may induce ecotoxicological or inhibitory effects. In some cases, biochars produced at low temperatures can release persistent volatile organic compounds that negatively impact seed germination and microbial activity (Ippolito et al., 2020; Duwiejua et al., 2020). The risk related to the use of biochar-based fertilizers also requires further research, especially possibility of releasing toxic substances from biochar under environmental conditions (Marciniczyk and Oleszczuk, 2022). This is because the properties of biochar are greatly determined by the feed-stock characteristics and the pyrolysis conditions used during its production (Coelho et al., 2025; Rai et al., 2026). Consequently, when biochar is properly managed it serves as a sustainable management practice that supports circular economy principles, reduces the volume of organic wastes, enhances soil health, and contributes to the reduction

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of greenhouse gas emissions.

Within a circular economy framework, pruning wastes, as lignocellulosic biomass, provide an ideal feedstock for biochar production. Among lignocellulosic residues there can also be a great deal of variety. Although the production of biochar from olive-derived residues has been previously investigated, existing studies have mainly focused on their valorisation for energy-related applications or on specific environmental applications, such as the removal of contaminants from aqueous solutions (Al Afif et al., 2024; Kyritidou et al., 2022; Campos et al., (2020) evaluated biochars produced from olive pruning residues under different pyrolysis conditions concluding that the high presence of ashes and water holding capacity, together with alkaline pH, high aromaticity and low hydrophobicity, make biochar promising material to be used as an amendment in the restoration of soils contaminated with potentially pollutant metallic cations or for the recovery of acid soils. However, the effectiveness of olive pruning-derived biochars as soil amendments, particularly as a source of nutrients and in improving soil hydrophysical properties, remains insufficiently investigated.

In this context, olive oil production plays a central role in the Mediterranean agri-food sector. In the 2022/2023 season, Spain produced about 0.77 million tons of olive oil, followed by Italy 0.30 million of tons and Greece 0.18 million of tons, together accounting for more than 60% of global output (Di Loreto et al., 2025). Related to this olive oil production, it is estimated that every year in Spain are generated between 4 and 5 million of tons of alperujo and 7 million of tons of pruning wastes (Pareja-Sánchez et al., 2025). These pruning residues are estimated to reach 2000–2500 kg of wet matter per hectare per year (Malheiro et al., 2013; Fernández-Lobato et al., 2024) and require proper management. The conversion of this biomass waste into biochar can be a promising sustainable valorisation strategy to mitigates fire hazards and other environmental impacts but also to facilitate the recovery and recycling of essential nutrient which can be reintroduced into the soil promoting a circular economy approach for olive waste management (Panić et al., 2025; Pinto et al., 2022). The main objective of this research is to study the potential of biochar derived from olive tree pruning waste as a soil amendment, focusing on evaluating its efficacy as fertilizer and effect on hydrophysical soil properties. To achieve this, three biochars were prepared at pyrolysis temperatures of 350 °C, 500 °C and 700 °C. Biochars were widely characterized and applied as amendments to a Mediterranean nutrient-deficient soil. The effect on the turfgrass growth, nutrient content and chemical, biological and hydrophysical soil properties were evaluated. Turfgrass was selected because is widely used in urban landscapes and sports fields requiring high inputs of water and fertilizers to maintain quality. Investigating biochar impact on turfgrass growth can provide valuable insights into more environmentally friendly management practices.

2. Materials and methods

2.1. Biochar preparation

Olive pruning residue (leaves and stems) was collected in the province of Ávila (Spain). The residue was dried and ground lower than 5 cm. Three biochar were prepared as follows: For each treatment, approximately 20 g of olive pruning waste were taken and placed in a closed nickel cup inside an electrical furnace (Heron model). Slow pyrolysis was carried out under oxygen-limited conditions, with restricted air access provided by the closed cup, at 3 °C/min heating rate until three final temperatures: 350, 500 and 700 °C were reached and final temperature was maintained for 1 h, giving rise to B-RO-350, B-RO-500 and B-RO-700, respectively. Yield of the pyrolysis process was calculated from the final weight of biochar produced and the initial weight of waste introduced into the furnace.

2.2. Biochar characterization

The pH and electrical conductivity (EC) were determined in a water suspension (4 g L⁻¹) using a pHmeter (Bante Instruments) and a conductimeter XS COND 5110 (XS Instruments), respectively.

The specific surface area (S_{BET}) of biochars was determined by N₂ adsorption-desorption isotherms using an ASAP 2420 Micrometrics porosimetry system. Samples were degassed under vacuum at 150 °C for 12 h before analysis in order to exclude moisture and volatile contaminants. Volatile matter (VM), ash content and fixed carbon (FC) for the biochars were determined by thermogravimetric analysis (TGA) using a Lasbys Setaram instrument. About 20 mg of each sample were heated at 20 °C min⁻¹ up to 600 °C under a nitrogen atmosphere (40 mL min⁻¹). At this temperature, air was introduced until a constant weight was reached. The weight loss between 30 and 150 °C was attributed to moisture content, between 150 and 600 °C to VM, and the final weight corresponded to ash content. FC was calculated by difference.

Scanning electron microscopy analysis of biochars was performed using a Phenom ProX SEM (Thermo Fisher Scientific).

The total metal content was obtained by acid digestion using 0.5 g of biochar, HNO₃, and HCl (3:1 v/v), in Teflon containers using a sample preparation block system (SPB Probe, Perkin – Elmer). It was then quantified by inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Scientific iCAP PRO, USA).

The water-soluble fraction of metals from the biochars samples over short- and medium-term periods was determined using double-deionized water. The extraction was performed by thoroughly, 0.5 g of the biochars samples was stirred with 20 mL of water, the suspension of biochar and water was subjected to continuous stirring for two distinct contact times, 2 h (short term) or 24 h (medium term). Following agitation, the suspensions were centrifuged (4500 rpm for 15 min). The resulting supernatant was filtered for subsequent determination of water-soluble metal concentrations, determined by ICP-OES (Thermo Scientific iCAP PRO, USA).

