Short-Term Responses of Mediterranean Forest Leptosols to Organic Amendments: Effects on Soil Physicochemical Properties and Carbon Storage

Fernanda Roverato Moura

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Supervisor:
Prof Dra. Felícia Maria da Silva Fonseca

Co-supervisor:
Prof Dr. Paulo César Conceição

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Abstract

Climate change and soil degradation have intensified the need for sustainable management strategies capable of improving soil quality and enhancing carbon sequestration in terrestrial ecosystems. The present study evaluated the effects of different organic amendments on the physicochemical properties and soil organic carbon dynamics of a Mediterranean forest soil located in northeastern Portugal, one year after the establishment of a permanent experimental field. The experimental design consisted of six treatments: green waste (RV), stabilized compost (CE), and donkey manure (EB), applied at 5 and 10 Mg ha^{-1}, in addition to an untreated control (SO). Soil samples were collected at depths of 0–5 cm, 5–10 cm, and 10–20 cm to evaluate physical and chemical properties, including bulk density, permeability, porosity, soil organic matter, pH, total nitrogen, extractable phosphorus and potassium, soil organic carbon concentration, and soil organic carbon stock. Most soil physical properties remained relatively stable across treatments, although donkey manure and stabilized compost tended to promote lower bulk density and higher porosity and water retention. Significant increases in soil pH were mainly observed under CE10 (Stabilized Compost at 10 Mg ha^{-1}) and EB10 (Donkey Manure at 10 Mg ha^{-1}), indicating reduced soil acidity. Organic amendments also promoted higher trends of soil organic matter, total nitrogen, soil organic carbon, extractable phosphorus, and potassium, particularly in surface layers. EB5 (Donkey Manure at 5 Mg ha^{-1}) and CE10 (Stabilized Compost at 10 Mg ha^{-1}) showed the highest trends for soil organic carbon accumulation in the 0–5 cm layer. Overall, the results suggest that organic amendments, particularly donkey manure and stabilized compost, may contribute to improving soil quality and promoting carbon accumulation in Mediterranean forest soils undergoing ecological restoration.

Keywords: Mediterranean soils, organic amendments, soil organic carbon, ecological restoration, soil quality.

Resumo

As mudanças climáticas e a degradação do solo intensificaram a necessidade de estratégias de manejo sustentável capazes de melhorar a qualidade do solo e aumentar o sequestro de carbono em ecossistemas terrestres. O presente estudo avaliou os efeitos de diferentes emendas orgânicas sobre as propriedades físico-químicas e a dinâmica do carbono orgânico de um solo florestal mediterrânico localizado no nordeste de Portugal, um ano após a instalação de um campo experimental permanente. O delineamento experimental consistiu em seis tratamentos: resíduos verdes (RV), composto estabilizado (CE) e estrume de burro (EB), aplicados nas doses de 5 e 10 Mg ha^{-1}, além de um controle sem aplicação de emendas (SO). Amostras de solo foram coletadas nas profundidades de 0–5 cm, 5–10 cm e 10–20 cm para avaliação das propriedades físicas e químicas, incluindo densidade do solo, permeabilidade, porosidade, matéria orgânica do solo, pH, nitrogênio total, fósforo e potássio extraíveis, concentração de carbono orgânico do solo e estoque de carbono orgânico do solo. A maioria das propriedades físicas permaneceu relativamente estável entre os tratamentos, embora o estrume de burro e o composto estabilizado tenham apresentado tendência de promover menor densidade do solo e maiores valores de porosidade e retenção de água. Aumentos significativos no pH foram observados principalmente nos tratamentos CE10 (dose de 10 Mg ha^{-1}Composto Estabilizado) e EB10 (dose de 10 Mg ha^{-1} de Estrume de Burro), indicando redução da acidez do solo. As emendas orgânicas também promoveram tendências de aumento nos teores de matéria orgânica, nitrogênio total, carbono orgânico do solo, fósforo e potássio extraíveis, especialmente nas camadas superficiais. Os tratamentos EB5 (dose de 5 Mg ha^{-1} de Estrume de Burro) e CE10 (dose de 10 Mg ha^{-1} de Composto estabilizado) apresentaram as maiores tendências de acúmulo de carbono orgânico na camada de 0–5 cm. De modo geral, os resultados sugerem que as emendas orgânicas, especialmente o estrume de burro e o composto estabilizado, podem contribuir para a melhoria da qualidade do solo e para o acúmulo de carbono em solos florestais mediterrânicos em processo de restauração ecológica.

Palavras-chave: solos mediterrânicos, emendas orgânicas, carbono orgânico do solo, restauração ecológica, qualidade do solo.

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List of Acronyms

ANOVA – Analysis of Variance

COP21 – 21st Conference of the Parties

FAO – Food and Agriculture Organization

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC – Intergovernmental Panel on Climate Change

IPMA – Instituto Português do Mar e da Atmosfera

ICNF – Instituto da Conservação da Natureza e das Florestas

NDCs – Nationally Determined Contributions

SAC – Special Area of Conservation

SCS – Soil Conservation Service

UCAR – University Corporation for Atmospheric Research

USDA – United States Department of Agriculture

List of Abbreviations

BD – Bulk Density (g cm^{-3})

C/N – Carbon-to-Nitrogen ratio (dimensionless)

CE – Stabilized Compost

CE5 – Stabilized Compost at 5 Mg ha^{-1}

CE10 – Stabilized Compost at 10 Mg ha^{-1}

CF – Coarse Fragment content (%)

EB – Donkey Manure

EB5 – Donkey Manure at 5 Mg ha^{-1}

EB10 – Donkey Manure at 10 Mg ha^{-1}

ECEC – Effective Cation Exchange Capacity (cmolc kg^{-1})

EG – Coarse Elements / Coarse Fragments (%)

FC – Field Capacity (%)

GHG – Greenhouse Gas

Kf – Final Permeability (cm h^{-1})

Ki – Initial Permeability (cm h^{-1})

MacroP – Macroporosity (%)

MicroP – Microporosity (%)

MWHC – Maximum Water Holding Capacity (%)

PD – Particle Density (g cm^{-3})

RV – Green Waste

RV5 – Green Waste at 5 Mg ha^{-1}

RV10 – Green Waste at 10 Mg ha^{-1}

SO – Original Soil

SOC – Soil Organic Carbon (g kg^{-1})

SOM – Soil Organic Matter (g kg^{-1})

TN – Total Nitrogen (g kg^{-1})

List of Symbols

CO_2 – Carbon dioxide

K – Hydraulic Conductivity (cm h^{-1})

K_2O – Potassium oxide

N – Nitrogen

N_2 – Dinitrogen

N_2O – Nitrous oxide

NH_4^+ – Ammonium

NO_3^- – Nitrate

P – Porosity (%)

P_2O_5 – Phosphorus pentoxide

pH – Potential of Hydrogen (dimensionless)

pH H_2O – Soil pH measured in water (dimensionless)

pH KCl – Soil pH measured in potassium chloride solution (dimensionless)

1. INTRODUCTION

Climate change has intensified scientific and political interest in strategies to reduce atmospheric greenhouse gas concentrations and increase the resilience of terrestrial ecosystems. Among the main challenges associated with this process are rising global temperatures, changes in precipitation patterns, and the increasing frequency of extreme events, all of which are largely linked to anthropogenic activities intensified over recent decades (IPCC, 2023). In this context, the sustainable management of natural resources has become a central component of international climate mitigation policies.

The evolution of international climate governance has reinforced these concerns over the past decades. The adoption of the Paris Agreement in 2015 represented an important milestone by establishing global targets to balance carbon emissions with their removal by natural reservoirs. Within this framework, soil has been increasingly recognized as a strategic component for climate change mitigation due to its high carbon storage potential (Amelung et al., 2020; IPCC, 2023). In parallel, international initiatives such as the “4 per 1000” program, launched during COP21, emphasized the importance of increasing global soil organic carbon stocks by 0.4% per year through sustainable land management practices and the enhancement of soil organic matter as a climate change mitigation strategy (Bruni et al., 2021).

Soils are not only affected by climate change but also actively regulate climate through complex biogeochemical feedback mechanisms. Small variations in soil organic carbon stocks can significantly alter atmospheric carbon dioxide concentrations due to the large amount of carbon stored globally in soils (Lal, 2004; Friedlingstein et al., 2022). Consequently, soil carbon dynamics play a key role in regulating atmospheric CO_2, meaning that soil degradation and management practices can either amplify or mitigate climate change feedbacks.

From an ecological perspective, soil is a highly complex natural system that performs essential functions related to nutrient cycling, water retention, structural stability, and the maintenance of ecosystem productivity. In addition, terrestrial ecosystems play a fundamental role in the global carbon cycle, with soils representing one of the largest terrestrial carbon reservoirs (Lal, 2004; Paustian et al., 2016). Soil degradation can compromise these functions by reducing fertility, increasing susceptibility to erosion, and decreasing the capacity for carbon retention and stabilization.

Ecological restoration strategies have gained increasing importance as tools for recovering soil functionality, improving ecosystem services, and enhancing landscape resilience under climate change scenarios (FAO & ITPS, 2021). Soil restoration approaches frequently focus on increasing soil organic matter inputs, promoting vegetation establishment, and improving soil physicochemical conditions that support long-term ecosystem recovery processes.

Management practices aimed at increasing soil organic matter have been widely studied as alternatives to improve soil quality and enhance carbon sequestration capacity (Lal, 2010). The application of organic amendments, such as plant residues, stabilized compost, manure, and vermicompost, can significantly improve soil physical and chemical properties, contributing to the recovery of degraded areas and increasing ecosystem resilience (Angelova et al., 2013; Larney & Angers, 2012; Amelung et al., 2020).

The effects of organic amendments on soil properties are strongly influenced by their chemical composition, degree of stabilization, and decomposition dynamics. Amendments with low carbon-to-nitrogen ratios generally promote faster nutrient mineralization, whereas more stabilized materials may contribute preferentially to long-term soil carbon accumulation (Bernal et al., 1998; Chantigny, 2003). Consequently, different organic residues may produce contrasting short- and long-term effects on soil physicochemical properties and carbon sequestration processes.

Soil responses to organic amendment application are conditioned by edaphoclimatic factors, characteristics of the applied material, and land-use history. Processes related to organic matter decomposition, nutrient mineralization, and carbon stabilization occur gradually, meaning that some soil physicochemical changes become evident only over time (Lehmann et al., 2020; Chassé et al., 2021).

In Mediterranean environments, these dynamics are particularly relevant due to shallow, stony soils with limited water retention capacity and high susceptibility to erosion, especially in mountainous regions dominated by Leptosols derived from schist and granite (Agroconsultores & Coba, 1991; Aguiar, 2001).

Mediterranean ecosystems are highly vulnerable to climate change due to recurrent drought, irregular precipitation, wildfires, and low soil organic matter content (García-Ruiz et al., 2013; IPCC, 2023), which together limit vegetation productivity and soil recovery capacity. Therefore, short-term assessments are essential to capture early changes in soil physicochemical properties, including pH, nutrient availability, and organic matter fractions, which are critical for understanding initial restoration trajectories (Memoli et al., 2017).

Despite the growing body of research on organic amendments and soil carbon sequestration, relatively few studies have examined short-term soil physicochemical responses in Mediterranean forest ecosystems characterized by shallow soils (Leptosols) with high coarse fragment content and under restoration-oriented management (Bastida et al., 2015; Novara et al., 2019). Moreover, most existing research has focused on agricultural systems or has assessed isolated soil properties rather than integrated indicators of soil recovery. Consequently, there is still limited understanding of how different organic amendments influence early-stage soil restoration processes under Mediterranean environmental constraints.

1.1 Objective

The present study aims to evaluate the effects of different organic amendments on the physicochemical properties and soil organic carbon stocks of Mediterranean forest soils one year after the establishment of a field experiment.

It was hypothesized that applying organic amendments would improve soil physicochemical properties and increase soil organic carbon content during the short-term evaluation period. Additionally, amendments characterized by greater nutrient availability were expected to produce stronger short-term effects on soil quality indicators, while more stabilized materials were expected to promote more persistent improvements over time.

1.2 Specific objectives

The specific objectives of this study are to assess the effects of organic amendments on soil physical and chemical properties, quantify soil organic carbon and total nitrogen contents, evaluate key nutrients (phosphorus and potassium), and estimate soil organic carbon stocks. Temporal changes one year after amendment application are also analyzed to assess early soil recovery dynamics.

1.3 Scientific relevance

By evaluating the short-term effects of distinct organic amendments under Mediterranean restoration conditions, this study contributes to advancing the understanding of early soil recovery mechanisms in environmentally vulnerable ecosystems. The findings may support the development of sustainable restoration strategies that enhance soil functionality, carbon sequestration potential, and ecosystem resilience under future climate change scenarios.

1.4 Organization of the Thesis

This dissertation is organized into five interrelated parts that provide the theoretical, methodological, and analytical framework of the study.

Initially, the introduction presents the context of the topic, its relevance within the scope of climate change and sustainable soil management, and the objectives that guided the research.

Subsequently, the literature review summarizes the main theoretical foundations of climate change, soil degradation, the application of organic amendments, and the dynamics of soil organic carbon in Mediterranean forest soils.

The following part describes the materials and methods adopted in the study, including characterization of the experimental area, the experimental design, field sampling procedures, laboratory analyses, and the statistical methods used for data interpretation.

Next, the results are presented and discussed, with emphasis on changes observed in soil physicochemical properties and soil organic carbon dynamics throughout the evaluated period.

Finally, the last part summarizes the main conclusions from the evaluation of soil physicochemical properties and soil organic carbon stocks under the application of organic amendments.

2. LITERATURE REVIEW

2.1 Climate Change and Soil Carbon Sequestration

The increase in atmospheric greenhouse gas (GHG) concentrations has intensified global concern regarding climate change and its environmental consequences. Anthropogenic activities such as fossil fuel combustion, deforestation, and land-use change have substantially altered the global carbon balance, particularly through the continuous release of carbon dioxide (CO_2) into the atmosphere (Jacobi et al., 2011; Friedlingstein et al., 2023; IPCC, 2023). As a result, terrestrial and oceanic carbon sinks have become insufficient to fully offset current emission rates.

This imbalance has contributed to progressive global warming and significant changes in global climatic patterns. Rising temperatures, alterations in precipitation regimes, and the increasing occurrence of extreme climatic events, including droughts, floods, and heatwaves, have been widely associated with ongoing climate change (IPCC, 2007; ICNF, 2013). These environmental changes directly affect ecosystem functioning by influencing water availability, nutrient cycling, vegetation productivity, and ecological stability.

In response to these challenges, international climate governance has evolved considerably over recent decades. The Kyoto Protocol, established in 1997, was one of the first international efforts to reduce greenhouse gas emissions through legally binding commitments for developed countries. Subsequently, the Paris Agreement, adopted in 2015, introduced a broader and more flexible framework based on nationally determined contributions (NDCs), seeking to limit global temperature increase to well below 2°C above pre-industrial levels while pursuing efforts to restrict warming to 1.5°C (Dimitrov, 2016; Rei et al., 2017; Gössling et al., 2023).

In parallel, terrestrial ecosystems have attracted increasing attention for their capacity to store and regulate carbon. Soil, in particular, represents one of the largest carbon reservoirs in the biosphere, storing approximately 1500 Pg of organic carbon within the first meter of soil depth (Batjes, 1996; Lal, 2004; Paustian et al., 2016). Beyond climate regulation, soil organic carbon plays a fundamental role in maintaining soil fertility, structural stability, water retention, and overall ecosystem functioning. In addition to its role in carbon storage, soil organic carbon is increasingly recognized as a key regulator of ecosystem multifunctionality. Higher soil organic carbon contents are frequently associated with improvements in nutrient retention, microbial diversity, water regulation, and resistance to environmental disturbances (Delgado-Baquerizo et al., 2020; Lehmann et al., 2020). These interactions are particularly relevant in degraded Mediterranean ecosystems, where soil organic carbon depletion may simultaneously compromise productivity, biodiversity, and ecosystem resilience (Bastida et al., 2015). Consequently, strategies aimed at increasing soil organic carbon may generate multiple co-benefits that extend beyond climate change mitigation alone.

Within this context, international initiatives such as the "4 per 1000" program have reinforced the relevance of sustainable soil management for increasing soil organic carbon stocks and mitigating climate change (Martin et al., 2021).

Nevertheless, soil carbon sequestration should not be considered a permanent or uniform process. The accumulation and stabilization of soil organic carbon depend on multiple interacting factors, including climate conditions, soil properties, land-use history, vegetation cover, and management practices (Sanderman et al., 2017; Rumpel et al., 2020). Consequently, the capacity of soils to function as long-term carbon sinks varies substantially across ecosystems and environmental conditions.

2.2 Soil Degradation and Physicochemical Constraints in Mediterranean Environments

Soil degradation is a complex process driven by interactions between natural factors and anthropogenic activities, leading to deterioration of soil structure, fertility, and ecological functionality (IPBES, 2018).

Mediterranean environments are particularly vulnerable to degradation due to their climatic characteristics, including irregular precipitation patterns, intense rainfall events, and prolonged drought periods. These conditions, combined with steep slopes and long-term land-use pressures, substantially increase soil susceptibility to erosion and structural decline (Aguiar, 2001; IPBES, 2018).

In northeastern Portugal, soils are predominantly derived from schist and granite and are commonly classified as Leptosols. These soils are generally shallow, highly stony, and characterized by low water retention capacity and limited nutrient availability, conditions that constrain vegetation development and overall soil productivity (Agroconsultores & Coba, 1991; Aguiar, 2001).

Soil degradation frequently involves the disruption of soil structure, reductions in aggregate stability, and decreased porosity. Such alterations negatively affect water infiltration and increase surface runoff, thereby intensifying erosion processes and accelerating soil loss (Borrelli et al., 2021; Delgado-Baquerizo et al., 2020).

Simultaneously, degraded soils often exhibit low base saturation, reduced cation exchange capacity, and limited availability of essential nutrients. These physicochemical constraints compromise soil fertility and negatively affect ecosystem functioning and resilience (Bünemann et al., 2018).

Furthermore, legacies of historical land-use practices may limit soil recovery capacity, making ecological restoration processes more dependent on long-term and targeted management strategies (Waring & Bradford, 2024).

2.3 Organic Amendments as a Soil Management Strategy

Sustainable soil management practices increasingly rely on the application of organic amendments to improve soil function and support the recovery of degraded ecosystems. Organic materials such as plant residues, compost, manure, and vermicompost contribute to the accumulation of soil organic matter and influence several physicochemical and biological processes within the soil environment (Lal, 2004; Murphy, 2015).

2.3.1 Effects on Soil Physical Properties

The incorporation of organic residues can substantially modify soil physical conditions, particularly by improving soil structure and aggregation processes. Organic matter promotes the formation and stabilization of soil aggregates, which are essential for maintaining structural integrity, increasing resistance to erosion, and reducing susceptibility to degradation (Barzegar et al., 2002; Karami et al., 2012).

The stabilization of macro- and microaggregates also contributes to the physical protection of soil organic carbon by limiting its exposure to microbial decomposition. This process favors long-term carbon stabilization and contributes to the maintenance of soil structure over time (Aoyama et al., 1999; Wang et al., 2013).

Organic amendments may additionally reduce soil bulk density while increasing total porosity and improving pore distribution. These changes enhance water infiltration, aeration, and water retention capacity, factors that are particularly relevant in

Mediterranean environments where water availability frequently limits ecosystem productivity (Murphy, 2015; Pereira, 2019).

Improvements in soil physical quality may further reduce compaction, increase soil friability, and facilitate root penetration, thereby supporting vegetation establishment and increasing ecosystem resilience under environmental stress conditions. Changes in aggregate stability may also serve as early indicators of carbon stabilization processes, particularly under short-term evaluations where significant variations in total soil organic carbon are not yet detectable (Esmaeilzadeh & Ahangar, 2014).

2.3.2 Effects on Soil Chemical Properties

Organic amendments also play an important role in regulating soil chemical properties and nutrient dynamics. During organic matter decomposition and mineralization, nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are gradually released into the soil solution, becoming available for plant uptake (Krull et al., 2004; Angelova et al., 2013).

The efficiency of these processes is strongly influenced by the composition and quality of the applied organic material, particularly its carbon-to-nitrogen (C/N) ratio. Organic residues with high C/N ratios tend to favor nutrient immobilization, whereas materials with lower ratios generally promote nutrient mineralization and greater nutrient availability (Wang et al., 2015).

In addition to nutrient supply, soil organic matter increases cation exchange capacity and buffering capacity, improving nutrient retention, reducing leaching losses, and promoting greater pH stability (Lal, 2008; Santos, 2022). Organic amendments may also stimulate microbial activity and biological functioning, influencing nutrient cycling processes and overall soil fertility.

Overall, the accumulation and stabilization of soil organic matter contribute not only to improvements in soil quality and ecosystem functioning but also to enhanced soil carbon sequestration potential under sustainable land management systems.

2.3.3 Effects on Soil Biological Properties

In addition to their influence on soil physical and chemical properties, organic amendments can substantially affect soil biological functioning. The incorporation of organic materials increases the availability of energy sources and nutrients for soil microorganisms, stimulating microbial biomass, enzymatic activity, and overall biological activity within the soil system (Bastida et al., 2008; Lazcano et al., 2013).

Enhanced microbial activity directly contributes to nutrient cycling, organic matter decomposition, aggregate formation, and soil carbon stabilization (Six et al., 2004; Lehmann et al., 2020). Soil fauna, including earthworms and mesofauna organisms, may also benefit from increased organic matter availability, promoting bioturbation and improving soil structure.

In Mediterranean ecosystems, where environmental stress frequently limits biological activity, the application of organic amendments may play an important role in restoring soil ecological functioning and supporting vegetation establishment during ecological restoration processes (Bastida et al., 2015).

2.4 Soil Carbon and Nitrogen Dynamics

2.4.1 Carbon Cycle

The carbon cycle is a fundamental biogeochemical system that regulates the exchange of carbon among the atmosphere, biosphere, hydrosphere, and pedosphere. In terrestrial ecosystems, carbon enters the system primarily through photosynthesis, during which atmospheric carbon dioxide (CO_2) is assimilated by plants and incorporated into biomass. This carbon is subsequently transferred to the soil through litter deposition, root turnover, and rhizodeposition, representing the main inputs of organic carbon into soil systems (Pacheco & Helene, 1990; UCAR, 2007).

Once incorporated into the soil, organic carbon undergoes several transformation mechanisms predominantly mediated by soil microorganisms. These mechanisms include decomposition, mineralization, and humification. During decomposition, complex organic compounds are broken down into simpler molecules, releasing carbon as CO_2 through microbial respiration. Simultaneously, part of the organic carbon is transformed into more stable soil organic matter fractions through humification, contributing to the formation of humic substances and long-term carbon persistence.

The stabilization of soil organic carbon is strongly influenced by physical and chemical protection mechanisms. Among the most relevant processes is the formation of soil aggregates, which physically protect organic matter from microbial decomposition. In addition, the interaction between organic compounds and mineral particles, particularly clay minerals, promotes the formation of stable organo-mineral associations, thereby increasing carbon retention within the soil matrix (Schmidt et al., 2011). Recent studies suggest that the persistence of soil organic carbon is not determined solely by the intrinsic recalcitrance of organic compounds, but rather by the interactions among microbial processing, mineral protection, and environmental accessibility (Lehmann & Kleber, 2015; Cotrufo et al., 2019). According to the soil continuum model, organic matter undergoes continuous transformation through microbial activity, generating compounds that may subsequently become stabilized through association with mineral surfaces or physical occlusion within aggregates (Kleber et al., 2007). This perspective has shifted the understanding of soil carbon persistence from a purely biochemical paradigm toward an ecosystem-level process controlled by biological, physical, and mineralogical interactions (Schmidt et al., 2011).

Despite these stabilization mechanisms, soil carbon persistence depends on continuous interactions among biological activity, environmental conditions, and soil stabilization mechanisms. Soil disturbance, erosion, and land-use changes may substantially accelerate carbon losses from terrestrial systems. Erosion processes can transport carbon throughout the landscape and into aquatic environments, where it may either be redeposited or mineralized (Lal, 2004).

Leaching also represents an important pathway for carbon loss, particularly through dissolved organic carbon transport. These mechanisms demonstrate the highly dynamic nature of soil carbon, which is continuously regulated by environmental conditions, soil properties, vegetation cover, and management practices.

Overall, soil organic carbon dynamics are governed by the balance between carbon inputs derived from vegetation, transformation and stabilization mechanisms within the soil, and carbon losses through respiration, erosion, and leaching. The interactions among these mechanisms ultimately determine the capacity of soils to function as either long-term carbon sinks or as net carbon sources under changing environmental conditions, as illustrated in Figure 1.

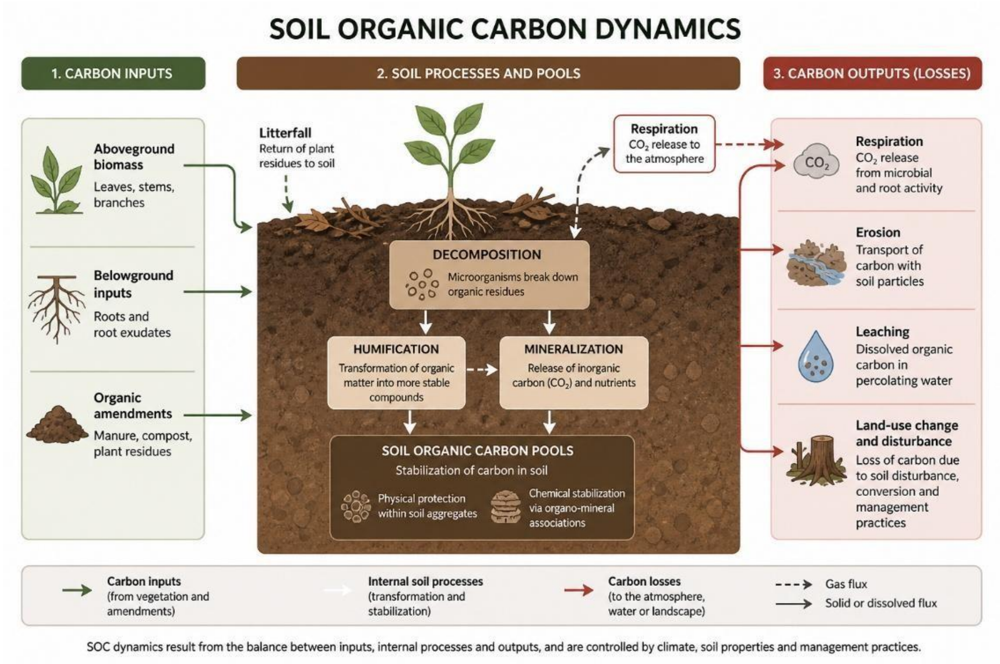

Figure 1. Conceptual representation of soil organic carbon dynamics, including carbon inputs from vegetation, transformation processes such as decomposition and stabilization, and carbon losses through respiration, leaching, and erosion. **Source:** adapted from Lal (2004).

2.4.2 Nitrogen Cycle

Nitrogen is an essential nutrient for plant growth and plays a central role in soil fertility and ecosystem functioning. Although the atmosphere contains approximately 78% nitrogen as dinitrogen (N_2), this form is not directly available to most living organisms and must first be converted into reactive forms through biological and physicochemical mechanisms (UCAR, 2007; Bernhard, 2010).

Biological nitrogen fixation, performed by specialized microorganisms such as symbiotic and free-living bacteria, converts atmospheric nitrogen into ammonium (NH_4^+), making it available for plant uptake. Nitrogen may also enter soil systems through atmospheric deposition and organic inputs derived from plant residues and organic amendments.

Within the soil environment, nitrogen undergoes several microbially mediated transformations. Organic nitrogen associated with plant residues and soil organic matter is mineralized into inorganic forms. Subsequently, ammonium may be oxidized into nitrate (NO_3^-) through nitrification.

Because nitrate is highly mobile in soil, it can be absorbed by plants or lost through leaching processes. Under anaerobic conditions, nitrate may also be reduced to gaseous forms, such as N_2 and nitrous oxide (N_2O) through denitrification, resulting in nitrogen losses to the atmosphere.

The nitrogen cycle is closely interconnected with the carbon cycle, as both are strongly regulated by soil organic matter dynamics and microbial activity. The decomposition of organic residues provides microorganisms with both energy (carbon) and nutrients (nitrogen), establishing a strong functional relationship between carbon and nitrogen cycling.

The coupling between carbon and nitrogen dynamics is particularly important in soils amended with organic residues, since microbial decomposition processes are strongly regulated by substrate stoichiometry and nutrient availability (Manzoni et al., 2010; Mooshammer et al., 2014). Imbalances between carbon and nitrogen inputs may alter microbial efficiency, decomposition rates, and nutrient mineralization patterns, ultimately influencing both soil fertility and carbon sequestration potential.

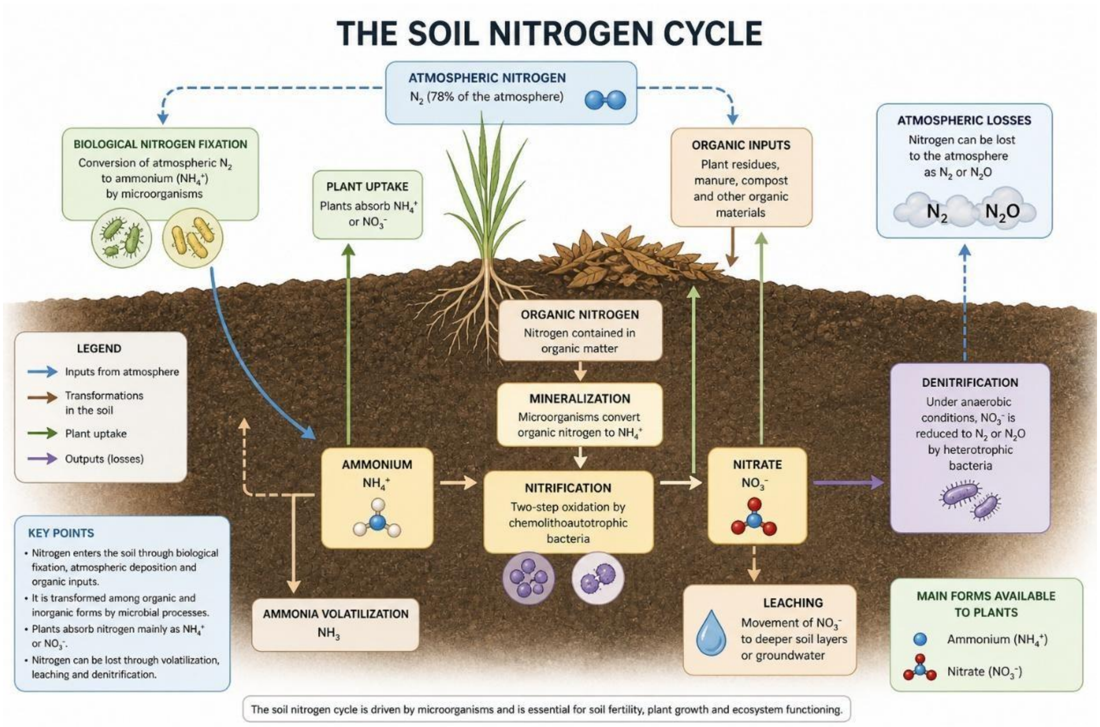

Figure 2. Conceptual representation of the soil nitrogen cycle, including nitrogen inputs, transformation processes, plant uptake, and loss pathways. **Source:** Based on UCAR (2007) and Bernhard (2010).

2.4.3 C/N Ratio

The carbon-to-nitrogen (C/N) ratio is a key parameter controlling organic matter decomposition and nutrient cycling in soils. This ratio reflects the balance between carbon, which serves primarily as an energy source for microorganisms, and nitrogen, which is essential for microbial growth and metabolism (Matschullat et al., 2018).

Organic residues characterized by high C/N ratios (C/N > 30), such as lignin-rich plant materials, generally decompose more slowly because microorganisms require additional nitrogen to process carbon-rich substrates. Under these conditions, nitrogen immobilization may occur, temporarily reducing nutrient availability for plants. Conversely, organic materials with lower C/N ratios (C/N < 20) tend to decompose more rapidly, favoring mineralization mechanisms and increasing nitrogen availability within the soil system (Wang et al., 2015; Lu et al., 2023).

The C/N ratio is influenced by several factors, including vegetation type, soil properties, climatic conditions, and ecosystem characteristics. Forest ecosystems commonly exhibit higher C/N ratios due to the accumulation of recalcitrant organic matter, contributing to greater carbon accumulation and storage in soils.

2.4.4 Soil Carbon Stocks

Soil carbon stocks represent the amount of carbon stored within soil systems and constitute a major component of the global carbon cycle. Carbon is distributed among different soil compartments, including surface organic horizons, mineral horizons, root systems, and deeper soil layers (Lorenz & Lal, 2018).

The quantity of carbon stored in soil is determined by the balance between carbon inputs, such as plant residues and root biomass, and carbon outputs from decomposition, erosion, leaching, and respiration processes. This balance is strongly influenced by climatic conditions, soil texture, vegetation cover, and land-use practices.

Management strategies that promote organic matter accumulation while minimizing soil disturbance, including the application of organic amendments, may enhance soil carbon storage capacity. In contrast, intensive land use and soil degradation processes can significantly reduce carbon stocks and compromise soil functioning (Fonseca et al., 2014; Fonseca et al., 2019; Murphy et al., 2019).

Carbon sequestration in soils is closely associated with mechanisms such as humification, aggregate stabilization, and organo-mineral interactions, all of which contribute to the physical and chemical protection of organic carbon. These mechanisms increase carbon persistence in soil and enhance the capacity of terrestrial ecosystems to function as carbon reservoirs.

Understanding soil carbon stocks is therefore essential for evaluating the role of soils in climate regulation and for developing sustainable management strategies aimed at enhancing carbon sequestration in terrestrial ecosystems

2.5 Temporal Dynamics of Soil Properties and Carbon

Soil processes are inherently dynamic and occur over a wide range of temporal scales, making the interpretation of responses to management practices particularly complex. Changes in physicochemical properties following the application of organic amendments do not occur instantaneously but are governed by a series of biological, physical, and chemical mechanisms that evolve over time (Lehmann et al., 2020).

In the short term, responses are often dominated by rapid mechanisms such as the initial decomposition of organic inputs, shifts in soil moisture conditions, and temporary fluctuations in nutrient availability. These early responses may include increases in microbial activity, short-term nutrient release, and minor modifications in soil structure. However, such changes do not necessarily indicate long-term improvements in soil quality or carbon stabilization.

In contrast, long-term changes are associated with slower mechanisms, including the stabilization of soil organic carbon, the formation of stable aggregates, and the development of organo-mineral associations. These processes are essential for improving structural stability, increasing carbon persistence, and enhancing overall ecosystem functioning, although they generally require extended periods to become fully established (Chassé et al., 2021; Lehmann et al., 2020).

The temporal evolution of soil properties is also strongly influenced by environmental conditions, intrinsic soil characteristics, and land-use history. In Mediterranean environments, where soils frequently present shallow profiles, high stoniness, and limited water availability, these mechanisms may occur more slowly due to edaphoclimatic constraints (Amelung et al., 2020).

Additionally, legacy effects associated with previous land-use practices may significantly influence ecosystem recovery and responses to management interventions. Degraded systems can exhibit limited recovery capacity, and improvements in physicochemical properties may follow nonlinear and delayed trajectories (Waring & Bradford, 2024).

Temporal responses to organic amendment application are additionally influenced by the quality and decomposition rate of the applied materials. Amendments characterized by labile organic fractions may promote rapid nutrient release and short-term microbial stimulation, whereas more stabilized materials such as mature composts tend to contribute more gradually to long-term carbon accumulation and aggregate stabilization (Bernal et al., 1998; Chantigny, 2003). Therefore, the temporal trajectory of soil recovery may differ substantially according to amendment composition and environmental conditions.

Another important aspect is that soil properties do not respond uniformly over time. Physical attributes, such as bulk density, porosity, and aggregate stability, may exhibit relatively rapid responses following the incorporation of organic amendments. In contrast, chemical properties, including nutrient availability and long-term carbon stabilization, often require longer periods to exhibit significant and persistent changes (Kan et al., 2021).

The predominance of short-term studies in the scientific literature represents an important limitation for understanding soil dynamics, since these studies may not capture the full extent of ecosystem responses to management practices. Early results may either overestimate or underestimate the effectiveness of management interventions, depending on the specific mechanisms being evaluated (Robinson et al., 2024).

In this context, comparative analyses across different evaluation periods, even over relatively short intervals such as one year, can provide valuable insights into the direction and magnitude of changes occurring within the system. Such assessments help identify early trends and improve understanding of temporal dynamics under specific management conditions.

Therefore, long-term monitoring of physicochemical properties and soil organic carbon is essential for accurately evaluating the effectiveness of organic amendments and their contribution to improving soil quality, structural stability, and ecosystem resilience, particularly in environmentally constrained systems such as Mediterranean soils.

2.6 Synthesis and Research Gap

The literature demonstrates that soil plays a central role in climate regulation and ecosystem functioning, particularly through its capacity to store organic carbon and regulate physicochemical processes. However, the effectiveness of management strategies to enhance soil quality and carbon sequestration depends strongly on environmental conditions, soil characteristics, and land-use history.

Mediterranean soils are especially vulnerable to degradation due to their shallow profiles, high stoniness, low organic matter content, and climatic constraints. These characteristics limit water retention, nutrient availability, and structural stability, reducing ecosystem resilience and making soil recovery processes particularly challenging. In Mediterranean regions, projected climate change scenarios are expected to intensify existing degradation processes through increased drought frequency, reduced vegetation cover, and greater rainfall irregularity (García-Ruiz et al., 2013; IPCC, 2023). These conditions may further accelerate erosion processes, reduce organic matter inputs, and compromise soil structural stability. Consequently, Mediterranean soils are considered highly vulnerable to desertification processes, particularly in marginal mountainous areas where ecological recovery is naturally slow and strongly constrained by water availability (Costa et al., 2018; IPBES, 2018). Among available management strategies, the application of organic amendments has been widely recognized as a promising approach for improving soil properties and increasing soil organic carbon. Nevertheless, soil responses to these practices are highly variable and depend on the characteristics of both the applied materials and the receiving environment.

Although numerous studies have evaluated the effects of organic amendments, much of the available knowledge remains based on short-term assessments. Consequently, important mechanisms associated with soil recovery and carbon stabilization, such as aggregate formation, humification, and organo-mineral interactions, remain insufficiently understood under Mediterranean conditions.

Additionally, the temporal evolution of soil properties may not occur uniformly, with physical indicators often responding more rapidly than chemical properties and total soil organic carbon. This highlights the importance of comparative evaluations conducted under consistent experimental conditions over time.

Furthermore, relatively few studies have simultaneously evaluated multiple soil physicochemical indicators under restoration-oriented management strategies in Mediterranean forest systems characterized by high coarse fragment content and shallow Leptosols (García-Orenes et al., 2016; Novara et al., 2019). Most available studies focus either on agricultural systems or on isolated soil variables, limiting the integrated understanding of soil recovery processes under ecologically constrained environments.

Additionally, there remains limited knowledge of the short-term responses of Mediterranean forest soils to the surface application of organic amendments without mechanical incorporation, despite this representing a common practice in ecological restoration and forest management programs (Gómez-Rey et al., 2012; Bastida et al., 2015).

In this context, the present study addresses these limitations by evaluating the temporal evolution of soil physicochemical properties and soil organic carbon stocks one year after the application of different organic amendments in a Mediterranean forest soil. By comparing results obtained under the same experimental conditions at different evaluation periods, this study aims to improve understanding of short-term soil responses and their implications for soil recovery and carbon stabilization processes.