The bioavailable metal fraction in the different biochar samples was determined following the method proposed by Lindsay and Norvell (1978) for soil analysis, with slight modifications for its application to biochar samples. The extracting agent consisted of an aqueous DTPA-TEA (diethylenetriaminepentaacetic acid-triethanolamine), solution prepared with 5×10^{-3} M diethylenetriaminepentaacetic acid (DTPA), 0.01 M calcium chloride (CaCl₂), and 0.1 M triethanolamine (TEA), adjusted to pH 7. For the extraction, 0.5 g of each biochar sample was suspended in 20 mL of the extracting solution and shaken for 2 h. After extraction, the suspensions were filtered, and the concentrations of the bioavailable metals in the extract were determined by ICP-OES (Thermo Scientific iCAP PRO, USA).

The mobile metal fraction in the biochar samples was quantified using a single-step extraction with 0.01 M CaCl₂, following the procedure described by Houba et al. (2000), with slight adjustments for its application to biochar samples. The extraction was performed by accurately weighing 0.06 g of each biochar sample and adding 10 mL of the 0.01 M CaCl₂ solution. The suspensions were subjected to continuous mechanical agitation for 2 h. After extraction, the samples were centrifuged and the supernatants were subsequently filtered. The metal concentration in the resulting extract were determined by ICP-OES (Thermo Scientific iCAP PRO, USA).

Hydrophysical characterization of the biochar, was conducted using the standard Richards Pressure Plate Apparatus (Richards, 1954). The biochar samples were carefully placed into rubber rings set directly on the pressure plate membranes corresponding to 1/3 kPa (FC) and 15 kPa (PM). Under these conditions, the membranes were saturated and subsequently placed into pressure pots adjusted to their respective pressures for 24 h to allow equilibrium. Following the equilibration period, the biochar samples were transferred and dried in an oven at 105 °C for 24 h until constant weight. The available water (AW), expressed as percentage. All measurements were conducted in triplicate for each biochar

sample.

2.3. Selection, preparation and characterization of soil

Selected soil was characterized as follows: The initial pH and electrical conductivity (EC) were determined using a soil:water ratio of 1:2.5 (g mL^{-1}) with a pHmeter BANTE instrument in the case of pH (Thomas, 1996) and a XS COND 510 conductivimeter (Rhoades, 1996) in the case of EC. Organic carbon (C_{oxi}) oxidized with dichromate was determined by the Walkley–Black method (Nelson & Sommers, 1996). Kjeldahl nitrogen content ($\text{N}_{\text{Kjeldahl}}$) was done by Kjeldahl's method (Bremner, Sparks, 1996) and the phosphorous (P) was analyzed with Shimadzu UV-1203 UV spectrophotometer at 430 nm using Olsen's method (Watanabe and Olsen, 1965). The soil metal content was determined with the same methodology described for the analysis of the biochar using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Thermo Scientific iCAP PRO, USA). Finally, the soil texture was determined following the methodology of Bouyoucos (Bouyoucos, 1962). All analyses were performed in triplicate.

The soil classified as a haplic Cambisol, was collected in central Spain and its main properties are summarized in Table 1. This soil is representative of many regions of the Mediterranean landscape. It has a sandy loam texture, acid pH (6.39) and moderately high organic matter content (3.19%).

2.4. Turfgrass growth experiments

Selected soil (S) was amended with 5% (w/w) of biochar, a rate selected based on previous studies reporting the use of similar application rates under controlled soil conditions (Méndez et al., 2012; Paz-Ferreiro et al., 2015; Velez et al., 2018) and under field conditions (Christou et al., 2022). The biochars used were B-RO-350, B-RO-500 and B-RO-700, producing the soil treatments S-RO350, S-RO-500 and S-RO-700, respectively. The selected soil (S) without biochar addition was also included as control. For all soil treatments, the biochar and soil were thoroughly mixed by manual homogenization, and 100 g of soil were placed in each container. The containers measured $10 \text{ cm} \times 6.2 \text{ cm} \times 6.2 \text{ cm}$. The turfgrass species used was *Lolium perenne*, and the seeding density was 40 g m^{-2} (equivalent to 400 kg ha^{-1}). Each treatment was replicated three times, following a randomized block design. The samples were incubated during 42 days at 21°C under alternating light–dark cycles of 12 h light/12 h dark.

The analysis of biomass growth was conducted during 42 days,

during which the aerial biomass was harvested every 7 days to determine the fresh mass, oven-dried at 80°C for 24 h, and weighed again to determine dry mass. At the end of the experiment, the remaining plant material was weighed, and both shoots and roots were carefully washed with abundant distilled water to remove adhering soil particles.

The total metal concentration in the turfgrass samples was determined following acid digestion. A 0.5 g of samples was digested using a 10 mL acid mixture of 65% HNO_3 and 48% HCl (Almendros et al., 2015). The final elemental concentration in the aqueous extracts was determined by ICP-OES (Thermo Scientific iCAP PRO). The quantified elements included heavy and trace metals, Zn, Pb, Ni, Cr, Mn, Fe, Cu, Co, Li, alongside alkaline and alkaline earth elements Ca, Mg, K, Na and nutrients like P. Concentrations were reported in mg/kg .

2.5. Soil characterization

After 42 days of incubation, 10 g of each soil sample were collected from pots used for the turfgrass growth experiment, of these 5 g were subjected to chloroform fumigation, while the remaining 5 g were used as non-fumigated controls. Fumigated samples were placed in a desiccator containing 60 mL of chloroform and evacuated to -60 mb for 2 h, followed by a 24-hour exposure period. Thereafter, residual chloroform was removed under an extractor hook for 1 h. Both fumigated and non-fumigated samples were extracted with 25 mL of 0.5 M K_2SO_4 by shaking for 30 min and filtered. A 5 mL aliquot of each extract was oxidized with 5 mL of 0.1 N $\text{K}_2\text{Cr}_2\text{O}_7$ and 5 mL of concentrate H_2SO_4 , incubated at 105°C for 90 min, and titrated against 0.2 N Mohr's salt using o-phenanthroline as an indicator. Microbial biomass C was calculated as the difference between fumigated and non-fumigated extracts, applying a correction factor ($\text{Kc} = 0.45$) as proposed by Vance et al. (1987).

Total nitrogen (N) was determined in soils samples amended with biochar after turfgrass growth, was determined using the Kjeldahl method, 0.8 g of soil was digested with 10 mL of concentrated H_2SO_4 and a catalytic paste containing K_2SO_4 and CuSO_4 (10:1 w/w) at approximately 380°C until a clear digest was obtained. The solution was subsequently made alkaline with NaOH (40%) and distilled using a BUCHI Multikeyl unit coupled to a 702 SM Titrino for automated ammonia collection and titration with 0.01 N HCl.

pH and EC in the were determined at a ratio 1:2.5 (Thomas 1996; Rhoades, 1996).