Therefore, understanding the short-term temporal dynamics of soil physicochemical properties following organic amendment application is essential for identifying early indicators of soil recovery and carbon stabilization in Mediterranean restoration systems (Lehmann et al., 2020; Chassé et al., 2021). Comparative evaluations conducted under consistent field conditions may contribute to improving sustainable soil management strategies and to advancing current knowledge regarding ecosystem recovery processes under environmentally vulnerable conditions.

3. MATERIAL AND METHODS

3.1 Study Area

The study was carried out in a Mediterranean forest ecosystem located in northeastern Portugal, Trás-os-Montes region, within the municipality of Vimioso, parish union of Algoso, Campo de Víboras, and Uva (Figure 3). The study area is centred at approximately 41°27' N, 6°34' W (41°25'–41°30' N, 6°33'–6°35' W), at a mean altitude of approximately 650 m a.s.l. (ranging from ~600 to ~700 m). The experimental area is integrated into the Natura 2000 Network, specifically within the Special Area of Conservation (SAC) and Special Protection Area (SPA) of the Sabor and Maçãs rivers, and is also included in the Meseta Ibérica Transboundary Biosphere Reserve.

This research was developed under the UP4REHAB Project (Landscape Unit for Habitat Restoration in Algoso), an initiative focused on habitat restoration and soil conservation in mountainous Mediterranean environments under increasing climatic and environmental pressures.

The experimental field covers approximately 34 ha and is characterized by mountainous terrain with steep slopes frequently exceeding 25%. The area underwent substantial land-use changes approximately four decades ago, when terraces were constructed for eucalyptus plantations. These interventions significantly altered the original landscape structure, increasing soil disturbance and erosion susceptibility.

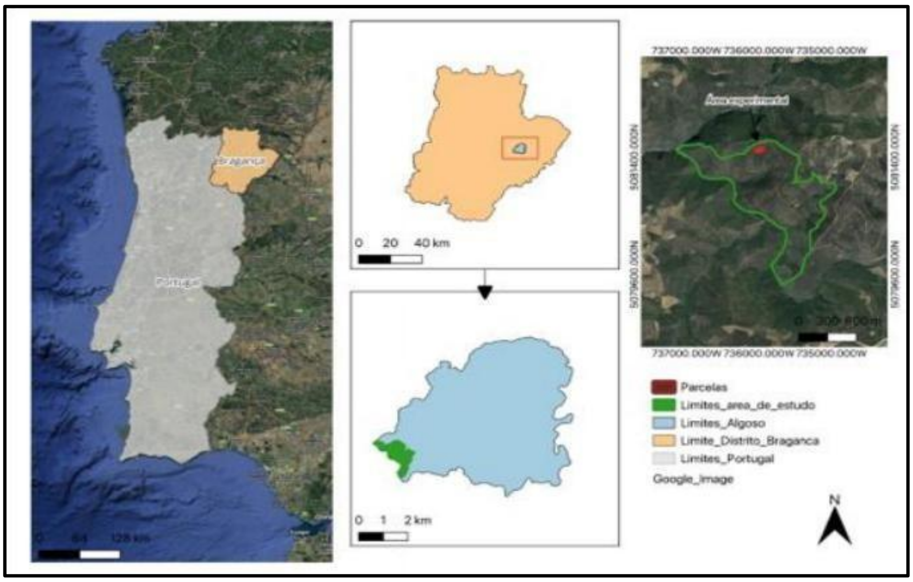

Figure 3. Geographic location of the permanent experimental field in Algoso, municipality of Vimioso, northeastern Portugal. **Source:** Fonseca (2024).

The regional climate is Mediterranean with continental influences, characterized by hot and dry summers, cold winters, and marked interannual variability in precipitation. According to the climatological normals (1991–2020) from the Bragança meteorological station, the mean annual temperature is approximately 12 °C, with the warmest months occurring in summer and frequent winter minimum temperatures below 0 °C. Mean annual precipitation is concentrated mainly between autumn and winter, while summer months are markedly dry (Figure 4). Semi-arid conditions predominate across most of the study area, imposing important limitations on vegetation development and soil-forming processes.

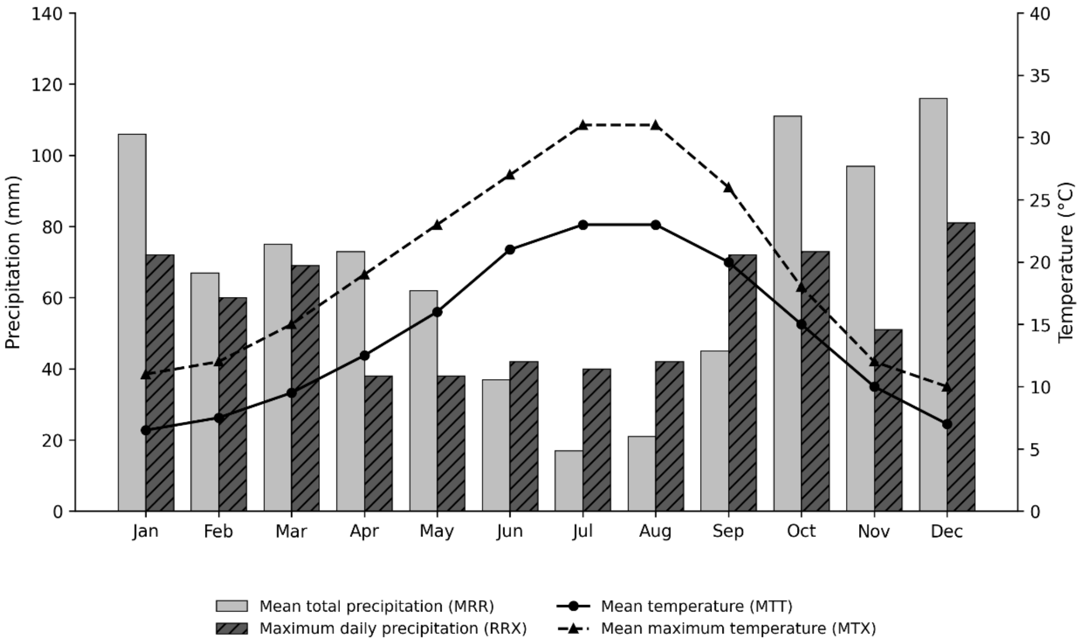

Figure 4. Monthly climograph (1991–2020) for the Bragança meteorological station, northeastern Portugal, combining mean total precipitation (MRR) and maximum daily precipitation (RRX) with mean temperature (MTT) and mean maximum temperature (MTX). **Source:** adapted from IP

The application of the organic amendments was scheduled for October, based on the combined analysis of temperature and precipitation patterns shown in Figure 4. By this month, mean temperatures have declined from the summer peak to moderate levels (around 15 °C), reducing the risk of rapid organic matter mineralization and moisture loss immediately after application. At the same time, October marks the onset of the autumn rainfall period, but with a still moderate volume of precipitation compared to the following months (November and December), which lowers the risk of surface runoff, erosion, and nutrient leaching on the steep slopes of the experimental field. This combination of milder temperatures and moderate, gradually increasing rainfall provided more favorable conditions for amendment incorporation and initial soil-amendment interaction, while minimizing losses associated with either excessive heat and drought or intense early-winter precipitation events.

Soils are predominantly derived from schist parent material and are generally classified as Leptosols. These soils are typically shallow, highly stony, and characterized by low water retention capacity and limited nutrient availability. Their reduced depth, high erodibility, and structural fragility constitute important constraints to ecosystem functioning and natural recovery processes.

The study site corresponds to a forest area currently undergoing ecological restoration, where the application of organic amendments is being evaluated as a strategy to improve soil physicochemical properties and enhance soil organic carbon storage.

3.2 Experimental Design

A permanent experimental field was established in October 2023 to evaluate the effects of organic amendments on soil physicochemical properties and soil organic carbon dynamics. The organic amendments were produced at the Local-Based Composting Station (ECBL) established within the UP4REHAB project. The green waste (RV) and stabilized compost (CE) were derived from vegetation residues generated during Mediterranean scrub management and fire-risk reduction interventions carried out within the landscape unit, which were subsequently shredded, composted and returned to the soil following a circular economy approach. The donkey manure (EB) was obtained from locally kept animals (*Equus asinus*).

The experimental design consisted of seven treatments: three types of organic amendments (Table 1) applied at two rates, along with an untreated control. The treatments were: green waste (RV) applied at 5 Mg ha^{-1} (RV5) and 10 Mg ha^{-1} (RV10); stabilized compost (CE) applied at 5 Mg ha^{-1} (CE5) and 10 Mg ha^{-1} (CE10); donkey manure (EB) applied at 5 Mg ha^{-1} (EB5) and 10 Mg ha^{-1} (EB10); and a control treatment without amendment application.

Table 1 - Main characteristics of the organic amendments used in the experimental design.

Amendment	Description	Main characteristics
RV	Shredded green waste	High C/N (>30)
CE	Stabilized compost	Humified organic matter
EB	Donkey manure	Nutrient-rich amendment

Each experimental plot was 500 m² (20 m × 25 m), allowing adequate spatial representation of soil variability. The treatments were applied on the soil surface without incorporation, simulating realistic management practices commonly used in forest systems.

The experimental field was installed on sloped terrain (>30%), and the layout plots were designed to minimize variability associated with topography and soil heterogeneity.

The present study focuses on the comparison between two evaluation moments: an initial post-application assessment and a second evaluation conducted one year after the amendment application, allowing the analysis of short-term temporal dynamics.

3.3 Soil Sampling

Soil sampling for the present study was conducted in December 2024, approximately one year after the application of the organic amendments, allowing the evaluation of short-term temporal changes in soil properties under field conditions.

Field assessments were conducted prior to soil sampling to qualitatively evaluate the system's response to the applied treatments. These observations focused on the decomposition stage of the organic amendments and on indicators of biological activity in the soil. Particular attention was given to the presence of fungal hyphae, soil mesofauna activity (including larvae, earthworms, and fecal residues), and the emergence of herbaceous vegetation, especially leguminous species, which may reflect early changes in soil conditions.

For soil sampling, a systematic approach was adopted for each treatment. Two transects were established following the direction of the maximum slope, and three sampling points were defined along each transect, resulting in a total of six sampling points per treatment.

The spatial distribution of sampling points within the experimental plots is shown in Figure 5.

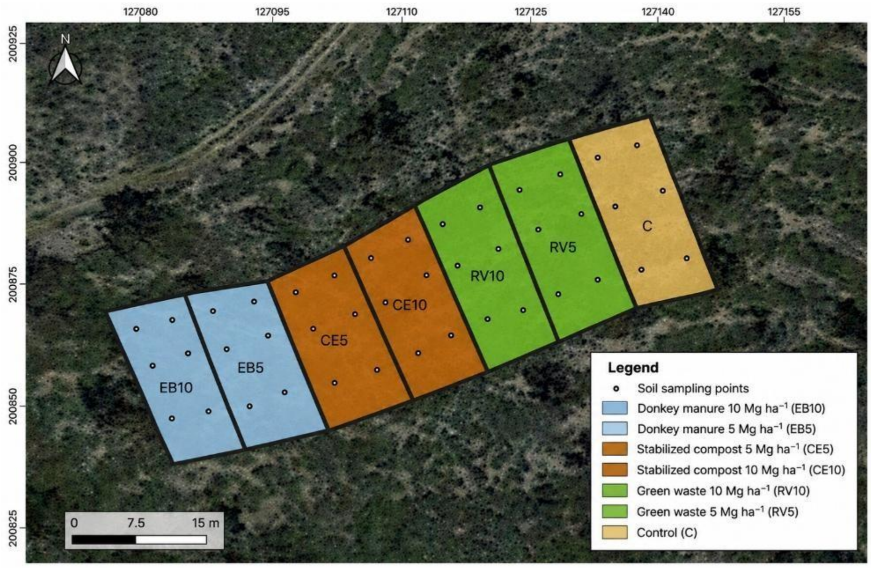

Figure 5. Spatial distribution of soil sampling points within the experimental plots in the permanent field. **Source:** Fonseca (2024).

At each sampling point, disturbed soil samples were collected at depths of 0–5 cm, 5–10 cm, and 10–20 cm. These depth intervals were selected to capture surface responses to amendment application and short-term vertical variability in soil properties. In addition, undisturbed soil samples were collected at 0–5 cm depth using cylindrical cores with a known volume (100 cm^3) to preserve soil structure. Undisturbed samples were used to determine soil physical properties, including bulk density, permeability, porosity, maximum water holding capacity, and field capacity. Disturbed samples were primarily used to analyze soil chemical properties. This combined sampling approach allowed a comprehensive assessment of soil chemical properties across treatments and depths, and soil physical properties at the surface layer

3.4 Laboratory Analyses

Soil samples were processed at the Soil Laboratory of the School of Agriculture of the Polytechnic Institute of Bragança (Portugal).

Disturbed soil samples were oven-dried at 45°C for 48 hours. After drying, a portion of each sample was manually sieved through 2 mm and 1 mm mesh to determine aggregate stability. The remaining portion of the samples was processed using a mechanical sieve shaker to separate coarse elements (particles > 2 mm) from the fine earth fraction (particles < 2 mm).

The fine-earth fraction was subsequently used to determine soil chemical properties, while the separation of coarse elements allowed the quantification of their contribution to soil composition.

3.4.1 Physical properties

3.4.1.1 Coarse Elements Content

The coarse fraction of the soil, defined as particles larger than 2 mm, was separated from the fine-earth fraction using a mechanical sieve shaker. After separation, the coarse material was weighed and expressed as a percentage of the total soil sample mass.

3.4.1.2 Soil Bulk Density

Undisturbed soil samples were collected using cylindrical cores with a volume of 100 cm³ at 0–5 cm depth and oven-dried at 105°C for 48 hours. After drying, the samples were weighed to determine their dry mass. Soil bulk density (BD) was then calculated using the following equation:

$$BD = \frac{M_{dry}}{V}$$

where BD is the soil bulk density (g cm^{-3}), M_{dry} is the dry mass of the sample (g), and V is the volume of the cylinder (cm^3).

3.4.1.3 Soil Permeability

Undisturbed soil samples collected at 0–5 cm depth and maintained in cylindrical metal rings with a volume of 100 cm^3 (20 cm^2 × 5 cm) were used to determine soil permeability. The samples were placed in a constant-head closed-circuit permeameter, which allows the simultaneous analysis of multiple samples. Each sample was connected to a 40 mL burette, enabling the measurement of the volume of water flowing through the soil per unit of time.

Before installation in the permeameter, the external surface of the rings was cleaned to remove any residual material. A layer of hydrophilic gauze was placed at the base of each ring, followed by a filter to ensure proper water flow and prevent soil loss. The rings were then mounted onto the support system with the filter positioned downward, allowing water flow through the sample under conditions that simulate natural infiltration. The system was secured using clamps and a nylon stopper to ensure proper sealing.

Once assembled, the samples were saturated for 48 hours to achieve steady-state conditions. Permeability measurements were subsequently carried out over four consecutive days. During this period, the volume of water collected in each burette was recorded at intervals of up to 30 minutes.

At the end of the measurements, the samples were removed from the permeameter and allowed to rest. They were then weighed after 1 hour and after 24 hours, and finally oven-dried at 105°C for 48 hours to determine the dry mass.

Soil permeability (K) was calculated according to Darcy's Law:

$$K = \frac{V \cdot L}{A \cdot t \cdot \Delta H}$$

where $K$is the hydraulic conductivity (cm h^{-1}), V is the volume of water passing through the sample (cm^3), $L$is the length of the soil sample (cm), A is the cross-sectional area (cm^2), $t$is the time interval (h), and $\Delta H$is the hydraulic head difference (cm).

Initial permeability (K_i) was determined from measurements obtained on the first day after saturation, while final permeability (K_f) was calculated as the average of the measurements obtained during the following three days.

Based on the calculated Kvalues, soil permeability classes were assigned according to the criteria presented in Table 2.

Table 2. Soil permeability classification (SCS/USDA)

Permeability class	Value (cm h^{-1})
Very rapid	> 25.40
Rapid	12.70 – 25.40
Moderately rapid	6.35 – 12.70
Moderate	2.00 – 6.35
Moderately slow	0.50 – 2.00
Slow	0.13 – 0.50
Very slow	< 0.13

3.4.1.4 Total Porosity

Total porosity (P) was calculated based on the difference between the mass of the soil samples after 1 hour of drainage (saturated mass) and after oven-drying at 105°C (dry mass), relative to the volume of the soil sample:

$$P(\%) = 100 \times \frac{M_{sat} - M_{dry}}{V}$$

where $P$is the total porosity (%), M_{sat} is the mass of the saturated soil sample after 1 hour of drainage (g), M_{dry} is the mass of the oven-dried sample (g), and V is the volume of the cylinder (cm^3).

3.4.1.5 Field Capacity and Maximum Water Holding Capacity

Field capacity (FC) was calculated based on the difference between the mass of the soil samples after 24 hours of drainage (moist mass) and the oven-dried mass, relative to the dry mass:

$$FC(\%) = 100 \times \frac{M_{moist} - M_{dry}}{M_{dry}}$$

where $FC$is the field capacity (%), $M_{moist}$is the mass of the soil sample after 24 hours of drainage (g), and $M_{dry}$is the mass of the oven-dried sample (g).

Maximum water holding capacity ($MWHC$) was calculated using the difference between the saturated mass (after 1 hour of drainage) and the dry mass:

$$MWHC(\%) = 100 \times \frac{M_{sat} - M_{dry}}{M_{dry}}$$

where $MWHC$ is the maximum water holding capacity (%), M_{sat} is the mass of the saturated soil sample after 1 hour of drainage (g), and M_{dry} is the mass of the oven-dried sample (g).

3.4.1.6 Microporosity and Macroporosity

Microporosity (MicroP) was estimated by converting gravimetric field capacity into volumetric water content, assuming a water density of 1 g cm^{-3}. This conversion is based on the relationship between gravimetric water content (g water g^{-1} soil), bulk density (g soil cm^{-3} soil), and water density (g water cm^{-3} water), which yields volumetric water content (cm^3 water cm^{-3} soil), numerically equivalent to a volumetric fraction. Microporosity was therefore calculated as:

$$\text{MicroP}(\%) = FC \times BD$$

where MicroP is the microporosity (%), FC is the gravimetric field capacity expressed as a decimal fraction (g water g^{-1} soil), and BD is the soil bulk density (g cm^{-3}).

This approach assumes a water density of 1 g cm^{-3} and is commonly used for comparative purposes in soil physical studies.

Macroporosity ($MacroP$) was determined as the difference between total porosity and microporosity:

$$MacroP(\%) = P - MicroP$$

where $MacroP$ is the macroporosity (%), $P$is the total porosity (%), and $MicroP$is the microporosity (%).

3.4.2 Chemical properties

The fine-earth fraction (< 2 mm) of the soil samples obtained after sieving was placed in sealed plastic bags and sent to the Soil Laboratory of the University of Trás-os-Montes and Alto Douro (UTAD) for chemical analyses. Chemical properties were evaluated for all treatments and soil depths (0–5, 5–10, and 10–20 cm).

3.4.2.1 Initial soil characterization

Additional chemical properties were determined for the original soil (SO) in order to characterize the initial soil conditions of the experimental area (Table 3). These data were obtained from the initial characterization of the experimental field described by Mossio (2024) and were determined using the same analytical methodologies adopted in the present study.

Table 3. Chemical characterization of the original soil (adapted from Mossio, 2024).

Depth	pH		P_2O_5	K_2O	Olsen P	S
Cm	H_2O	KCl	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
0-5	5.5	4.7	10.3	140.6	6.3	7.7
5-10	5.2	4.4	4.4	125.5	4.4	6.3
10-20	5.1	4.3	3.3	104.6	3.3	5.6

Depth	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	ECEC	CEC_p	SOM	Total N
Cm	cmol$_c$ kg^{-1}							%	g kg^{-1}
0-5	3.8	1.5	0.3	0.1	0.4	6.0	15.6	3.8	1.3
5-10	2.2	1.1	0.3	0.1	0.5	4.1	16.4	2.2	0.8
10-20	1.9	1.0	0.2	0.1	0.5	3.8	13.4	1.6	0.8

3.4.2.2 Soil organic matter (SOM)

Soil organic matter (SOM) was evaluated due to its importance as an indicator of soil quality, nutrient cycling, and ecosystem recovery in Mediterranean environments. SOM content was estimated from SOC concentration using the conventional conversion factor of 1.724 (Nelson & Sommers, 1996). Although this factor has been critically reviewed (Prybil, 2010), it remains widely applied in soil science studies for comparative purposes

$$SOM = SOC \times 1.724$$

where SOM is soil organic matter content, and SOC is soil organic carbon concentration.

Soil organic carbon concentration used for SOM estimation was determined by dry combustion at 1000°C using an elemental analyzer, following the methodology described by Neves (2015).

Table 4. Classification of soil organic matter content for soils with coarse texture (Santos, 2015).

SOM (%)	Classification
> 20	Organic
10 – 20	Very high
5 – 10	High
2 – 5	Medium
0.5 – 2	Low
< 0.5	Very low

3.4.2.3 Soil organic carbon concentration

Soil organic carbon (SOC) concentration was evaluated for its role in soil fertility, nutrient cycling, aggregate stability, and carbon sequestration processes. Soil organic carbon is considered one of the main indicators of soil quality and plays a fundamental role in the physical, chemical, and biological functioning of Mediterranean ecosystems (Lal, 2004; Lehmann & Kleber, 2015).

Soil organic carbon concentration used for SOM estimation was determined according to the methodology described by Neves (2015).

3.4.2.4 Soil organic carbon stock

Soil organic carbon stock (SOC stock) was evaluated for its importance to soil quality, carbon sequestration, and long-term ecosystem sustainability. Soil carbon storage is closely associated with soil structure, nutrient retention, aggregate stability, and the recovery of degraded soils under conservation management practices (Lal, 2004; Lehmann & Kleber, 2015; Han et al., 2025).

The amount of soil organic carbon stored in the mineral soil layers (Mg C ha^{-1}) was calculated based on soil organic carbon concentration, soil bulk density, layer thickness, and coarse fragment content correction. Soil organic carbon concentration used for SOM estimation was determined according to the methodology described by Neves (2015).

Soil organic carbon stock was calculated for the 0–5 cm layer only, as undisturbed soil samples for bulk density determination were collected at this depth. The high coarse fragment content and shallow profile of the studied Leptosols made reliable undisturbed core extraction at greater depths impractical, precluding SOC stock estimation for the 5–10 cm and 10–20 cm layers.

The calculation followed the approach described by Percival et al. (2000) and Fonseca et al. (2019), according to the following equation:

$$SOC_{stock} = SOC \times BD \times z \times (1 - CF)$$

where SOC_{stock} is the soil organic carbon stock (Mg C ha^{-1}), SOC is the soil organic carbon concentration (g kg^{-1}), BD is the soil bulk density (g cm^{-3}), z is the thickness of the soil layer (m), and CF is the coarse fragment content expressed as a volumetric fraction (v v^{-1}).

3.4.2.5 Total nitrogen (TN)

Total nitrogen (TN) was evaluated due to its close relationship with soil fertility, organic matter dynamics, microbial activity, and ecosystem recovery processes. In Mediterranean soils, nitrogen is considered an important indicator of soil quality because it is strongly associated with nutrient cycling and biological functioning (Andrés-Abellán et al., 2019).

Total nitrogen was determined according to the methodology described by Neves (2015). This method allows quantification of total nitrogen in soil samples through complete combustion of the organic material.

Table 5. Classification of total nitrogen content in soil (Hill Laboratories, n.d.)

Total N (g Kg^{-1})	Classification
< 0.5	Very low
0.5 – 1.0	Low
1.0 – 2.0	Medium
2.0 – 3.5	High
> 3.5	Very high

3.4.2.6 Extractable potassium (K)

Extractable potassium (K) was evaluated due to its importance in soil fertility, nutrient cycling, and plant physiological processes. Potassium plays a fundamental role in osmotic regulation, enzyme activation, photosynthesis, and water-use efficiency, being considered an essential macronutrient for plant development. In dryland and Mediterranean-like environments, potassium availability is strongly influenced by soil properties, organic matter content, and management practices (Musa et al., 2025).

Extractable potassium was determined using the Egner–Riehm method, as described by Balbino (1968), with extraction performed using ammonium lactate and ammonium acetate solution at pH 3.8. Potassium concentration was determined by atomic absorption spectrometry.

Table 6. Classification of extractable potassium (K_2O) content in soil (Santos, 2015).

K_2O (mg Kg^{-1})	Classification
< 25	Very low
26 – 50	Low
51 – 100	Medium
101 – 200	High
> 200	Very high

3.4.2.7 Extractable phosphorus (P)

Extractable phosphorus (P) was evaluated due to its importance in nutrient cycling, microbial activity, and soil fertility. Phosphorus is an essential macronutrient involved in energy transfer, root development, and several metabolic processes in plants. In Mediterranean soils, phosphorus availability is strongly influenced by organic matter decomposition, soil pH, and fertilization practices, being considered an important component of soil quality and ecosystem functioning (Dong et al., 2025).

Extractable phosphorus was determined using the Egner–Riehm method, as described by Balbino (1968), with extraction performed using ammonium lactate and ammonium acetate solution at pH 3.8. Phosphorus concentration was determined by segmented flow analysis.

Table 7. Classification of extractable phosphorus (P_2O_5) content in soil (Santos, 2015).

P_2O_5 (mg Kg^{-1})	Classification
< 25	Very low
26 – 50	Low
51 – 100	Medium
101 – 200	High
> 200	Very high

3.4.2.8 Soil pH

Soil pH was evaluated due to its importance in controlling nutrient availability, microbial activity, and several chemical and biological processes associated with soil functioning and recovery. In Mediterranean environments, soil pH is considered an important indicator of soil quality because it directly influences nutrient dynamics, vegetation establishment, and ecosystem functioning (Andrés-Abellán et al., 2019).

Soil pH was determined both in distilled water (pH H_2O) and potassium chloride solution (pH KCl) using standard laboratory procedures with a glass electrode pH meter. The determination in water was used to assess active soil acidity, whereas pH KCl was used to evaluate exchangeable acidity associated with the soil exchange complex.

Table 8. Soil classification according to pH (H_2O) (Costa, 2018).

pH (H_2O)	Classification
< 4.5	Very acid
4.6 – 5.5	Acid
5.6 – 6.5	Slightly acid
6.6 – 7.5	Neutral
7.6– 8.5	Slightly alkaline
8.6 – 9.5	Alkaline
> 9.5	Very alkaline

3.5 Statistical Analysis

The dataset was initially screened for outliers by visual inspection of boxplots generated in Jamovi software. Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test to determine the most appropriate statistical method for each variable.

For normally distributed data, a one-way analysis of variance (ANOVA) was performed at the 5% significance level to evaluate differences among treatments, considering each soil depth separately. When the assumption of normality was not satisfied, the nonparametric Kruskal–Wallis test was applied at the same significance level. When statistically significant differences were detected ($p < 0.05$), Tukey's post hoc test was used to compare means.

In some variables, the Kruskal–Wallis test detected overall significant differences among treatments ($p < 0.05$), while subsequent pairwise comparisons did not identify statistically significant differences between specific treatment pairs. This pattern likely reflects the combination of high natural soil variability, the relatively small sample size per treatment ($n = 6$), and the conservative nature of the Dwass–Steel–Critchlow–Fligner correction. Under these conditions, the global test may detect heterogeneity in the distribution of values but may lack sufficient power to resolve individual pair differences. Results showing this pattern are therefore interpreted as indicative trends rather than confirmed statistical differences.

All statistical analyses and graphical outputs were performed using Jamovi and Microsoft Excel.

4. RESULTS AND DISCUSSION

The results presented in this chapter should be interpreted in the context of the relatively short evaluation period of one year. Processes such as organic matter stabilization, nutrient cycling, and carbon sequestration occur gradually and may require longer periods to become fully detectable, particularly in Mediterranean Leptosols characterized by high spatial variability and coarse fragment content. The high proportion of coarse fragments (consistently exceeding 60% across treatments) likely exerted a dominant influence on soil physical behavior, potentially masking treatment effects on bulk density, porosity, permeability, and water retention. These constraints may explain the limited statistical significance observed across several variables.

4.1 Soil physical properties

4.1.1 Coarse elements

Soils in the Trás-os-Montes region are commonly characterized by a high content of coarse fragments, reflecting their shallow nature and limited pedogenic development associated with mountainous landscapes (Figueiredo, 2012; Figueiredo & Fonseca, 2009). These conditions are typical of Leptosols, which frequently present a high proportion of particles larger than 2 mm (Fonseca et al., 2022).

Coarse fragment content varied across treatments and soil depths, as shown in Figure 6.

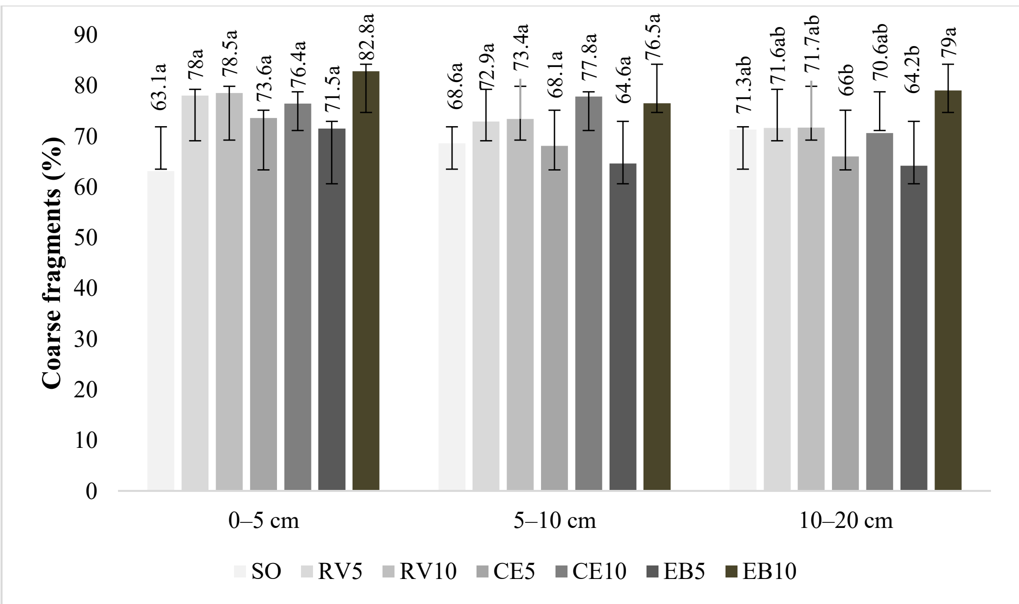

Figure 6. Coarse fragments (EG) at depths 0–5, 5–10, and 10–20 cm under treatments SO

(original soil), RV (green residues, 5 and 10 Mg ha⁻¹), CE (stabilized compost, 5 and 10 Mg ha⁻¹), and EB (donkey manure, 5 and 10 Mg ha⁻¹). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments according to Tukey's test or pairwise comparisons following Kruskal–Wallis tests ($p < 0.05$) ($n = 126$).

In the present study, coarse fragment content (%EG) consistently exceeded 60% across all treatments and soil depths, confirming the stony nature of the studied soils.

At the 0–5 cm depth, treatment effects on coarse fragment content were detected using the Kruskal–Wallis test ($p < 0.05$). However, pairwise comparisons did not identify differences between individual treatments ($p > 0.05$), indicating that the observed variability was distributed among treatments. Nevertheless, descriptive analysis suggests a tendency toward lower coarse fragment content under EB5 and CE5 treatments compared to the original soil (SO).

Similarly, at the 5–10 cm depth, the Kruskal–Wallis test also indicated significant differences among treatments ($p < 0.05$). However, pairwise comparisons again failed to identify statistically significant differences between individual treatments. Even so, lower %EG values were observed under CE5 and EB5 relative to SO, suggesting a tendency toward reduced coarse fragment content under these treatments.

At the 10–20 cm depth, data met the assumptions of normality and homogeneity of variances, and therefore a one-way ANOVA followed by Tukey's test was applied. Significant differences among treatments were observed ($p < 0.05$). Tukey's test indicated that EB10 differed significantly from CE5 and EB5, with EB10 showing the highest coarse fragment content at this depth. In contrast, EB5 and CE5 presented the lowest mean values.

Overall, although statistically significant differences were not consistently detected between individual treatments at all depths, the combined analysis indicates lower coarse fragment contents under EB5 and CE5 treatments. Compared with the earlier study conducted in the same experimental area, where lower coarse fragment contents after three months were mainly associated with manure-based treatments (EB), the results obtained after one year indicate that this tendency persists and is now also observed for the compost treatment at the lower application rate (CE5).

The observed variability is consistent with the heterogeneous nature of Mediterranean Leptosols. According to Pires et al. (2016), increased coarse fragment content in surface layers may be associated with soil degradation processes, particularly the selective removal of fine particles by water erosion, which may explain part of the variability observed in the present study.

Despite potential limitations related to water retention and root development, coarse fragments can also help reduce soil erosion by minimizing the impact of raindrops and surface runoff (Figueiredo, 2012). When combined with organic amendments that promote soil cover and structural improvement, these characteristics may support soil recovery and stabilization processes.

In highly skeletal Mediterranean soils, coarse fragments may exert contrasting effects on ecosystem functioning. Although excessive stoniness can restrict rooting depth and reduce the volume of fine earth available for nutrient retention, coarse fragments may also contribute to erosion mitigation, thermal buffering, and preferential infiltration processes (Poesen & Lavee, 1994; Cousin et al., 2003).

4.1.2 Soil bulk density

Soil bulk density (BD) is defined as the ratio between the dry mass of soil and its total volume, including pore spaces (Santos et al., 2012). In the present study, no statistically significant differences in BD were observed among treatments at the 0–5 cm depth, according to one-way ANOVA ($p > 0.05$) (Figure 7).

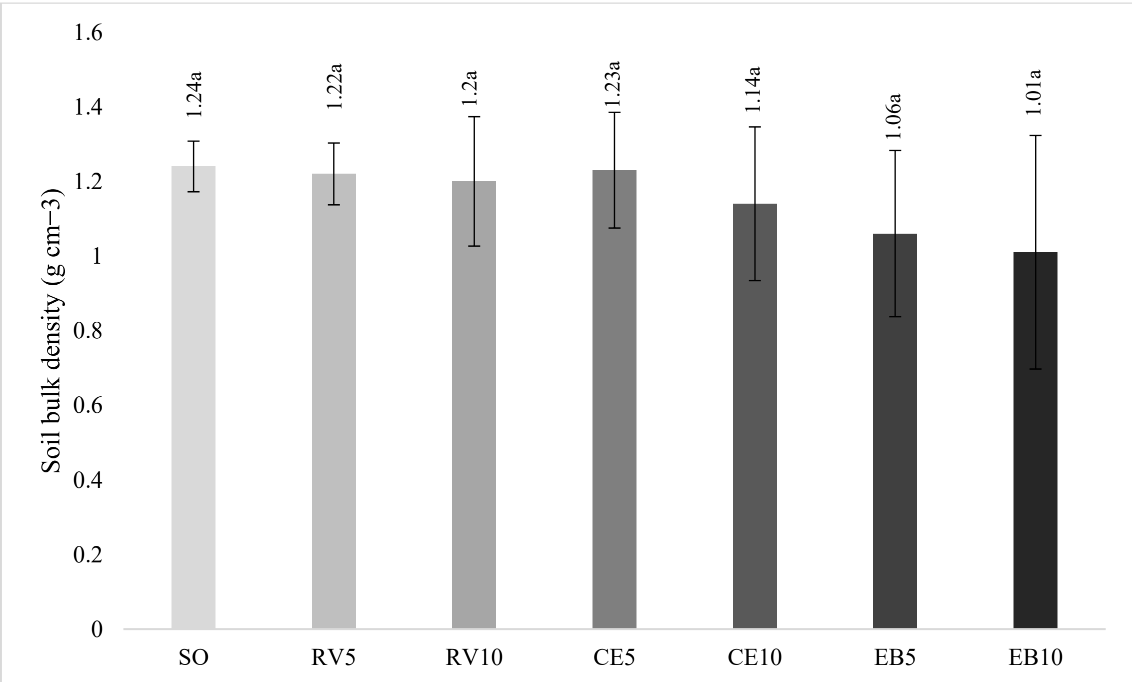

Figure 7. Soil bulk density (BD) at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation ($n = 42$). The same letters above the bars indicate that there are no significant differences among treatments according to Tukey's test ($p < 0.05$).

Although BD varied among treatments, no significant effect was detected in the first year, suggesting that applying organic amendments did not affect soil compaction during that period. This response may be attributed to several factors, including the surface-applied amendments, which may have limited their influence on bulk density. Furthermore, the natural spatial variability of the soil may have contributed to the dispersion of values across replicates.

The addition of organic matter is widely recognized as an important factor in improving soil structure and reducing bulk density, as it promotes greater aggregation and increases both micro- and macroporosity (Kumar et al., 2020). Previous studies have reported negative relationships between soil organic matter content and bulk density, indicating that increases in organic matter generally contribute to lower BD values (Wang et al., 2012; Chaudhari et al., 2013).

In the present study, this tendency was partially reflected in the results. Treatments receiving organic amendments, particularly EB5 (1.06 g cm^{-3}) and EB10 (1.01 g cm^{-3}), showed lower mean BD values compared to the original soil (1.24 g cm^{-3}), although these reductions were not statistically significant.

Overall, the results indicate that soil bulk density remained relatively stable across treatments during the first year after amendment application. Nevertheless, the observed trends suggest a potential gradual improvement in soil physical conditions under organic amendments, especially manure-based treatments.

The tendency toward lower bulk density under EB treatments may reflect the initial incorporation of low-density organic materials and early aggregate formation processes promoted by microbial activity.

4.1.3 Soil permeability

Soil permeability (K) refers to the rate at which water moves through the soil and is directly related to infiltration and drainage processes. These properties play a key role in controlling surface runoff and soil erosion dynamics (Figueiredo, 2011).

In the present study, permeability values were classified as very rapid (> 25 cm h^{-1}) across all treatments, including the control, indicating a high capacity for water movement through the soil. Both initial (Ki) and final (Kf) permeability did not show statistically significant differences among treatments according to the Kruskal–Wallis test ($p > 0.05$) (Figures 8 and 9).

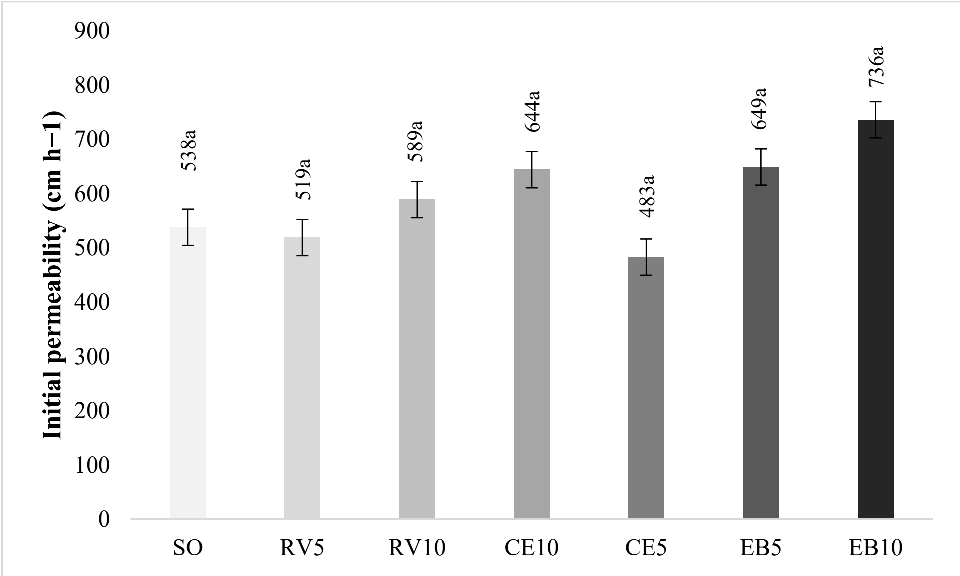

Figure 8. Initial soil permeability (Ki) at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments in pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 42$).