2.6. Statistical analysis

For statistical analysis, SPSS 15.0 software was used. Initially, the means and standard deviation of the data were estimated. The assumptions of normality and homogeneity of variances were verified. Subsequently, an analysis of variance (ANOVA) was applied to verify significant differences between the means. For multiple comparisons, Duncan's test was employed, and differences were considered statistically significant at a 95% confidence level ($P < 0.05$).

3. Results and discussion

3.1. Biochar properties

Table 2 shows the main characteristics of the three biochars prepared by pyrolysis of selected olive pruning waste (B-RO-350, B-RO-500 and B-RO-700). As expected, the C (%) content increases and the H content (%) decreases with increasing pyrolysis temperature due to carbonization/polymerization reactions that take place during pyrolysis. Consequently, the H/C ratio decreases from 0.75 for B-RO-350–0.21 for B-RO-700 indicating a progressive increase in the degree of aromaticity and, consequently, greater stability of the biochar prepared at higher temperatures. This trend is also reflected in the oxygen O (%) content, which decreases drastically from 14.67% in B-RO-350–7.84% for B-RO-500

Table 1
Selected soil characterization.

Properties	Value
pH	6.39
EC ($\mu\text{S/cm}$)	31
MOT (%)	3.19
C_{org} (%)	0.72
OM_{ox} (%)	1.24
N (%)	0.02
P (mg/kg)	103
K (mg/kg)	3408
Cu (mg/kg)	0.06
Ni (mg/kg)	0
Zn (mg/kg)	0
Cr (mg/kg)	0
Cd (mg/kg)	0
Pb (mg/kg)	0
Sand (%)	28
Silt (%)	64
Clay (%)	8
Texture	Loam
Field capacity (%)	20.7
Wilting point (%)	11.2
Available water (%)	9.4

Table 2

Main characteristics of biochars.

Biochar	C (%)	H (%)	N (%)	S (%)	O (%)	Ash (%)	H/C	O/C	FC (%)	VM (%)	pH	EC ($\mu\text{S cm}^{-1}$)	S_{BET} (m^2g^{-1})	Porosity (%)	Average pore diameter (volume, nm)	Average pore diameter (area, nm)
B-RO-350	66.95	4.21	1.85	0.00	14.67	12.3	0.75	0.16	64.13	22.96	8.0a	140a	4.5	59.28	7039	35.46
B-RO-500	72.30	2.68	1.59	0.00	7.84	15.6	0.44	0.08	71.56	12.28	8.2a	310b	30.2	63.87	5233	26.15
B-RO-700	74.63	1.29	1.24	0.00	1.85	21.0	0.21	0.02	74.01	4.28	8.7b	335b	284.7	64.06	3771	21.77

For the same metal, different letters indicate statistically significant differences ($P < 0.05$) by Duncan test

and 1.85% for B-RO-700. This suggests that while devolatilization is significant at 500 °C, the biochar structure still retains a substantial fraction of oxygen-containing functional groups. Oxygen reduction is expected due to the devolatilization and decomposition of oxygen-containing functional groups, such as carboxyl and carbonyl groups, which are released as CO, CO₂, and H₂O at high temperatures, resulting in a decrease in the O/C ratio from 0.16 for B-RO-350–0.02 for B-RO-700 (Gascó et al., 2025). This evolution in elemental composition directly influences the proximate analysis of biochar. Increasing pyrolysis temperature leads to a significant loss of VM, which is reduced from 22.96% for B-RO-350–4.28% for B-RO-700, while the FC content increases rising from 64.13% for B-RO-350–74.01% for B-RO-700 (Gascó et al., 2018). Furthermore, the ash content also increases from 12.3% for B-RO-350–21.0% in B-RO-700, due to the concentration of inorganic components as the organic matter is volatilized (Gasco et al., 2025, Muzyka et al., 2023).

Regarding the surface properties, the pH of the biochars prepared from the pyrolysis of olive pruning wastes is alkaline, with values increasing with temperature from 8.0 to 8.7. This pH increase with pyrolysis temperature is commonly attributed to the decomposition of acidic functional groups (decarboxylation) and the concentration of alkaline salts and inorganic carbonates in the resulting biochar (Gascó et al., 2025, Mendez et al., 2013). The electrical conductivity (EC) shows a significant increase, rising from 14 $\mu\text{S cm}^{-1}$ (B-RO-350) to 335 $\mu\text{S cm}^{-1}$ (B-RO-700), reflecting the concentration of soluble salts and minerals in the solid residue with increasing pyrolysis temperature (Gascó et al., 2018). Finally, the specific surface area (S_{BET}) also increases with temperature. A significant increase for pore development is observed at 500 °C, where S_{BET} increases seven-fold from 4.53 m^2g^{-1} for B-RO-350–30.18 m^2g^{-1} for B-RO-500. The maximum S_{BET} value of 284 m^2g^{-1} was achieved for B-RO-700. This is a relatively high value for a biochar that has not been chemically or physically activated. SEM micrographs of the biochars (Fig. 1) shows the heterogeneous structure with the presence of large cavities formed during pyrolysis process. The brighter regions correspond to mineral compounds, indicating that the mineral fraction originally present in the feedstock becomes concentrated during pyrolysis, with mineral phases segregated from the carbonaceous structure and deposited on the carbonaceous surface.