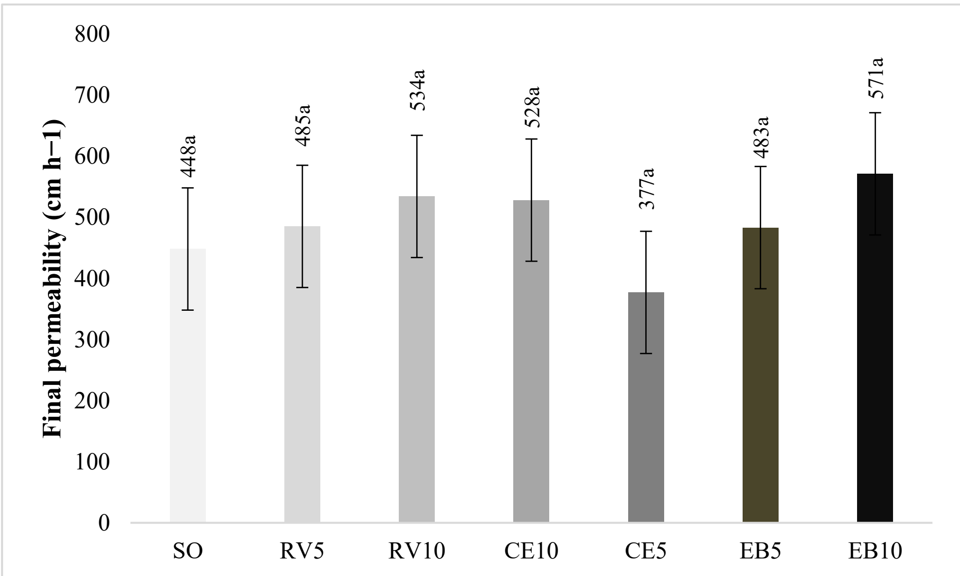

Figure 9. Final soil permeability (Kf) at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments according to pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 42$).

Although slight variations in permeability values were observed across treatments, no treatment consistently outperformed the others, and pairwise comparisons did not reveal significant differences. These results indicate that the application of organic amendments did not substantially alter soil hydraulic behavior within the evaluated period.

While organic matter is widely recognized for its influence on soil permeability through improvements in soil structure, aggregation, and water retention (Arthur et al., 2013; Murphy, 2015; Andanvan & Varun, 2017), these effects remained limited under the studied conditions. This may be associated with the dominant influence of intrinsic soil characteristics, particularly the high coarse fragment content, which may override potential improvements from organic amendments.

The high variability in permeability values reflects the soil's heterogeneous nature, particularly the presence of macropores and preferential flow pathways that dominate water movement and may obscure potential management effects. In coarse-textured and stony soils, flow is often controlled by preferential rather than matrix flow, making permeability measurements less sensitive to short-term changes in management practices (Jarvis, 2007). Overall, soil permeability remained relatively stable across treatments, indicating that intrinsic soil characteristics exerted a stronger control over water movement than organic amendments during the evaluated period.

4.1.4 Soil porosity

Total porosity (P), macroporosity (MacroP), and microporosity (MicroP) at 0–5 cm depth under the different treatments are presented in Figures 10, 11, and 12, respectively, in order to evaluate the effects of organic amendments on soil structure.

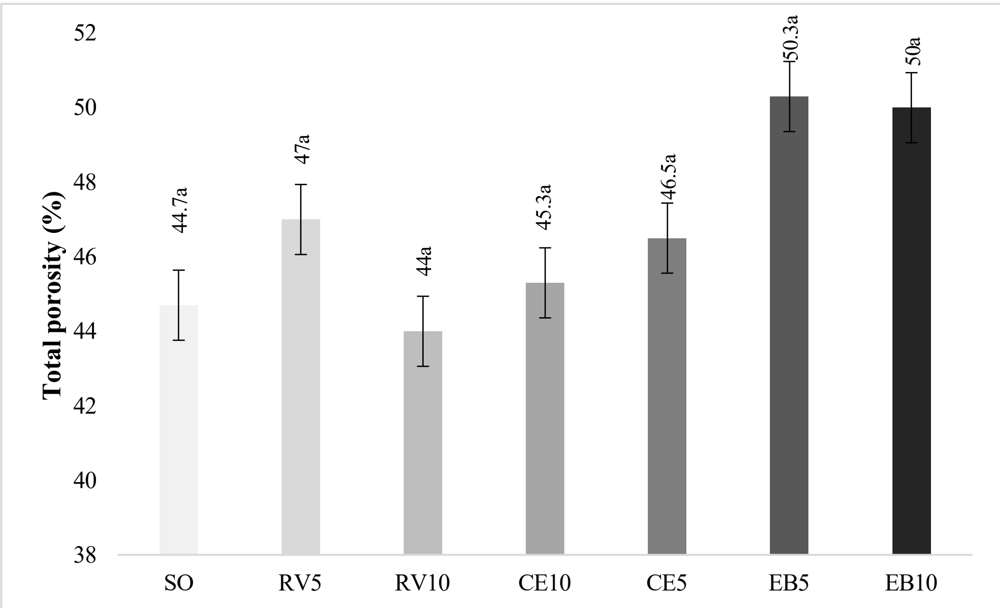

Figure 10. Total soil porosity at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments according to Tukey's test ($p < 0.05$) ($n = 42$).

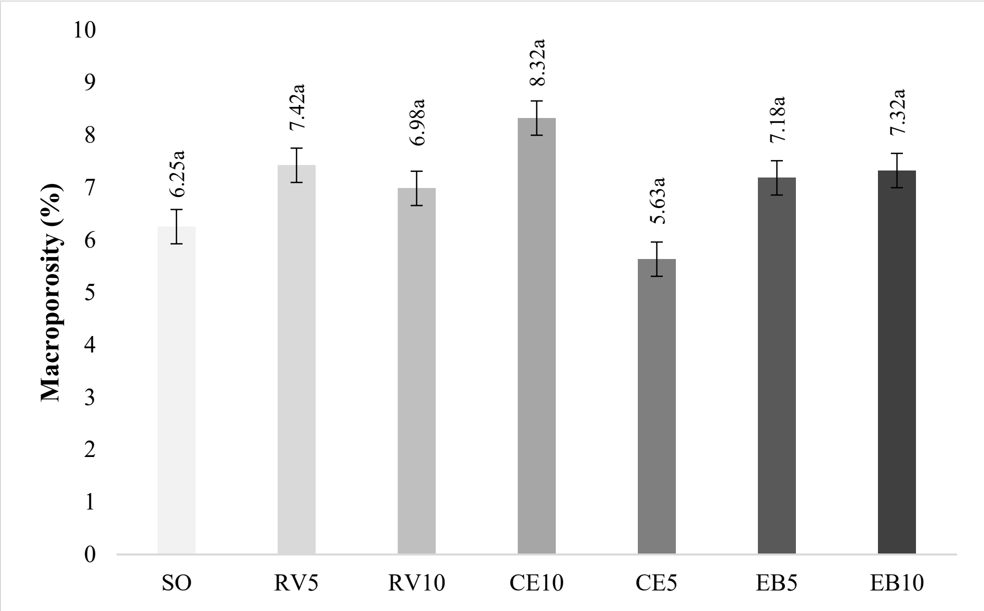

Figure 11. Soil macroporosity at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha⁻¹), CE (stabilized compost, 5 and 10 Mg ha⁻¹), and EB (donkey manure, 5 and 10 Mg ha⁻¹). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments according to pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 42$).

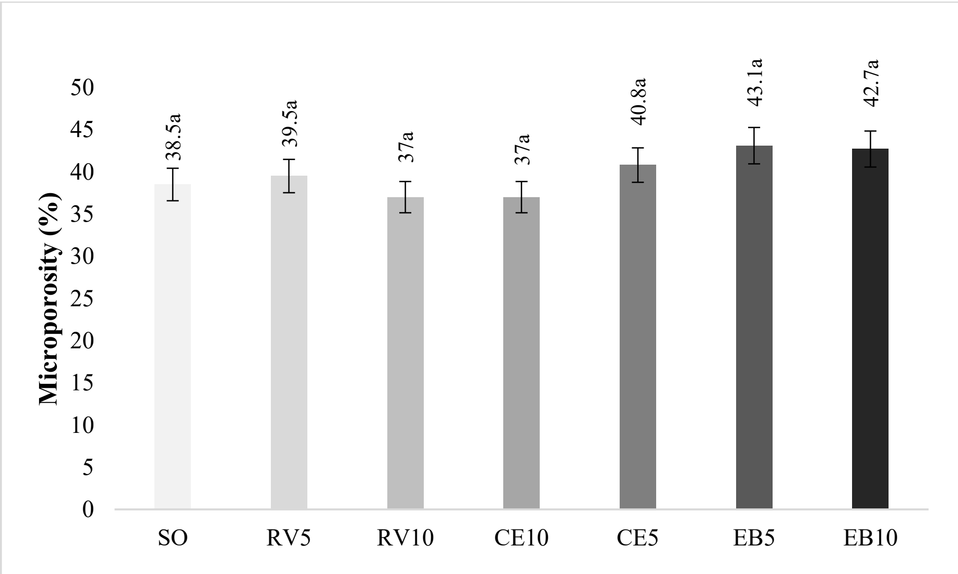

Figure 12. Soil microporosity at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha⁻¹), CE (stabilized compost, 5 and 10 Mg ha⁻¹), and EB (donkey manure, 5 and 10 Mg ha⁻¹). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments according to Tukey's test ($p < 0.05$) ($n = 42$).

Total porosity did not differ significantly among treatments, as indicated by one-way ANOVA ($p > 0.05$). However, some trends were observed. Treatments receiving organic amendments, particularly EB5 and EB10, showed a higher mean total porosity (approximately 50%) than the original soil (approximately 45%), suggesting a potential improvement in soil structure. Nevertheless, these differences were not statistically significant.

Similarly, soil microporosity showed no treatment effect ($p > 0.05$). Despite this, slightly higher microporosity values were observed under EB5 and EB10 treatments, indicating a tendency toward increased water-retaining pore spaces. Microporosity is closely related to soil water retention and aggregation; however, the absence of significant changes suggests that the applied organic amendments were not sufficient, within the evaluated timeframe, to promote detectable improvements in pore distribution.

Macroporosity also showed no statistically significant variation among treatments, as determined by the Kruskal–Wallis test ($p > 0.05$). Although values were relatively similar across treatments, the highest macroporosity was observed under the CE10 and RV5 treatments, suggesting slight improvements in soil aeration and water movement. However, these variations were not consistent enough to reach statistical significance.

These results differ from earlier observations in the same experimental area, where short-term evaluations approximately three months after application showed increases in total porosity and microporosity under specific treatments, particularly EB and CE. The absence of similar effects after one year suggests that changes in soil porosity may not follow a linear temporal pattern and may be influenced by soil heterogeneity and stabilization processes over time.

Furthermore, when analyzed alongside bulk density and permeability results, the data suggest that although structural changes, such as the reduction in bulk density observed in EB treatments, are not yet sufficient to produce measurable differences in pore distribution or water flow to produce measurable differences in pore distribution or water flow. This highlights the dominant influence of inherent soil properties over short- to medium-term management practices.

Overall, the results indicate that soil porosity remained relatively stable across treatments, although slight trends suggest potential structural improvement under organic amendments. Organic amendments may initially stimulate the formation of transient biopores and unstable aggregates before more persistent structural changes become detectable at the field scale.

4.1.5 Field capacity and maximum water holding capacity

Field capacity (FC) and maximum water-holding capacity (MWHC) at the 0–5 cm depth under the different treatments are presented in Figures 13 and 14, respectively, in order to evaluate the effects of organic amendments on soil water retention.

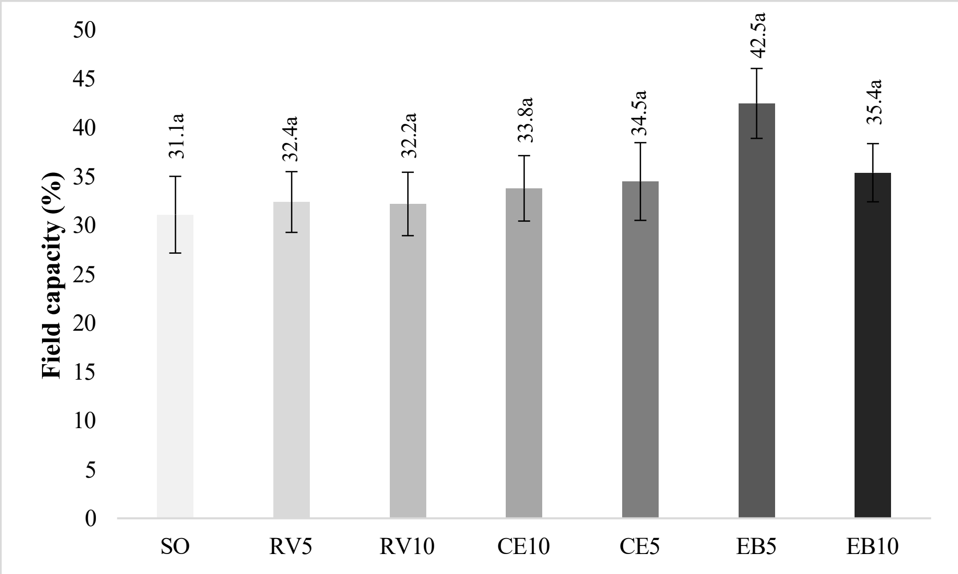

Figure 13. Soil field capacity at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments in pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 42$).

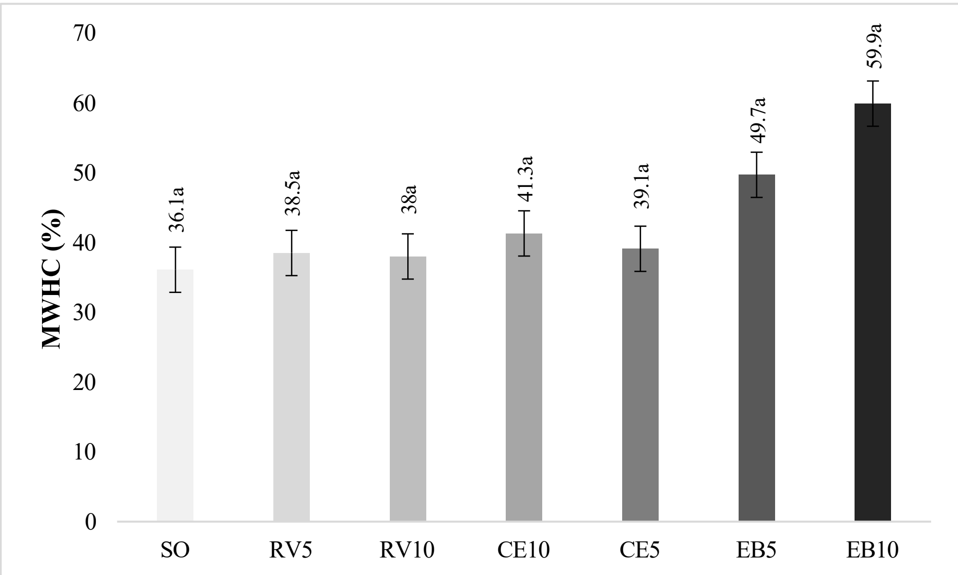

Figure 14. Maximum water holding capacity (MWHC) at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}),

and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments in pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 42$).

Field capacity did not differ significantly among treatments, as indicated by the Kruskal–Wallis test ($p > 0.05$). Although variability was observed among samples, no consistent pattern associated with the application of organic amendments was identified. Mean values remained relatively similar across treatments, indicating that the soil's ability to retain water after drainage remained stable.

Similarly, maximum water-holding capacity showed no treatment effect ($p > 0.05$). Despite this, slightly higher values were observed in treatments receiving organic amendments, particularly EB and CE, suggesting a tendency toward increased water retention potential. However, these variations were not consistent enough to reach statistical significance.

These results agree with previous observations from the same experimental area, where no statistically significant differences were detected shortly after amendment application, although slightly higher values were reported in treatments receiving organic inputs. This suggests that the influence of organic amendments on soil water retention may be limited in the short to medium-term. The lack of significant differences in both FC and MWHC may be explained by several factors.

Overall, the results suggest that field capacity and maximum water-holding capacity were not significantly influenced by the application of organic amendments within the evaluated period. The limited response of FC and MWHC may indicate that increases in organic matter were still insufficient to substantially modify the soil pore-size distribution. Improvements in water retention are generally associated with increases in microporosity and aggregate stability, processes that often require repeated organic inputs and longer stabilization periods (Rawls et al., 2003).

4.1.6 Particle density

Particle density (PD) considers only the volume of the soil solid fraction, excluding pore spaces (Costa, 2018). Soil particle density at 0–5 cm depth under the different treatments is presented in Figure 15.

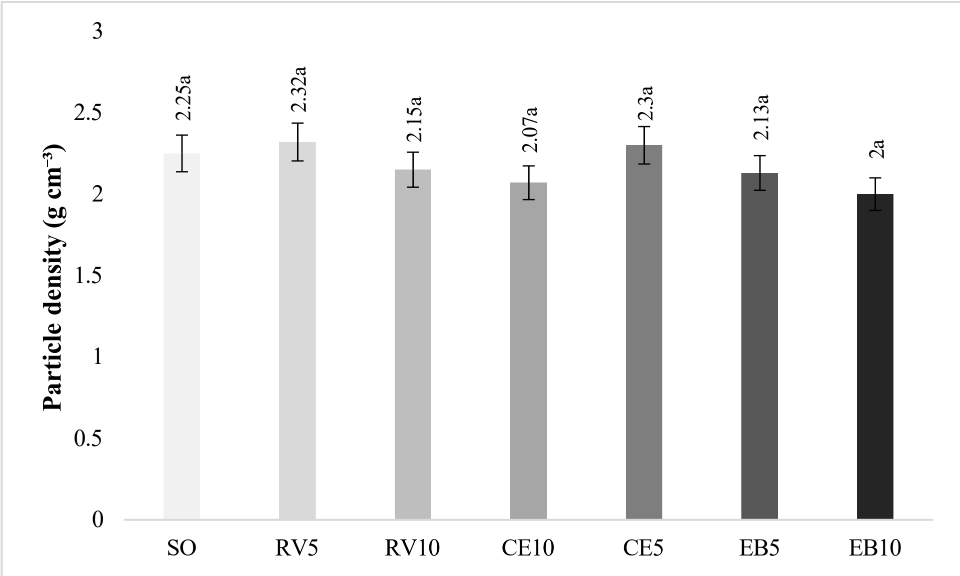

Figure 15. Soil particle density (PD) at 0–5 cm depth under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments according to Tukey's test ($p < 0.05$) ($n = 42$).

Particle density showed no statistically significant variation among treatments, as indicated by one-way ANOVA ($p > 0.05$). Although some variation in mean values was observed among treatments, these differences were not statistically significant. Values remained relatively consistent across treatments, indicating that the application of organic amendments did not substantially alter the soil's mineral composition.

The observed values were within the expected range reported in the literature, typically 2.3-2.9 g cm^{-3} (Porta et al., 2003), confirming the reliability of the measurements.

These results differ from previous observations conducted in the same experimental area, where short-term evaluations showed statistically significant differences among treatments, with higher values observed under EB application. The absence of similar differences after one year suggests that the initial variations may reflect short-term variability rather than persistent changes in soil properties.

This behavior is consistent with the nature of particle density, which is primarily determined by the mineral fraction of the soil and is generally not influenced by short- to medium-term management practices. Therefore, the absence of significant differences indicates that the treatments did not alter the intrinsic soil properties.

4.2 Soil chemical properties

4.2.1 Soil organic matter

Soil organic matter (SOM) content varied among treatments and depths (figure 16).