Table 3 shows the elemental composition of three biochars. All three samples showed high contents of macronutrients calcium (Ca) and potassium (K), followed by magnesium (Mg) and sodium (Na). Biochars exhibit a high calcium (Ca) content that increases with temperature (from 27.3 g kg⁻¹ to 54.1 g kg⁻¹) which may be related to the concentration of the mineral fraction in the ash during pyrolysis and with values comparable to those of manure biochars prepared at 350 and 700°C (22.7–61.5 g kg⁻¹) (Cantrell et al., 2012). This content is higher than that reported for other biochars from different feedstocks. For example, sewage sludge derived biochars that are typically characterized by high Ca concentrations reaching up to 20.8–24 g kg⁻¹ (Goncalves et al., 2026; Figueiredo et al., 2021). Potassium (K) is frequently considered one of the most labile and plant available cations in biochar. Potassium values ranged from 5.8 to 10.4 g/kg for B-RO-350 to B-RO-700. These values are similar to those reported for biochars

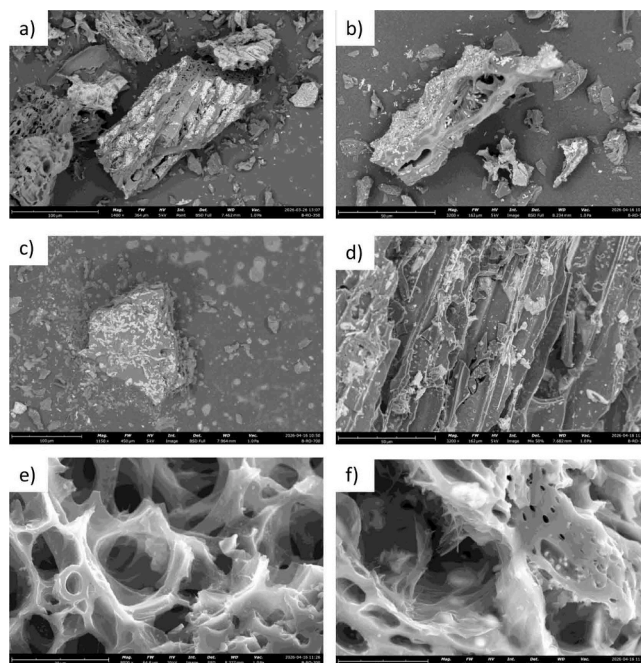


Fig. 1. SEM-EDX micrographs of olive pruning-derived biochars: a) B-RO-350, b) B-RO-500 and c), d), e) and f) B-RO-700.

prepared from other lignocellulosic biomass (Wang et al., 2022), higher than those reported for biochars from sewage sludge (Goncalves et al., 2026), but lower than those reported for of manure wastes (Cantrell et al., 2012; Cely et al., 2015). Sodium (Na) and magnesium (Mg) contents ranged from 2.7 to 2.8 g/kg for B-RO-350–5.1–5.6 g/kg for B-RO-700, respectively. These values are lower than those reported for biochars prepared from different manure wastes (Cantrell et al., 2012) but higher than those obtained from other lignocellulosic biomass such as corn stalk or spruce wood (Wang et al., 2022). In conclusion, the analysis of Ca, Mg, Na and K contents highlight the potential of biochar derived from olive tree pruning wastes as a potential source of essential plant nutrient. Additionally, quantification of total metal concentration was performed in order to determine the concentration of some micronutrients and potential pollutants. The total metal content increased with rising pyrolysis temperature, consistent with the enrichment of the mineral fraction resulting from the progressive loss of volatile organic matter. All three biochars showed relatively low concentrations of lead (Pb), nickel (Ni), and chromium (Cr), which may indicate a low contribution of these elements to the potential risk of soil contamination. The three biochars showed concentration of some micronutrients such as zinc (Zn) (34.1–76.1 mg kg⁻¹), copper (Cu) (23.1–44.5 mg kg⁻¹), manganese (Mn) (26.31–45.9 mg kg⁻¹) or iron (Fe) (166–391 mg kg⁻¹) suggesting that olive biochar could provide these elements when applied to soils with corresponding nutrient deficiencies.

Table 3

Total metal content of biochars.

Biochar	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)	Na (g kg ⁻¹)	K (g kg ⁻¹)	Zn (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Co (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Ni (mg kg ⁻¹)	Cr (mg kg ⁻¹)	Li (mg kg ⁻¹)
B-RO-350	27.3 ± 1.5a	2.8 ± 0.2a	2.7 ± 0.2a	5.7 ± 0.8a	34.1 ± 1a	26.3 ± 2.9a	166 ± 15a	23.1 ± 3.0a	24.4 ± 2.2a	1.42 ± 0.61a	1.5 ± 0.1a	2.3 ± 0.2a	1.6 ± 0.5a
B-RO-500	35.22	3.8	3.0	8.3	61.4	34.0	252	37.5	26.2	1.63	2.8	3.8	3.5
B-RO-700	54.1 ± 2.1b	5.6 ± 0.2b	5.1 ± 0.3a	10.4 ± 0.9b	76.7 ± 3.8b	45.9 ± 2.2b	391 ± 10b	44.5 ± 4.4b	14.5 ± 2.0a	2.75 ± 0.06b	3.0 ± 0.3b	3.8 ± 0.5b	2.8 ± 0.1b
B-RO-700	54.1 ± 2.7c	5.6 ± 0.2c	5.1 ± 0.4b	10.4 ± 0.7c	76.7 ± 6.9c	45.9 ± 2.2c	391 ± 16c	44.5 ± 8.1c	14.5 ± 2.8d	2.75 ± 0.54c	3.0 ± 0.1b	3.8 ± 0.4b	2.8 ± 0.5c

For the same metal, different letters indicate statistically significant differences ($P < 0.05$) by Duncan test

Understanding metal speciation in biochars is essential, as it governs their mobility, toxicity, availability for plants and environmental behaviour (Zhao et al., 2026). Several methodologies have been studied. In our case, water soluble fractions after two extraction times (2 and 24 h), plant-available fraction (DTPA extraction) and mobile fraction (CaCl₂ extraction) were determined (Table 4). The metals present in biochar may not be entirely available for plant uptake. The DTPA extractable method can be used to estimate potentially plant-available fraction of metals, as it has the capacity to chelate a wide range of metallic elements. In our study, there were not significant differences the DTPA-extractable metal contents of the three biochar for Ca, Na, Zn, Cu, Pb, Ni, Cr and Li. Mg, Fe, K and Mn DTPA extracted increased with pyrolysis temperature (Lu et al., 2013; Zhang et al., 2013). This fact pattern may be related to the separation of the biochar carbon matrix and the mineral-rich ashes observed in Fig. 1. In contrast Zhao et al. (2026) observed that the DTPA-extractable fractions of metals tend to decline with rising pyrolysis temperature, particularly above 650 °C although this trend may depend on the feedstock and the specific metal considered (Wang et al., 2021; Méndez et al., 2012).

With respect to the mobile metal fraction determined by CaCl₂ extraction there was an increment in the Mg, Ca and K content with pyrolysis temperature while there was no significant effect for Na, Mn, Fe, Cu, Co, Pb, Ni and Li. Finally, regarding water-soluble metals, an overall increase in solubility was observed when the extraction time increased from 2 to 24 h for most elements, including K, Zn, Fe, Cu, and Co. This behaviour is consistent with progressive dissolution and/or desorption processes during prolonged contact with water, suggesting that longer equilibration periods promote the release of soluble metal fractions from the biochar matrix (Kolodnyńska et al., 2012). In contrast, soluble Na exhibited a decrease in concentration from 2 to 24 h of extraction. This unexpected trend may be attributed to secondary processes such as re-adsorption onto biochar surfaces, ion exchange with other cations released into solution, or the formation of less soluble

sodium-bearing phases over time (Yang et al., 2024). However, these mechanisms cannot be distinguished based on the extraction data alone. These results highlight the importance of clearly defining extraction conditions, particularly extraction time, when assessing water-soluble metals in biochars, as variations in methodology may significantly influence the measured concentrations.

The total phosphorus (P) concentrations ranged from 2.908 g kg⁻¹ to 4.460 g kg⁻¹ for B-RO-350 and B-RO-750, respectively (Fig. 2). These values were lower than those reported for biochars from sewage sludges or manures (Raccek et al., 2019; Wang et al., 2022). However, the total P concentration falls within the range reported for biochar prepared from different lignocellulosic wastes, which ranges from 1.5 g kg⁻¹ (rice husk biochar) to 32 g kg⁻¹ (sugarcane mill mud biochar). In accordance with the other inorganic components, the concentration of P in biochar increases with pyrolysis temperature which may be related to its concentration in the ash fraction. However, only total P was determined in the present study, and therefore its plant availability cannot be directly established from these data. Not all the P present in biochar is soluble when it is added to soil. This P retention can be beneficial for reducing P runoff, but it also means the P contained in biochar may be less immediately plant-available than in conventional fertilisers (Yadav et al., 2026). Therefore, the potential contribution of these biochars to plant P availability should be considered indirect and would require specific P availability or plant uptake measurements to be confirmed.

Finally, Fig. 3 shows the XRD analysis of biochars, indicating that the main components are predominantly amorphous, with an increasing amount of calcite with increasing pyrolysis temperature. The broad diffuse band between 15° and 30° indicates the presence of amorphous carbon in the biochar (Fig. 3). At 350 °C, the presence of residual cellulose (cel) is observed, with its peaks disappearing at higher temperatures.

Finally, to complete the evaluation of the potential application of the biochars from olive pruning waste as soil amendments, the

Table 4Metal content of biochars (mg kg⁻¹) after different extraction.

Soluble metal content after 2 h of extraction													
	Ca	Mg	Na	K	Zn	Mn	Fe	Cu	Co	Pb	Ni	Cr	Li
B-RO-350	974a	298ab	2300c	1867ab	12 cd	1.6a	8a	3.4ab	6.2c	0.37a	0.56bcd	ip	0.2a
B-RO-500	1591b	383abc	3517 f	3783d	11c	1.8a	11ab	3.7ab	5.7c	0.23a	0.38abc	ip.	0.3a
B-RO-700	1316b	479c	2365c	5797e	11 cd	1.0a	5a	2.3a	6.1c	0.11a	0.14ab	ip. ²	0.2a
Soluble metal content after 24 h of extraction													
B-RO-350	991a	290ab	978b	3180 cd	16.3 h	6 cd	19bc	9.8c	15d	0.42a	0.71 cd	ip	0.3a
B-RO-500	1843b	259a	1078b	5363e	29e	2.8ab	24 cd	10c	14.6d	0.22a	0.79d	ip	ip
B-RO-700	974ab	368ab	867b	8010 g	24e	2.8ab	10a	8.4c	15.5d	0.62a	0.42abc	ip.	ip
Plant-available content (DTPA extraction)													
B-RO-350	9587c	331ab	409a	1733a	2a	2.1a	5.2a	1.3a	1.4b	0.13a	0.03a	0.58a	0.14a
B-RO-500	9568c	420bc	352a	2587bc	5ab	3.5abc	8.5a	1.7a	1.2b	0.16a	0.12ab	0.33a	0.16a
B-RO-700	9616c	880e	410a	3316c	15.4d	13.9e	31.3d	3.2ab	ip	0.2a	0.09ab	0.23a	0.23a
Mobile metal content (CaCl ₂ extraction)													
B-RO-350	19398d	659d	2439 cd	3645d	8.5bc	5.2bc	3.9a	4.0ab	7.0c	0.21a	ip	1.8d	1.1bc
B-RO-500	27526e	690d	2297c	5275e	7.1bc	5.2bc	3.2a	3.6ab	6.7c	0.24a	0.009a	1.0c	0.9b
B-RO-700	38130 f	1723 f	2562 cd	7192 f	8.5bc	8d	4.7a	3.4ab	6.8c	0.18a	0.022a	1.2d	1.1bc

¹For the same metal, different letters indicate statistically significant differences ($P < 0.05$) by Duncan test. ²metal content in below detection level

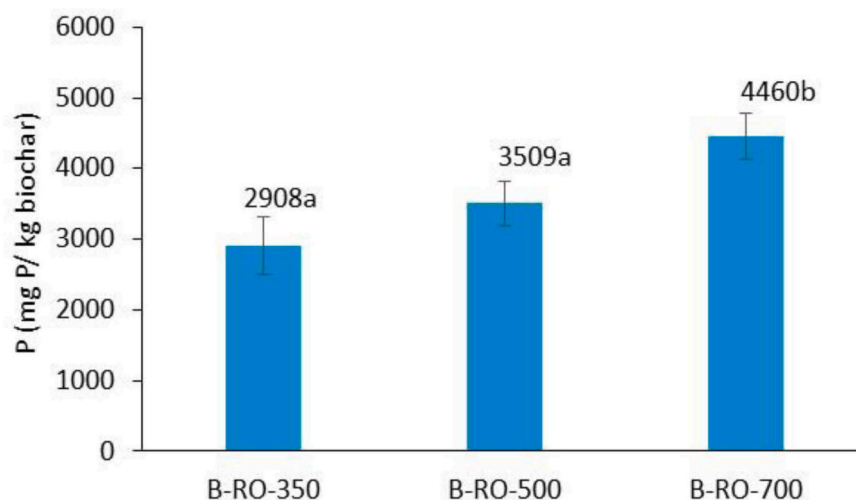


Fig. 2. Total P content of the olive pruning-derived biochars.