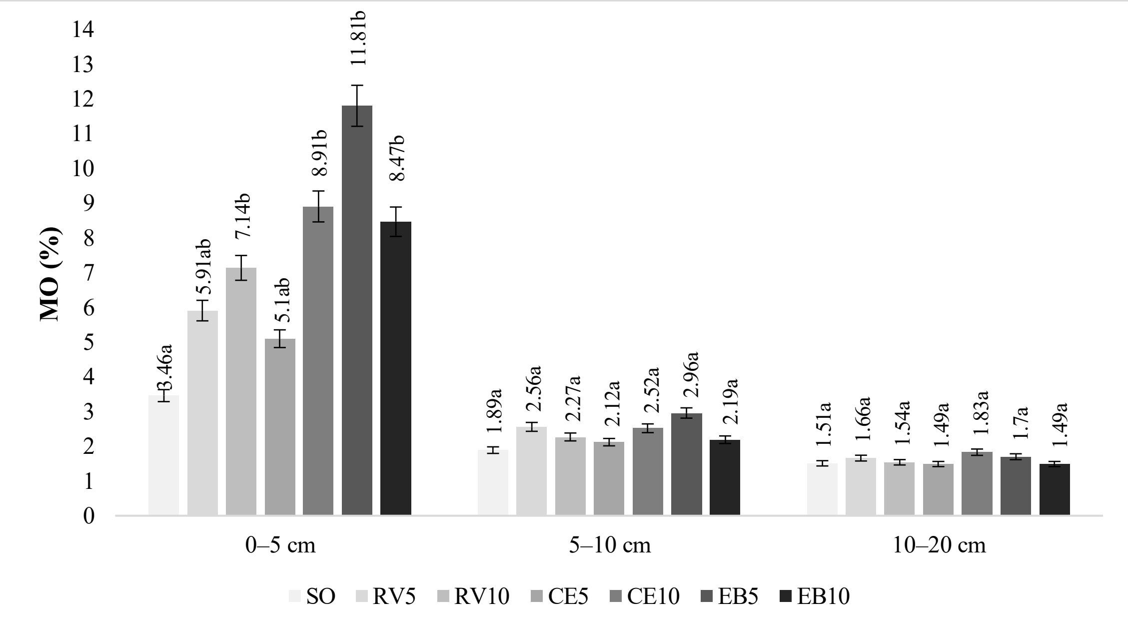

Figure 16. Soil organic matter (SOM) content at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV5 and RV10 (green residues, 5 and 10 Mg ha^{-1}), CE5 and CE10 (stabilized compost, 5 and 10 Mg ha^{-1}), and EB5 and EB10 (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments as determined by one-way ANOVA followed by Tukey's test or by pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) (n = 126).

At the 0–5 cm depth, statistically significant differences were observed among treatments ($p < 0.05$). Treatments RV10, CE10, EB5, and EB10 presented significantly higher SOM values than the original soil (SO), while RV5 and CE5 showed intermediate values not significantly different from either SO or the amended treatments. The highest SOM values were recorded under EB5 (11.81%), CE10 (8.91%), and EB10 (8.47%), while SO presented the lowest mean value (3.46%) (Figure 17).

At a depth of 5–10 cm, SOM values were substantially lower than those observed in the surface layer. No statistically significant differences were observed among treatments ($p > 0.05$). The highest mean values were observed under EB5, RV5, and CE10 treatments, while differences among treatments remained small. A similar pattern was observed at the 10–20 cm depth, where SOM values became more homogeneous among treatments, indicating a reduced influence of organic amendments with increasing soil depth.

The accumulation of soil organic matter is generally a gradual, long-term process driven by the continuous incorporation and transformation of organic residues into stable organic compounds. Increased soil organic matter contributes to improvements in soil structure, nutrient retention, aggregation, and carbon accumulation (Lehtinen et al., 2014).

For all treatments, soil organic matter content decreased with depth, with the highest values observed in the 0–5 cm layer and the lowest values in the 10–20 cm layer. This vertical distribution is frequently reported in soils and is mainly associated with the surface deposition of organic residues and the gradual movement and transformation of organic compounds through the soil profile (Schmidt et al., 2011).

The higher soil organic matter values observed in surface layers are likely associated with the surface application of organic amendments without soil incorporation, which tends to concentrate residue decomposition and organic matter accumulation near the soil surface. In deeper layers, the influence of treatments became less evident, suggesting limited vertical movement of organic compounds within the evaluated period.

Organic residues deposited on the soil surface are gradually transformed into soil organic matter through microbial decomposition and stabilization processes. The biochemical composition of organic amendments, particularly their C/N ratio, influences microbial metabolic efficiency and carbon use efficiency in Mediterranean soils (Boubehziz et al., 2026). Organic amendments also stimulate microbial biomass, diversity and enzymatic activity, promoting nutrient cycling and carbon stabilization process (Xu et al., 2025).

The significant differences observed in the 0–5 cm layer, particularly under manure-based and compost treatments, highlight the potential of organic amendments to improve SOM accumulation in surface horizons. In deeper layers, the absence of significant differences may be related to the intrinsic heterogeneity of the studied soil and to climatic conditions, particularly lower temperatures during autumn and winter, which may have reduced microbial activity and slowed decomposition and stabilization processes (Conant et al., 2011).

Furthermore, the composition and quality of the applied organic residues may influence decomposition dynamics and nutrient release. Organic materials differ in decomposition rates and mineralization potential, affecting nutrient availability and soil organic matter accumulation over time (Tou et al., 2025). These differences may partially explain the variability observed among treatments for soil organic matter, nitrogen, and carbon contents.

4.2.2 Soil organic carbon concentration

In the 0–5 cm layer, statistically significant differences in organic carbon concentration were observed among treatments ($p < 0.05$). Treatments RV10, CE10, EB5, and EB10 presented significantly higher values than the original soil (SO), while CE5 and RV5 showed intermediate values not significantly different from either SO or the amended treatments. At depths of 5–10 cm and 10–20 cm, no statistically significant differences were observed among treatments ($p > 0.05$), indicating a reduced influence of surface-applied amendments in deeper soil layers.

Figure 17 shows the organic carbon concentration at depths 0–5 cm, 5–10 cm, and 10–20 cm under the evaluated treatments.

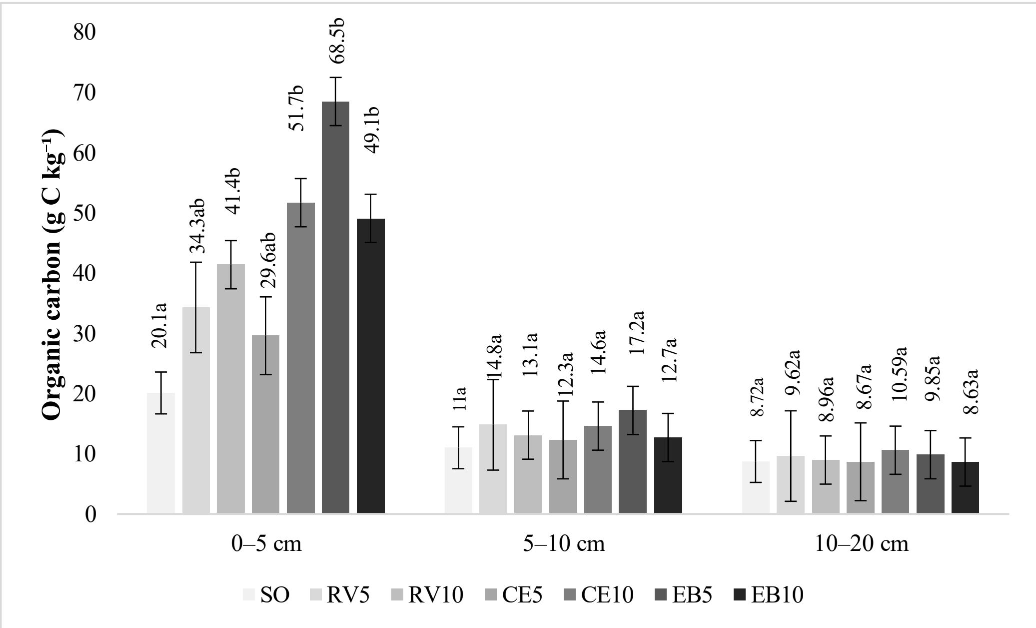

Figure 17. Soil organic carbon concentration at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV5 and RV10 (green residues, 5 and 10 Mg ha^{-1}), CE5 and CE10 (stabilized compost, 5 and 10 Mg ha^{-1}), and EB5 and EB10 (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments as determined by one-way ANOVA followed by Tukey's test or by pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 126$).

The highest organic carbon concentrations were found in the topsoil (0–5 cm), followed by a gradual reduction with increasing depth. This pattern is commonly associated with the accumulation of organic residues and greater microbial activity near the soil surface, where decomposition and nutrient cycling processes are more intense. Similar trends have been reported in global studies evaluating the application of farm-made organic fertilizers, which show that increases in soil organic carbon are usually more pronounced in superficial soil layers receiving direct organic inputs (Alvarez, 2025). Treatments amended with donkey manure (EB) and stabilized compost (CE) generally showed the highest average carbon concentrations, particularly in the surface layer, with significant differences relative to SO. Organic amendments are important sources of carbon input to the soil system and may contribute to gradual improvements in soil quality, aggregation, nutrient retention, and carbon sequestration over time (Lehmann & Kleber, 2015; Rumpel et al., 2020). In addition, organic fertilizers have been widely associated with increased soil organic carbon accumulation due to the continuous incorporation of organic residues into the soil profile (Alvarez, 2025).

The reduction in organic carbon concentration with depth observed in all treatments follows the natural distribution of soil organic matter in the profile. Surface horizons usually receive larger quantities of plant residues and support greater biological activity, resulting in higher carbon accumulation than subsurface layers (Schmidt et al., 2011).

4.2.3 Soil organic carbon stock

Figure 18 presents soil organic carbon stock (SOC) in the surface soil layer (0–5 cm) for the evaluated treatments.

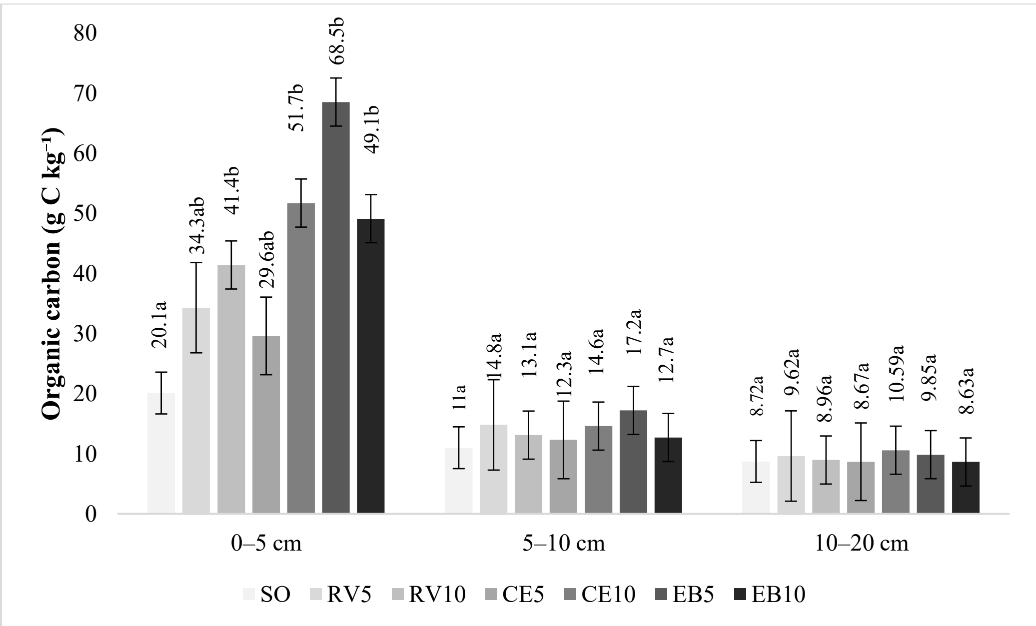

Figure 18. Soil organic carbon stock (SOC) in the 0–5 cm layer under the treatments SO (original

soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean ± standard deviation. The same letters above the bars indicate that there are no significant differences among treatments as determined by the Kruskal-Wallis test ($p > 0.05$) ($n = 42$).

To further assess the practical relevance of this result, the effect size of the Kruskal–Wallis test was calculated using epsilon squared (ε^2), yielding a value of 0.0939 ($p = 0.697$). According to conventional thresholds, this corresponds to a moderate effect size, indicating that the treatments accounted for a non-negligible proportion of the variability observed in SOC stock, even though this effect was not statistically significant. This discrepancy suggests that the high variability among replicates and the limited sample size likely reduced the statistical power of the test, preventing the detection of a significant difference despite a moderate underlying effect. In other words, the treatments may indeed be influencing SOC stock to a meaningful extent, but the experimental design was not sufficiently powered to confirm this statistically.

The treatments based on green residues (RV5 and RV10) presented intermediate SOC values, close to those observed in the original soil. Similarly, CE5 and EB10 also showed SOC values close to those of the original soil, indicating limited changes in carbon storage within the evaluated layer.

The high variability observed among replicates, especially in CE10 and EB5, may be associated with the natural heterogeneity of the soil and with the uneven distribution of organic residues applied on the soil surface. The addition of organic residues increases carbon inputs into the system and can enhance soil carbon stocks over time, though consistent changes may take longer observation periods to become statistically detectable.

Changes in soil carbon storage generally occur slowly, especially in systems where residues remain deposited on the soil surface. Organic matter decomposition, microbial activity, and humification processes are strongly influenced by environmental factors such as temperature, soil moisture, texture, and the quality of the applied organic material (Seitz et al., 2025; Rumpel et al., 2020). Moreover, appropriate soil management practices and conservation strategies can enhance soil organic carbon sequestration and contribute to long-term improvements in soil quality and ecosystem sustainability (Gao et al., 2025).

Although no significant differences were observed among treatments in the present study, the results indicate a potential increase in soil organic carbon stocks following the application of organic amendments, particularly in treatments with donkey manure and stabilized compost. Similar trends have been reported in studies evaluating carbon sequestration under conservation soil management, where organic amendments and reduced soil disturbance promoted gradual increases in soil organic carbon stocks over time (Gao et al., 2025).

SOC stock calculations were performed using a fixed-depth approach due to field constraints imposed by the shallow, stony soils. Although equivalent soil mass approaches may reduce potential bias associated with bulk density differences, their application was impractical under the present field conditions.

4.2.4 Total nitrogen

Total nitrogen (TN) contents at depths 0–5 cm, 5–10 cm, and 10–20 cm under the different treatments are presented in Figure 19.

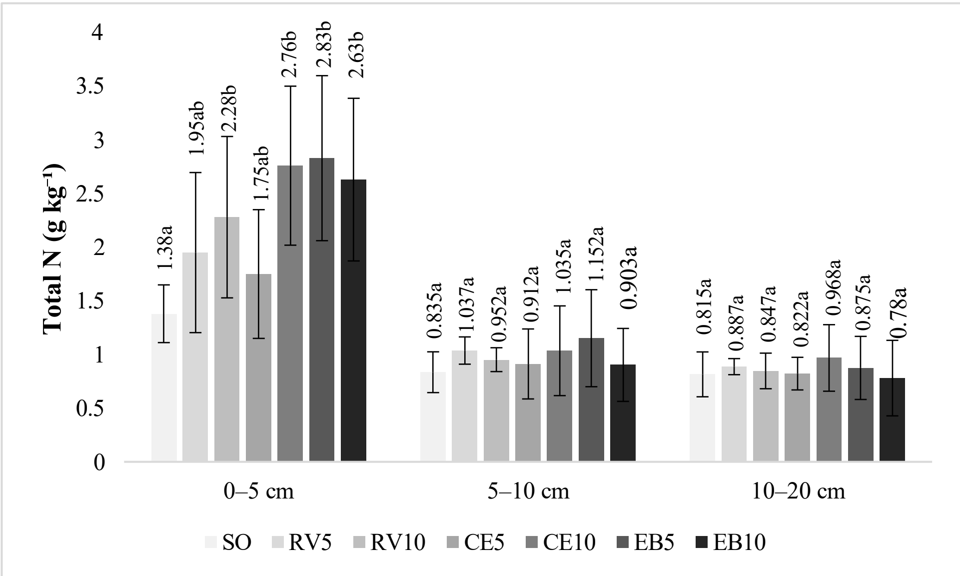

Figure 19. Total nitrogen (TN) content at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV5 and RV10 (green residues, 5 and 10 Mg ha^{-1}), CE5 and CE10 (stabilized compost, 5 and 10 Mg ha^{-1}), and EB5 and EB10 (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments as determined by one-way ANOVA followed by Tukey's test or by pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) ($n = 126$).

At the 0–5 cm depth, statistically significant differences were observed among treatments ($p < 0.05$). Treatments CE5, CE10, EB5, and EB10 presented significantly higher TN values than the original soil (SO), while RV5 and RV10 showed intermediate values not significantly different from either SO or the amended treatments. According to Hill Laboratories (n.d.), SO (1.38 g kg^{-1}), RV5 (1.95 g kg^{-1}), and RV10 (1.75 g kg^{-1}) were classified as medium TN content, whereas CE5 (2.28 g kg^{-1}), CE10 (2.76 g kg^{-1}), EB5 (2.83 g kg^{-1}), and EB10 (2.63 g kg^{-1}) reached high TN levels, highlighting the positive effect of these amendments on nitrogen accumulation in the surface layer.

At the 5–10 cm depth, total nitrogen also did not differ significantly among treatments ($p > 0.05$). Nevertheless, slightly higher concentrations were observed under EB5, RV5, and CE10 treatments compared to the original soil. In general, differences among treatments became smaller with increasing depth, suggesting a gradual reduction in the influence of surface-applied organic amendments throughout the soil profile.

Similarly, at the 10–20 cm depth, no statistically significant differences were observed among treatments according to the Kruskal–Wallis test ($p > 0.05$). Although CE10 had the highest mean nitrogen content, variation among treatments was relatively small and inconsistent. These results indicate that the effects of the amendments on nitrogen distribution were predominantly concentrated in the upper soil layers.

4.2.5 Extractable potassium

Figure 20 shows the extractable potassium (K) concentration at depths 0–5 cm, 5–10 cm and 10–20 cm under the different organic amendment treatments.

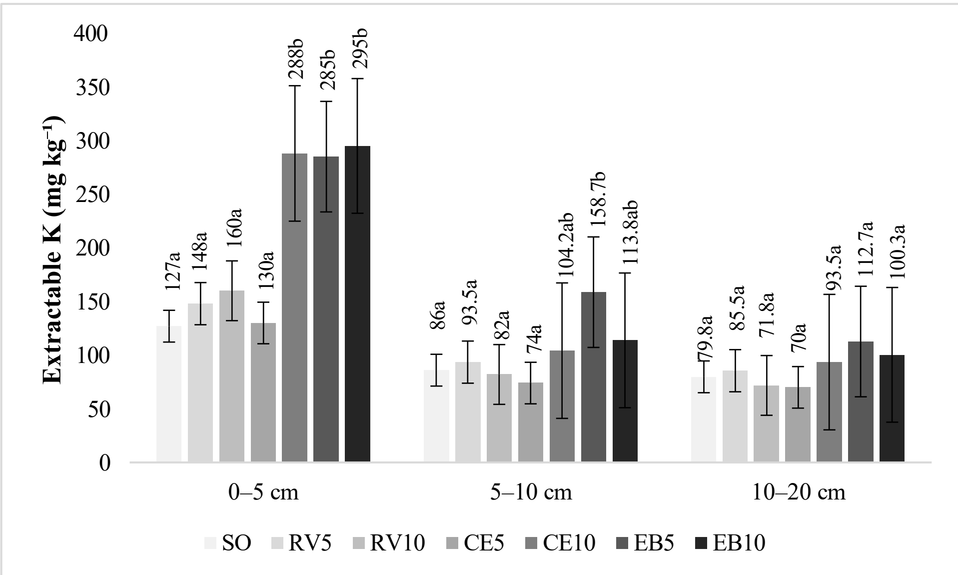

Figure 20. Extractable potassium (K) concentration at depths 0–5 cm, 5–10 cm and 10–20 cm under treatments SO (original soil), RV5 and RV10 (green residues, 5 and 10 Mg ha^{-1}), CE5 and CE10 (stabilized compost, 5 and 10 Mg ha^{-1}), and EB5 and EB10 (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments as determined by the Kruskal–Wallis test followed by Dwass–Steel–Critchlow–Fligner pairwise comparisons ($p < 0.05$) (n=126).

At the 0–5 cm layer, the Kruskal–Wallis test indicated a significant overall effect of treatments on potassium concentrations ($p < 0.05$). Treatments CE10, EB5, and EB10 presented significantly higher potassium concentrations than the original soil (SO), with values exceeding 200 mg kg^{-1}, classified as very high according to Santos (2015), whereas SO, RV5, RV10, and CE5 ranged between 101 and 200 mg kg^{-1}, classified as high. The highest concentrations were recorded under EB10 (295 mg kg^{-1}), CE10 (288 mg kg^{-1}), and EB5 (285 mg kg^{-1}).

At the 5–10 cm depth, potassium concentrations also differed significantly among treatments ($p = 0.035$) as determined by the Kruskal–Wallis test. Higher mean values were observed in EB5 and EB10, whereas lower concentrations occurred in CE5 and SO.

At the 10–20 cm layer, no significant differences among treatments were observed ($p > 0.05$). Nevertheless, CE10, EB5, and EB10 tended to present higher potassium concentrations than the original soil, whereas RV10 and CE5 showed comparatively lower values. The reduction in treatment effects with increasing depth suggests a greater influence of surface-applied amendments in the upper soil layers, where organic residues are concentrated and decomposition processes are more active.

Overall, treatments based on donkey manure (EB) and stabilized compost (CE10) significantly increased soil extractable potassium concentrations in the surface layer, with CE10, EB5, and EB10 reaching high classification levels (>200 mg kg^{-1}; Santos, 2015). Potassium availability in soils amended with organic residues is strongly associated with residue composition, mineralization rate, and nutrient release during decomposition processes. Previous studies conducted in dryland and Mediterranean-like environments have demonstrated that soil properties and management practices significantly influence extractable potassium dynamics and nutrient availability (Musa et al., 2025).

Potassium is an essential macronutrient involved in several physiological processes in plants, including osmotic regulation, enzyme activation, photosynthesis, and water-use efficiency. The incorporation of organic residues may improve potassium cycling and retention in the soil, particularly in surface horizons where organic matter accumulation and microbial activity are more pronounced. Organic amendments may also enhance nutrient retention by improving soil structure, cation exchange capacity, and biological activity.

4.2.6 Extractable phosphorus

Figure 21 shows the extractable phosphorus (P) concentration at depths 0–5 cm, 5–10 cm, and 10–20 cm under the evaluated treatments.

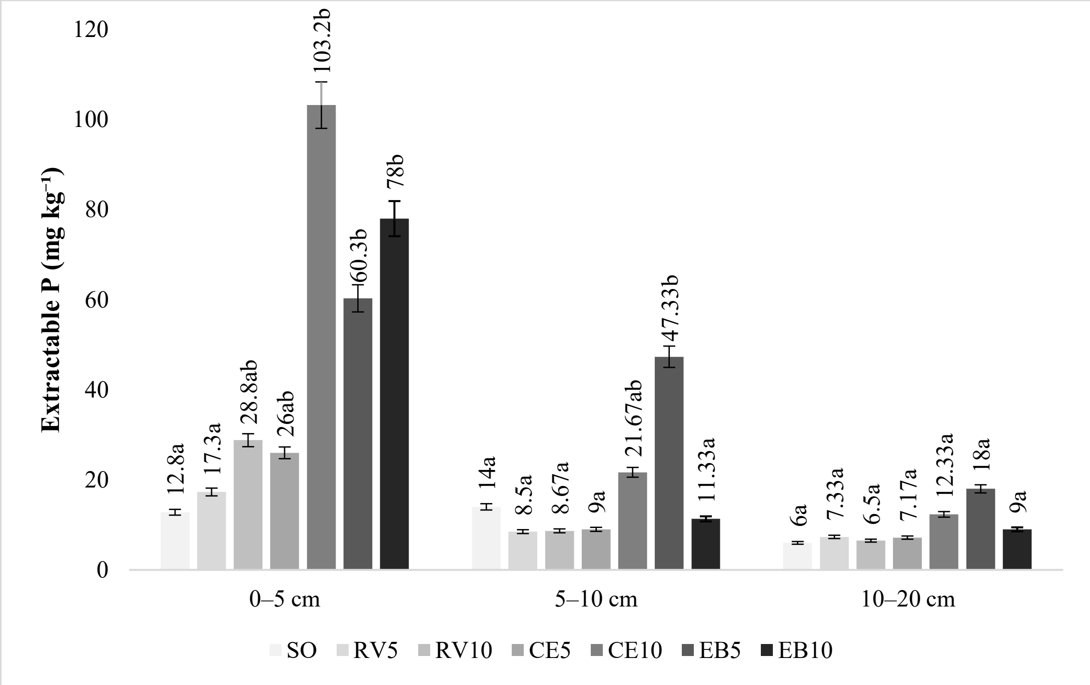

Figure 21. Extractable phosphorus (P) concentration at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV5 and RV10 (green residues, 5 and 10 Mg ha^{-1}), CE5 and CE10 (stabilized compost, 5 and 10 Mg ha^{-1}), and EB5 and EB10 (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments as determined by the Dwass–Steel–Critchlow–Fligner multiple-comparison test following the Kruskal–Wallis analysis ($p < 0.05$) (n=126).

At the 0–5 cm layer, significant differences among treatments were detected by the Kruskal–Wallis test ($p < 0.001$). Treatments CE10, EB5, and EB10 presented significantly higher phosphorus concentrations than SO and RV5, while RV10 and CE5 showed intermediate values. According to the classification proposed by Santos (2015), SO (12.8 mg kg^{-1}) and RV5 (17.3 mg kg^{-1}) were classified as very low, RV10 (28.8 mg kg^{-1}) and CE5 (26 mg kg^{-1}) as low, EB5 (60.3 mg kg^{-1}) and EB10 (78 mg kg^{-1}) as medium, and CE10 (103.2 mg kg^{-1}) as high extractable phosphorus content, highlighting the strong positive effect of compost and manure-based amendments on phosphorus accumulation in the surface layer.

In the 5–10 cm layer, phosphorus concentrations also differed significantly among treatments ($p = 0.045$). The EB5 treatment had the highest mean phosphorus concentration, followed by CE10, while RV5 and RV10 had the lowest values.

At the 10–20 cm depth, no significant differences were observed among treatments ($p > 0.05$). Nevertheless, CE10 and EB5 tended to present higher phosphorus concentrations than the remaining treatments, while SO, RV5, and RV10 showed comparatively lower values. The reduction in treatment effects with increasing depth suggests a greater influence of surface-applied organic amendments in the upper soil layers, where nutrient accumulation and microbial activity are generally more pronounced.

Overall, phosphorus concentrations decreased with soil depth for most treatments, indicating greater nutrient accumulation in the surface layers. This behavior is expected because phosphorus has low mobility in the soil profile and tends to remain concentrated near the soil surface, particularly when residues accumulate in the superficial layers. Similar patterns have been reported in Mediterranean soils, where phosphorus dynamics are strongly influenced by fertilization practices and organic matter decomposition processes (Dong et al., 2025).

The treatments based on stabilized compost (CE10) and donkey manure (EB5 and EB10) generally showed significantly higher phosphorus concentrations compared with the original soil, reaching medium and high classification levels respectively (Santos, 2015). Organic amendments can increase phosphorus availability through direct nutrient addition and through the mineralization of organic matter promoted by microbial activity. Furthermore, organic residues may enhance nutrient cycling and improve phosphorus retention in degraded low-fertility soils.

Phosphorus is an essential macronutrient involved in energy transfer, root development, and several plant metabolic processes. The addition of organic residues may improve phosphorus cycling and nutrient availability in soils, particularly in degraded systems where nutrient limitations are more pronounced. However, phosphorus dynamics are strongly influenced by soil properties, including pH, clay content, and the presence of iron and aluminum oxides, which can promote phosphorus adsorption and reduce nutrient mobility. In Mediterranean soils, phosphorus availability also plays an important role in regulating microbial activity and organic matter decomposition (Dong et al., 2025).

The high variability observed among some treatments, especially those based on donkey manure, may be associated with the heterogeneous distribution of residues on the soil surface and the relatively short experimental period. In acidic soils, phosphorus availability is strongly regulated by adsorption onto Fe and Al oxides, which may partially limit the efficiency of organic amendments in increasing plant-available phosphorus.

4.2.7 Soil pH

Soil pH measured in water (pH H_2O) and potassium chloride solution (pH KCl) was evaluated to assess the influence of organic amendments on soil acidity along the soil profile.

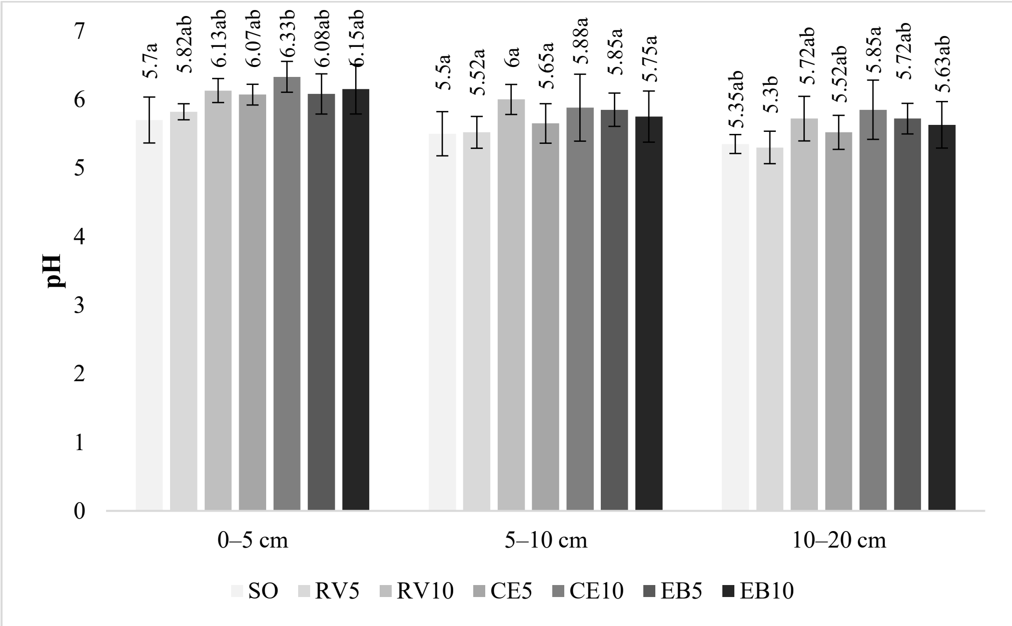

Figure 22. Soil pH measured in water (pH H_2O) at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments, determined by one-way ANOVA followed by Tukey's test or pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) (n = 126).

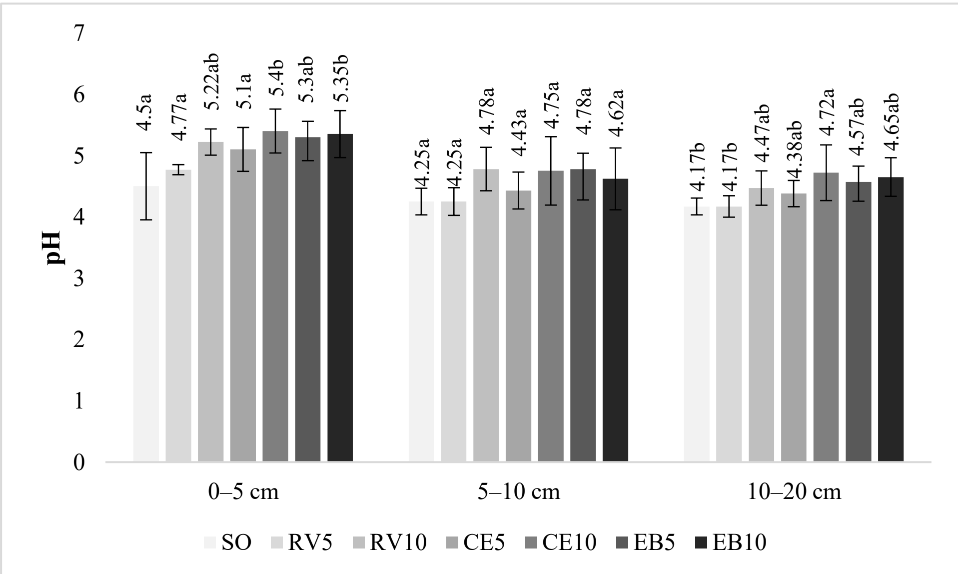

Figure 23. Soil pH measured in KCl solution (pH KCl) at depths 0–5 cm, 5–10 cm, and 10–20 cm under treatments SO (original soil), RV (green residues, 5 and 10 Mg ha^{-1}), CE (stabilized compost, 5 and 10 Mg ha^{-1}), and EB (donkey manure, 5 and 10 Mg ha^{-1}). Bars represent mean values ± standard deviation. Different letters above the bars indicate significant differences among treatments determined by one-way ANOVA followed by Tukey's test or pairwise comparisons following the Kruskal–Wallis test ($p < 0.05$) (n = 126).

At the 0–5 cm depth, significant differences among treatments were observed for both pH H_2O and pH KCl ($p < 0.05$) (Figures 22 and 23). According to the classification proposed by Costa (2018), SO presented an acid reaction (pH H_2O = 5.7), whereas all amended treatments reached slightly acid levels, with CE10 (6.33) and EB10 (6.15) recording the highest pH values. Compared with SO, CE10 and EB10 increased both pH H_2O and pH KCl, indicating a reduction in soil acidity following the application of organic amendments. RV10 and EB5 also showed higher pH values than SO, although with less pronounced effects. The stronger response observed in the 0–5 cm layer suggests that the amendments mainly influenced the soil surface, where residue accumulation and decomposition are more intense.

At the 5–10 cm depth, pH H_2O values did not differ significantly among treatments (Figure 22), although slightly higher values were still observed under RV10, CE10, and EB5 compared with SO. According to Costa (2018), values in this layer ranged from acidic to slightly acidic across all treatments. Similarly, pH KCl also did not show significant differences among treatments (Figure 23), although CE10 and EB10 maintained slightly higher values than SO. These results indicate that the amendments promoted only minor changes in soil acidity and exchange processes within the evaluated layer.

At the 10–20 cm depth, significant differences were again observed for both pH H_2O and pH KCl (Figures 22 and 23). CE10 and EB10 continued to show the highest pH values, classified as slightly acid (Costa, 2018), whereas SO (5.35) and RV5 (5.3) remained in the acid range. Compared with SO, the persistence of higher pH values under CE10 and EB10 suggests that part of the amendment effect extended to deeper soil layers, possibly due to the downward movement of soluble basic cations released during residue decomposition (Fonseca et al., 2017).

The increase in soil pH following amendment application is commonly associated with the addition of basic cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, which neutralize soil acidity and reduce exchangeable Al^{3+} (Brady & Weil, 2010). Organic matter decomposition may also promote proton consumption and increase soil buffering capacity. The stronger response observed for pH KCl compared with pH H_2O suggests that the amendments affected soil exchange processes and acidity dynamics, which are closely related to soil chemical functioning and organic carbon retention in amended soils (Wu et al., 2025).

Soil pH is considered one of the main indicators of soil quality and ecosystem functioning in Mediterranean environments. Andrés-Abellán et al. (2019) identified soil pH as an important component of soil quality assessment in Mediterranean forest soils due to its influence on nutrient availability and soil functioning. Therefore, the higher pH values observed under CE10 and EB10 compared with SO suggest that these amendments may contribute positively to soil recovery processes and improved soil functioning over time.

The increase in pH may also reduce Al toxicity and improve nutrient availability, particularly phosphorus availability, which is frequently constrained in acidic Mediterranean soils.

4.3 Integrated interpretation of soil responses to organic amendments

Overall, the application of organic amendments promoted modest but consistent improvements in several soil quality indicators, particularly in surface chemical properties such as pH, SOC, SOM, nitrogen, phosphorus, and potassium concentrations. In contrast, soil physical properties showed more limited responses during the first year after amendment application. This difference in responsiveness likely reflects the strong influence of intrinsic soil characteristics, especially the high coarse fragment content and shallow profile typical of Mediterranean Leptosols.

The results suggest that chemical indicators respond more rapidly to organic inputs than structural soil properties, which generally require longer periods to undergo detectable modifications. Surface application without incorporation is likely to have concentrated effects within the upper soil layer, where residue decomposition, microbial activity, and nutrient accumulation are more intense.

Although most variables did not show statistically significant differences among treatments, consistent trends observed under donkey manure and stabilized compost treatments indicate a potential trajectory of gradual soil recovery. These findings support the role of organic amendments as a relevant strategy for ecological restoration and soil rehabilitation in degraded Mediterranean environments, particularly under conditions of low soil fertility and high erosion susceptibility.

5. CONCLUSION

The application of organic amendments induced early but limited changes in soil properties one year after implementation, with soil chemical attributes responding faster than physical structure. The strongest effects were consistently observed in the surface layer (0–5 cm), reflecting the direct influence of surface-applied residues and enhanced biological activity in this horizon.

Soil physical properties exhibited high stability across treatments, with no consistent short-term changes in bulk density, porosity, or water-related indicators. This confirms the strong control exerted by the coarse-fragment-rich nature of Mediterranean Leptosols, where structural modifications are constrained and typically require longer timescales to develop.

In contrast, soil chemical indicators responded more rapidly to organic inputs. Increases in pH, available nutrients (P and K), and soil organic carbon and nitrogen were consistently observed, particularly under manure- and compost-based treatments. These trends indicate that organic amendments enhance soil fertility primarily through direct nutrient addition and early-stage decomposition, even when statistical significance is not consistently achieved due to high spatial variability.

Among treatments, manure application (EB) showed the most consistent improvement across chemical properties, likely due to its higher nutrient content and more labile organic fraction, which accelerates nutrient cycling and carbon incorporation into the soil system.

The absence of widespread statistically significant differences reflects the short duration of the experiment, combined with strong spatial heterogeneity and the inherent constraints of shallow, stony Mediterranean soils. Key processes such as aggregate stabilization, carbon stabilization, and long-term structural reorganization operate at longer temporal scales and are not fully captured within a one-year assessment.

Overall, the results demonstrate that organic amendments represent a promising strategy for improving soil fertility in degraded Mediterranean forest ecosystems, particularly under restoration contexts. However, their full benefits in terms of soil structure enhancement and carbon sequestration are expected to emerge only in the medium to long term, highlighting the importance of continued monitoring of this experimental system. These findings support the use of locally available organic amendments as a feasible strategy to improve soil fertility and promote ecological restoration in degraded Mediterranean forest ecosystems.

6. REFERENCES

Agroconsultores & Coba. (1991). Carta dos solos do Nordeste de Portugal. Universidade de Trás-os-Montes e Alto Douro (UTAD).

Aguiar, C. (2001). Flora e vegetação de Trás-os-Montes. Sociedade Portuguesa de Botânica. https://bibdigital.rjb.csic.es/medias/59/61/27/91/59612791-81c4-4df4-a8aa-fe4a94af5547/files/Aguiar_Fl-Nogeira-Montesinho.pdf

Alvarez, R. (2025). Increasing soil organic carbon by applying farm-made organic fertilizers as a function of soil depth: A global synthesis. Science of The Total Environment, 991, 179933. https://doi.org/10.1016/j.scitotenv.2025.179933

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. Nature Communications, 11, 5427. https://doi.org/10.1038/s41467-020-18887-7

Andanvan, S., & Varun, V. (2017). Infiltration, permeability, liquid limit and plastic limit of soil. IJIRST – International Journal for Innovative Research in Science & Technology, 4(6), 19–30.