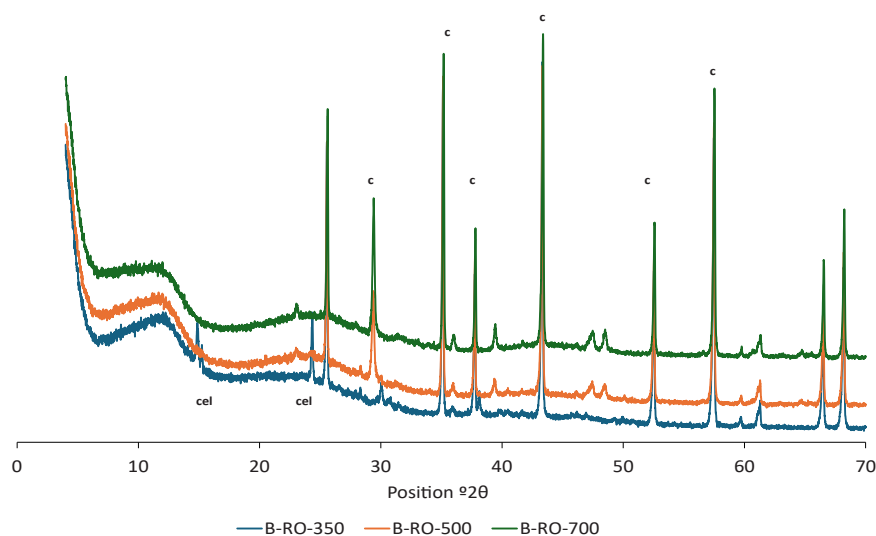


Fig. 3. X-ray diffraction patterns (XRD) of the olive pruning-derived biochars.

hydrophysical properties of three biochars were evaluated. As shown in Table 5, biochar B-RO-700 exhibits the highest $H_{1/3}$ kPa, H_{15} kPa and AW values, indicating that this biochar presents the most favourable hydrophysical properties. Indeed, the AW content in B700 is a 59.5% higher than in the other two biochars according to the increment of the pyrolysis temperature. This fact is according to Gascó et al. (2018) who described an increment on AW with the increment of temperature due to an increased in the pore volume of biochar between 200 and 30000 nm which is the pore range related with the water retention between 1/3 and 15 KPa.

Table 5

Biochar water content at 1/3 kPa $H_{1/3}$ kPa, 15 kPa H_{15} kPa and available water (AW).

	$H_{1/3}$ kPa (%)	H_{15} kPa (%)	AW (%)
B350	48.1 ± 3.3a	34.5 ± 2.1a	13.6 ± 2.1a
B500	64.7 ± 1.0b	49.5 ± 3.6b	15.2 ± 4.6a
B700	73.6 ± 1.4c	51.3 ± 1.0b	21.7 ± 2.3b

3.2. Evaluation of turfgrass growth in soil

Fig. 4 shows the evolution of the fresh (4.a) and dry (4.b) weight of the above ground part of the turfgrass. The addition of all three olive-pruning-waste-derived biochars increased turfgrass production compared to the control soil as follows:

Wet biomass: Control < SB-RO-350 (+3.8%) < SB-RO-500 (+21.2%) < SB-RO-700 (+26.2%)

Dry biomass: Control < SB-RO-700 (+17%) < SB-RO-500 (+20.8%) < SB-RO-350 (+41.9%)

The magnitude of this increase depends on the type of biochar. Fresh turfgrass weight is higher in soil amended with B-RO-700 biochar, whereas the increase in dry turfgrass weight is greater in soil amended with B-RO-350 biochar. This difference between fresh and dry biomass is relevant because fresh weight is strongly influenced by plant water content, whereas dry weight provides a better indication of actual biomass accumulation. Thus, the higher fresh biomass obtained with B-RO-700 may be partly related to greater water availability, while the greater increase in dry biomass observed with B-RO-350 suggests a stronger effect on actual plant biomass production.

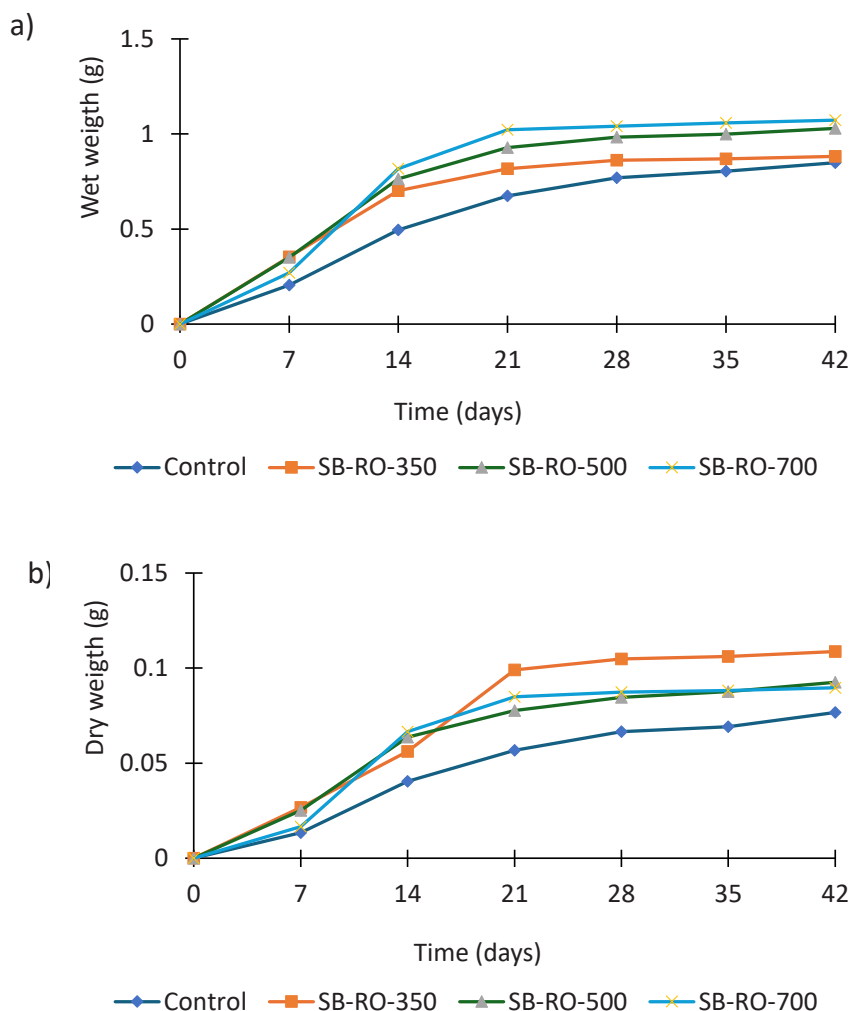


Fig. 4. Evolution of the fresh (3.a) and dry weight (3.b) of the above ground part of the turfgrass.

This result appears to be related to the hydrophysical properties of the biochars summarised in Table 5, as biochar B-RO-700 provides greater plant-available water, which may translate into a higher fresh weight of the turfgrass. Pyrolysis at 700 °C not only increases microporosity and S_{BET} (Table 1) but also promotes greater macroporosity (Fig. 1.e and 1.f), resulting in a porous structure that may contribute to the greater plant-available water observed for B-RO-700 (Table 5) as biochar porosity and specific surface area have been identified as important factors influencing soil water retention and available water content (Edeh et al., 2000). The greater plant-available water associated with B-RO-700 may therefore improve water supply to the turfgrass and contribute to the higher fresh biomass observed under this treatment. This effect may be particularly relevant for turfgrass, whose growth and quality are strongly dependent on adequate water availability. Previously, Gascó et al. (2018) described increment in turfgrass yield after partial peat replacement by pinewood biochar attributing this fact to the improvement of water holding capacity and nutrients contents as N. This finding is consistent with the present results, supporting the potential role of improved water retention and nutrient availability in the positive response of turfgrass to biochar addition. Indeed, the addition of biochar increased the N soil content (Fig. 5a). The increase in soil N may have contributed to the greater biomass production observed in the amended soils, as N availability is a key factor controlling turfgrass growth. Indeed, the analysis of nutrient content in the turfgrass (Table 6) shows that the addition of the three olive pruning biochars increased the K, P and Fe content in the aerial part that can contribute to turfgrass growth.

Potassium plays an important role in plant water relations and several physiological processes related to plant growth (Sardans and Peñuelas, 2021), phosphorus is essential for energy metabolism and plant development (Liu, 2021), and iron is involved in several metabolic and photosynthetic processes (Kobayashi et al., 2019). Therefore, the increased uptake of these nutrients may have contributed to the positive growth response observed following biochar application. There was not observed differences on the Ca, Mg, or Na contents. Regarding micronutrients as Zn and Cu, the highest content was obtained after the addition of B-RO-350 biochar. This result suggests that the effect of biochar addition was not simply a general increase in the uptake of all nutrients, but depended on the specific nutrient and biochar properties. Finally, the addition of biochar has other effects on soil properties that can contribute to highest turfgrass growth, such as an increase in pH, from 5.8 in the control soil to 8.3 in soil amended with B-RO-700 biochar (Fig. 5b). The increase in pH reflects the alkaline character of the biochars and may have contributed to the improvement of soil conditions for turfgrass growth by modifying nutrient availability and reducing the constraints associated with the initial acidic soil. However, the relationship between pH and nutrient availability is complex, and the higher pH observed for B-RO-700 should be considered when interpreting its effects on plant nutrient uptake. In addition, electrical conductivity (EC) is below the values to have a negative effect on plants (Fig. 5c). Overall, the results indicate that the positive effect of olive pruning-derived biochars on turfgrass growth is likely to result from the combined effects of water availability, nutrient supply and modification of soil

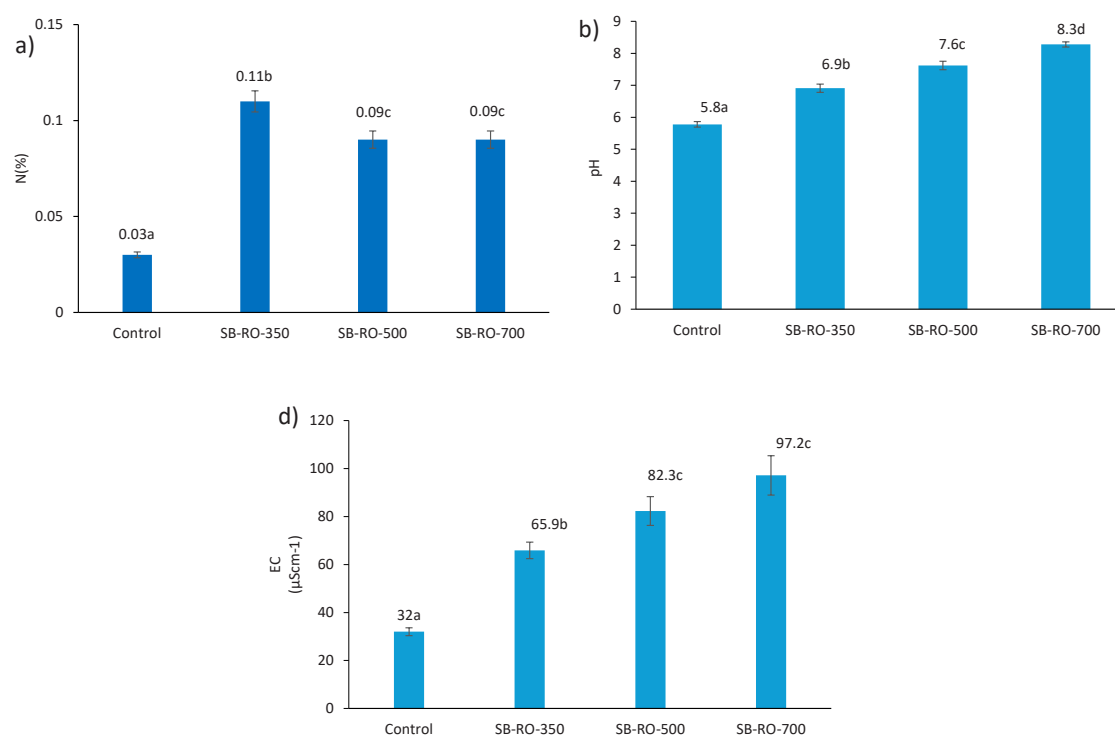


Fig. 5. Nitrogen content (5.a), pH (5.b) and electrical conductivity (5.c) of soil amended with biochars.

Table 6

Total metal content (mg/kg) in the aerial part of turfgrass after 42 days of growth.

Biochar	Ca	Mg	Na	K	P	Zn	Mn	Fe	Cu	Pb	Ni	Cr	Li
Control	9393b	3581ab	1936b	9048a	15913a	59.9a	52.2b	388.6a	28.7a	1.4ab	5.7a	1.9a	2.1b
B-RO-350	8754b	3148a	1156a	13212b	21135b	139.4b	51.2b	950.4c	182.7b	1.6b	6.0a	3.5b	3.7b
B-RO-500	7060a	2905a	1173a	12913b	19637b	49.8a	40.2ab	466.5ab	29.6a	0.6a	5.3a	1.7a	1.0a
B-RO-700	6022a	3011a	1671b	12887b	20833b	55.5a	34.3a	534.6b	31.1a	0.8a	5.8a	1.9a	0.8a

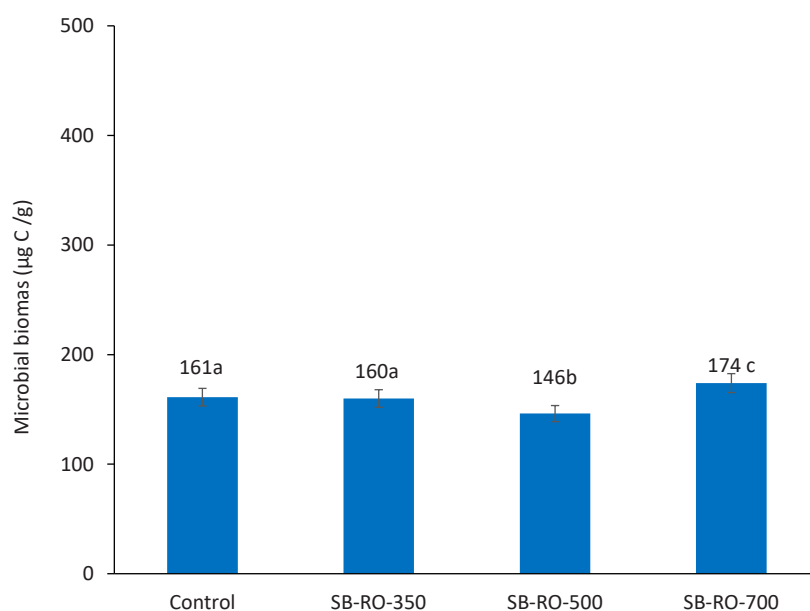


Fig. 6. Microbial biomass in soil amended with olive pruning-derived biochars.

chemical conditions, rather than from a single biochar property. The contrasting responses of fresh and dry biomass further suggest that the relative contribution of these mechanisms depends on pyrolysis temperature.

3.3. Evaluation of microbial biomass of soils

After the turfgrass had grown, the soil microbial biomass was evaluated. At the end of the experiment (Fig. 6), the soil amended with B-RO-750 showed an 8% higher microbial biomass than the control soil. This result is consistent with previous findings reported by Liang et al., (2010), who concluded that carbon can alter the cycling of non-black carbon in soil, and by Paz-Ferreiro et al. (2012) who found similar results after the addition of biochar derived from sewage sludge. However, no significant differences were observed between soils amended with B-RO-350 or B-RO-500 and the control soil. The differences in soil microbial biomass observed among the soils amended with the three biochars may be related to differences in the physicochemical properties of the biochars. Previous studies have shown that the effects of biochar on soil microorganisms depend on biochar properties (Li et al., 2020), including surface chemistry, porosity, pH and nutrient availability, which can be influenced by pyrolysis temperature (Lehmann et al., 2011; Paz-Ferreiro et al., 2015). In particular, changes in biochar pore structure can provide new habitats for microbial colonization and affect microbial abundance and community structure (Yang et al., 2022). Pyrolysis temperature can also modify the availability of labile carbon and nutrients, potentially influencing microbial growth and nutrient-use efficiency (Guo et al., 2020). Therefore, the higher microbial biomass observed with B-RO-750 may be associated with its physicochemical properties, such as its higher surface area and porosity (Table 2).

4. Conclusions

This research highlights the potential of olive pruning residues as a feedstock for biochar production with temperature-dependent agronomic performance.

Although biochars have a considerable amount of nutrients, not all of them are absorbed by the turfgrass during the experimental period. Amendment of soil with biochars increases the K, Fe, and P contents in the turfgrass, but not those of Ca, Mg, or Na. Concentrations of micronutrients (Zn and Cu) were higher in turfgrass grown in soil amended with biochar produced at 350 °C. However, this increase is not necessarily associated with greater bioavailability or mobility of these metals in biochars.

Although all biochar amendments significantly increased soil nitrogen content, pH, and electrical conductivity, microbial biomass increased only in soil amended with biochar produced at 700°C. This selective biological response suggests that changes in soil chemistry alone do not fully explain the observed microbial response.

All biochar amendments increased turfgrass biomass compared with the control, although the magnitude of the response depended on pyrolysis temperature, with biochar produced at 350°C producing the greatest increase in dry biomass and biochar produced at 700°C the greatest fresh biomass.

Overall, olive pruning residues proved to be a valuable feedstock for biochar production, yielding amendments with the potential to improve soil chemical, biological, and hydrophysical properties and to enhance the availability and uptake of selected nutrients by turfgrass. The results further indicate that the effects of biochar are strongly influenced by the physicochemical properties developed during pyrolysis, highlighting pyrolysis temperature as an important factor determining nutrient dynamics, microbial responses, and hydrophysical performance in the soil-plant system.

These findings suggest that pyrolysis temperature can be selected according to the intended agronomic function of the biochar, providing a basis for tailoring its properties to specific soil and crop requirements

while valorising olive pruning residues as a value-added soil amendment within circular resource management.

Statement of Novelty

The novelty of this study lies in how pyrolysis temperature affects the nutrient availability and agronomic properties of biochar produced from olive tree pruning residues, a less explored agricultural feedstock of biochars despite its high abundance in Mediterranean regions.

CRediT authorship contribution statement

Gabriel Gascó: Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Héctor Mateos:** Resources, Investigation. **Natalia M. Escobar:** Resources, Investigation. **Patricia Almendros:** Writing – review & editing, Validation, Resources, Methodology. **Ana Méndez:** Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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