Andrés-Abellán, M., Wic-Baena, C., López-Serrano, F. R., García-Morote, F. A., Martínez-García, E., Picazo, M. I., & Rubio, E. (2019). A soil-quality index for Mediterranean forest soils. European Journal of Soil Science, 70(5), 1001–1011. https://doi.org/10.1111/ejss.12798

Angelova, V. R., Akova, V. I., Artinova, N. S., & Ivanov, K. I. (2013). The effect of organic amendments on soil chemical characteristics. Bulgarian Journal of Agricultural Science, 19(5), 958–971.

Aoyama, M., Angers, D. A., N'Dayegamiye, A., & Bissonnette, N. (1999). Protected organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. Canadian Journal of Soil Science, 79(3), 419–425. https://doi.org/10.4141/S98-061

Arthur, E., Schjønning, P., Moldrup, P., Tuller, M., & de Jonge, L. W. (2013). Density and permeability of a loess soil: Long-term organic matter effect and the response to compressive stress. Geoderma, 193–194, 236–245. https://doi.org/10.1016/j.geoderma.2012.09.001

Balbino, L. R. (1968). O método de Egner-Riehm na determinação do fósforo e potássio assimiláveis em solos de Portugal. Revista Agronómica, 51, 47–58.

Barzegar, A. R., Yousefi, A., & Daryashenas, A. (2002). The effect of addition of different amounts and types of organic materials on soil physical properties and yield of wheat. Plant and Soil, 247, 295–301. https://doi.org/10.1023/A:1021561628045

Bastida, F., Selevsek, N., Torres, I.F., Hernández, T., García, C., (2015). Soil restoration with organic amendments: Linking cellular functionality and ecosystem processes. Scientific Reports 5, 15550. https://doi.org/10.1038/srep15550

Bastida, F., Zsolnay, A., Hernández, T., García, C. (2008). Past, present and future of soil quality indices: A biological perspective. Geoderma 147, 159–171. https://doi.org/10.1016/j.geoderma.2008.08.007

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47(2), 151–163. https://doi.org/10.1111/j.1365-2389.1996.tb01386.x

Bernal, M. P., Paredes, C., Sánchez-Monedero, M. A., & Cegarra, J. (1998). Maturity and stability parameters of composts prepared with a wide range of organic wastes. Bioresource Technology, 63(1), 91–99. https://doi.org/10.1016/S0960-58524(97)00084-9

Bernhard, A. (2010). The nitrogen cycle: Processes, players and human impact. Nature Education Knowledge, 3(10), 25.

Borrelli, P., Alewell, C., Alvarez, P., Ayach Anache, J. A., Baartman, J., Ballabio, C., ... & Panagos, P. (2021). Soil erosion modelling: A global review and statistical analysis. Science of the Total Environment, 780, 146494. https://doi.org/10.1016/j.scitotenv.2021.146494

Boubehziz, S., Cooledge, E. C., Chadwick, D. R., Barrón, V., Sánchez-Rodríguez, A. R., & Jones, D. L. (2026). Soil preservation in warming climate: Organic amendments enhance microbial carbon use efficiency in Mediterranean soils. European Journal of Soil Science, e70323. Advance online publication. https://doi.org/10.1111/ejss.70323

Brady, N. C., & Weil, R. R. (2010). Elements of the nature and properties of soils (3rd ed.). Pearson.

Bruni, E., Guenet, B., Huang, Y., Clivot, H., Virto, I., Farina, R., Kätterer, T., Ciais, P., Martin, M., & Chenu, C. (2021). Additional carbon inputs to reach a “4 per 1000” objective in Europe: Feasibility and projected impacts of climate change based on Century simulations of long-term arable experiments. Biogeosciences, 18, 3981–4004. https://doi.org/10.5194/bg-18-3981-2021

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pullman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. Soil Biology and Biochemistry, 120, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Chantigny, M.H., (2003). Dissolved and water-extractable organic matter in soils: A review on the influence of land use and management practices. Geoderma 113, 357–380. https://doi.org/10.1016/S0016-7061(02)00370-1

Chassé, M., Lutfalla, S., Cécillon, L., Baudin, F., Abiven, S., Chenu, C., & Barré, P. (2021). Long-term bare-fallow soil fractions reveal thermo-chemical properties controlling soil organic carbon dynamics. Biogeosciences, 18, 1703–1721. https://doi.org/10.5194/bg-18-1703-2021

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chakravarty, M., & Maity, S. (2013). Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. International Journal of Scientific and Research Publications, 3(2), 1–8. IJSRP article

Conant, R. T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyvönen, R., Kirschbaum, M. U. F., Lavallee, J. M., Leifeld, J., Parton, W. J., Megan Steinweg, J., Wallenstein, M. D., Wetterstedt, J. Å. M., & Bradford, M. A. (2011). Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. Global Change Biology, 17(11), 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Costa, J. B. (2018). Caracterização e constituição do solo (9. ed.). Lisboa: Fundação Calouste Gulbenkian. 528 p.

Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. Nature Geoscience 12, 989–994. https://doi.org/10.1038/s41561-019-0484-6

Cousin, I., Nicoullaud, B., Coutadeur, C., (2003). Influence of rock fragments on the water retention and water percolation in a calcareous soil. Catena 53, 97–114. https://doi.org/10.1016/S0341-8162(03)00037-7

Delgado-Baquerizo, M., Reich, P. B., Trivedi, C., Eldridge, D. J., Abades, S., Alfaro, F. D., Bastida, F., Berhe, A. A., Cutler, N. A., Gallardo, A., García-Velázquez, L., Hart, S. C., Hayes, P. E., He, J.-Z., Hseu, Z.-Y., Hu, H.-W., Kirchmair, M., Neuhauser, S., Pérez, C. A., … Singh, B. K. (2020). Multiple elements of soil biodiversity drive ecosystem functions across biomes. Nature Ecology & Evolution, 4, 210–220. https://doi.org/10.1038/s41559-019-1084-y

Dimitrov, R. S. (2016). The Paris agreement on climate change: Behind closed doors. Global Environmental Politics, 16(3), 1–11. https://doi.org/10.1162/GLEP_a_00361

Dong, X., Vera, A., García-Díaz, C., García, C., Zhang, W., & Bastida, F. (2025). Excessive phosphorus (P) fertilization reduces the soil priming effect in a Mediterranean soil. Applied Soil Ecology, 210, 106715.https://doi.org/10.1016/j.apsoil.2025.106715

Esmaeilzadeh, J., & Ahangar, A. G. (2014). Influence of soil organic matter content on soil physical, chemical and biological properties. International Journal of Plant, Animal and Environmental Sciences, 4(4), 244–252.

FAO & ITPS, (2021). Global Assessment of Soil Pollution. Food and Agriculture Organization of the United Nations, Rome.

Figueiredo, T. (2011). *Determinação laboratorial da condutividade hidráulica do solo e realização de exercícios sobre a exploração de aquíferos*. Mestrado em Tecnologia Ambiental, Escola Superior Agrária de Bragança, Portugal.

Figueiredo, T. (2012). *Pedregosidade dos solos em Trás-os-Montes: importância relativa e distribuição espacial*. Instituto Politécnico de Bragança, Portugal. 79 p. http://hdl.handle.net/10198/8525

Figueiredo, T., & Fonseca, F. (2009). Distribuição dos elementos grosseiros no solo e amostragem de solos pedregosos. *Encontro Anual da Sociedade Portuguesa da Ciência do Solo: Resumos*.

Fonseca, F. (2024). Relatório do projeto UP4REHAB sobre a monitorização dos solos. Projeto UP4REHAB.

Fonseca, F., Figueiredo, T., & Martins, A. (2014). Carbon storage as affected by different site preparation techniques two years after mixed forest stand installation. Forest Systems, 23(1), 84–92. https://doi.org/10.5424/fs/2014231-04233

Fonseca, F., Figueiredo, T., Nogueira, C., Queirós, A., (2017). Effect of prescribed fire on soil properties and soil erosion in a Mediterranean mountain area. Geoderma 307, 172-180.

Fonseca, F., Figueiredo, T., Vilela, A. M. A., Santos, R., Carvalho, A. L.Almeida, E. & Nunes, L. (2019) Impact of tree species replacement on carbon stocks in a Mediterranean mountain area, NE Portugal. Forest Ecology and Management 439: 181-188

Fonseca, F., Silva, D., Bueno, P., Hernández, Z., Royer, A.C., Figueiredo, T., (2022). Temporal dynamics of carbon storage in mountain shrub areas managed by prescribed fire. Catena 212, 106107.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., et al. (2023). Global Carbon Budget 2023. Earth System Science Data, 15(12), 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

Friedlingstein, P., O'Sullivan, M., Jones, M.W., et al., (2022). Global Carbon Budget 2022. Earth System Science Data 14, 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

Gao, H., Gong, J., Liu, J., Wen, X., Huang, L., & Maier, M. (2025). Modeling of soil organic carbon stock and sequestration potential in grassland and cropland in Qinghai-Tibet Plateau: Prediction and carbon management strategies based on different climate scenarios. Catena,246, 109545.https://doi.org/10.1016/j.catena.2025.109545

García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Arcenegui, V., & Caravaca, F. (2016). Soil structural stability and organic carbon in Mediterranean ecosystems affected by fire and agricultural management. Catena, 140, 1–10.

García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N., Beguería, S., (2013). Erosion in Mediterranean landscapes: Changes and future challenges. Geomorphology 198, 20–36. https://doi.org/10.1016/j.geomorph.2013.05.023

Gómez-Rey, M. X., Coutinho, J., & Gonzalez-Prieto, S. J. (2012). Distribution and evolution of nutrients in forest soils under Mediterranean climatic conditions. Plant and Soil, 353, 221–234.

Gössling, S., Balas, M., Mayer, M., & Sun, Y. (2023). A review of tourism and climate change mitigation: The scales, scopes, stakeholders and strategies of carbon management. *Tourism Management, 95*, 104681. https://doi.org/10.1016/j.tourman.2022.104681

Han, Z., Wu, X., Gao, H., Jia, A., & Gao, Q. (2025). Long-term conservation tillage increases soil organic carbon stability by modulating microbial nutrient limitations and aggregate protection. *Agronomy, 15*(7), 1571. https://doi.org/10.3390/agronomy15071571

ICNF. (2013). *Adaptação das florestas às mudanças climáticas*. Instituto da Conservação da Natureza e das Florestas, Portugal. https://www.icnf.pt/api/file/doc/8f0f4314f8a4f0d3

Intergovernmental Panel on Climate Change (IPCC). (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. https://www.ipcc.ch/report/ar6/syr/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2018). The IPBES assessment report on land degradation and restoration. IPBES Secretariat. https://doi.org/10.5281/zenodo.3237392

IPCC. (2007). Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, R. K. Pachauri & A. Reisinger, Eds.). IPCC, Geneva, Switzerland. https://www.ipcc.ch/report/ar4/syr/

Jacobi, P. R., Guerra, A. F. S., Sulaiman, S. N., & Nepomuceno, T. (2011). Mudanças climáticas globais: A resposta da educação. Revista Brasileira de Educação, 16(46), 135–148.http://educa.fcc.org.br/scielo.php?script=sci_arttext&pid=S14132478201100010000 8&lng=pt&tlng=pt

Jarvis, N., (2007). A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. European Journal of Soil Science 58, 523–546. https://doi.org/10.1111/j.1365-2389.2007.00915.x

Kan, Z.-R., Liu, W.-X., Liu, W.-S., Lal, R., Dang, Y. P., Zhao, X., & Zhang, H.-L. (2021). Mechanisms of soil organic carbon stability and its response to no-till: A global synthesis and perspective. Global Change Biology, 27(21), 5227–5246. https://doi.org/10.1111/gcb.15968

Karami, A., Homaee, M., Afzalinia, S., Ruhipour, H., & Basirat, S. (2012). Organic resource management: Impacts on soil aggregate stability and other soil physico chemical properties. *Agriculture, Ecosystems & Environment, 148*. https://doi.org/10.1016/j.agee.2011.10.021

Kleber, M., Sollins, P., Sutton, R., (2007). A conceptual model of organo-mineral interactions in soils: Self-assembly of organic molecular fragments into zonal structures on mineral surfaces. Biogeochemistry 85, 9–24. https://doi.org/10.1007/s10533-007-9103-5

Krull, E. S., Skjemstad, J. O., & Baldock, J. A. (2004). Functions of soil organic matter and the effect on soil properties. Grain Research & Development Corporation, Residue Management, Soil Organic Carbon and Crop Performance, Project No. CSO00029. https://grdc.com.au/ data/assets/pdf_file/0012/212034/functions-of-soil-organic-matter-and-the-effect-on-soil-properties.pdf.pdf

Kumar, Y., Kaushal, S., Kaur, G., & Gulati, D. (2020). Effect of soil organic matter on physical properties of soil. Just agriculture, 1(2), 25-30

Lal, R. (2004). Soil carbon sequestration mitigates climate change. Geoderma, 123(1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal, R. (2008). Promise and limitations of soils to minimize climate change. Journal of Soil and Water Conservation, 63(4), 113A–118A. https://doi.org/10.2489/jswc.63.4.113A

Lal, R. (2010). Global potential of soil carbon sequestration to mitigate the greenhouse effect. Critical Reviews in Plant Sciences, 29(3), 151–184. https://doi.org/10.1080/07352689.2010.484909

Larney, F. J., & Angers, D. A. (2012). The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science, 92(1), 19–38. https://doi.org/10.4141/cjss2010-064

Lazcano, C., Gómez-Brandón, M., Revilla, P., & Domínguez, J. (2013). Short-term effects of organic and inorganic fertilizers on soil microbial community structure and function. Biology and Fertility of Soils, 49, 723–733.

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528(7580), 60–68. https://doi.org/10.1038/nature16069

Lehmann, J., Hansel, C. M., Kaiser, C., et al. (2020). Persistence of soil organic carbon caused by functional complexity. Nature Geoscience, 13, 529–534. https://doi.org/10.1038/s41561-020-0612-3

Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., & Spiegel, H. (2014). Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. Soil Use and Management, 30(4), 524–538. https://doi.org/10.1111/sum.12151

Lorenz, K., & Lal, R. (2018). Soil carbon stock. In Carbon sequestration in agricultural ecosystems (pp. 39–116). Springer. https://doi.org/10.1007/978-3-319-92318-5_2

Lu, M., Zeng, F., Lv, S., Zhang, H., Zeng, Z., Peng, W., Song, T., Wang, K., & Du, H. (2023). Soil C:N:P stoichiometry and its influencing factors in forest ecosystems in southern China. Frontiers in Forests and Global Change, 6, 1142933. https://doi.org/10.3389/ffgc.2023.1142933

Manzoni, S., Trofymow, J.A., Jackson, R.B., Porporato, A., (2010). Stoichiometric controls on carbon, nitrogen, and phosphorus dynamics in decomposing litter. Ecological Monographs 80, 89–106. https://doi.org/10.1890/09-0179.1

Martin, M. P., Dimassi, B., Dobarco, M. R., Guenet, B., Arrouays, D., Angers, D. A., Blache, F., Huard, F., Soussana, J., & Pellerin, S. (2021). Feasibility of the 4 per 1000 aspirational target for soil carbon: A case study for France. Global Change Biology, 27(11). https://doi.org/10.1111/gcb.15547

Matschullat, J., Reimann, C., Birke, M., dos Santos Carvalho, D., & the GEMAS Project Team. (2018). GEMAS: CNS concentrations and C/N ratios in European agricultural soil. Science of The Total Environment, 627, 975–984. https://doi.org/10.1016/j.scitotenv.2018.01.214

Memoli, V., De Marco, A., Baldantoni, D., De Nicola, F., & Maisto, G. (2017). Short- and long-term effects of a single application of two organic amendments. Ecosphere, 8(11), e02009. https://doi.org/10.1002/ecs2.2009

Mooshammer, M., Wanek, W., Schnecker, J., et al., (2014). Stoichiometric controls of nitrogen and phosphorus cycling in decomposing beech leaf litter. Ecology 95, 2471–2480. https://doi.org/10.1890/13-1839.1

Mossio, L. S. M. (2024). Efeitos de curto prazo da aplicação de corretivos orgânicos em solos florestais (Dissertação de mestrado, Instituto Politécnico de Bragança, Escola Superior Agrária, Bragança, Portugal).

Murphy, B. W. (2015). Impact of soil organic matter on soil properties – A review with emphasis on Australian soils. Soil Research, 53(6). https://doi.org/10.1071/SR14246

Murphy, B., Newey, A., & Greene, R. (2019). Decomposition of plant litter and carbon turnover as a function of soil depth. In Going Downunder: Deep SOM Dynamics. https://conferences.com.au/decomposition-of-plant-litter-and-carbon-turnover-as-a-function-of-soil-depth/

Musa, M., Elsheikh, M. A., Siddig, M. M. S., et al. (2025). Integrating machine learning and environmental–soil variables for estimating soluble and exchangeable potassium in dryland regions: Agronomical implications. Plant and Soil, 516, 217–239. https://doi.org/10.1007/s11104-025-07717-8

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D. L. Sparks et al. (Eds.), Methods of Soil Analysis, Part 3: Chemical Methods (pp. 961–1010). SSSA/ASA.

Neves, A. F. F. (2015). Técnicas de análise laboratorial para solos, material vegetal e corretivos orgânicos (Dissertação de mestrado, Universidade do Minho, Portugal).

Novara, A., Pulido, M., Rodrigo-Comino, J., et al., (2019). Soil carbon dynamics after land-use change in Mediterranean ecosystems. Catena 182, 104–114.

Pacheco, M. R. P. dos S., & Helene, M. E. M. (1990). Atmosfera, fluxos de carbono e fertilização por CO_2. Estudos Avançados, 4(9), 204–220. https://doi.org/10.1590/S0103-40141990000200010

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. Nature, 532(7597), 49–57. https://doi.org/10.1038/nature17174

Percival, H. J., Parfitt, R. L., & Scott, N. A. (2000). Factors controlling soil carbon levels in New Zealand grasslands: Is clay content important? Soil Science Society of America Journal, 64(5), 1623–1630. https://doi.org/10.2136/sssaj2000.6451623x

Pereira, K. R. B. (2019). Propriedades físico-químicas de solos com diferentes teores de matéria orgânica nas regiões de montanha do NE de Portugal (Dissertação de mestrado, Escola Superior Agrária, Instituto Politécnico de Bragança, Portugal)

Pires, A., Fonseca, F., & Figueiredo, T. (2016). Pedregosidade como indicador do estado de degradação física dos solos. In III Encontro de Jovens Investigadores do Instituto Politécnico de Bragança: Livro de Resumos.

Poesen, J., Lavee, H., (1994). Rock fragments in top soils: Significance and processes. Catena 23, 1–28. https://doi.org/10.1016/0341-8162(94)90050-7

Porta, J., López-Acevedo, M., & Roquero, C. (2003). Edafología para la agricultura y el medio ambiente. Madrid: Ediciones Mundi-Prensa.

Prybil, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. Geoderma, 156(3–4), 75–83. https://doi.org/10.1016/j.geoderma.2010.02.003

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., (2003) . Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/S0016-7061(03)00094-6

Rei, F. C. F., Gonçalves, A. F., & Souza, L. P. de. (2017). Paris Agreement: Reflections and challenges for the international climate change regime. Veredas do Direito, 14(29), 81–99. https://doi.org/10.18623/rvd.v14i29.996

Robinson, D. A., Bentley, L., Jones, L., Feeney, C., Garbutt, A., Tandy, S., Lebron, I., Thomas, A., Reinsch, S., Norton, L., & Maskell, L. (2024). Five decades' experience of long-term soil monitoring, and key design principles, to assist the EU soil health mission. European Journal of Soil Science. https://doi.org/10.1111/ejss.13570

Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M. G., Kaonga, M., Koutika, L. S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J. F., Whitehead, D., & Wollenberg, E. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio, 49, 350–360. https://doi.org/10.1007/s13280-019-01165-2

Sanderman, J., Henry, B. K., & Bryan, B. A. (2017). Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences, 114(36), 9575–9580. https://doi.org/10.1073/pnas.1706103114

Santos, F. L., Martins, O. C., & Gonçalves, M. C. (2012). Hidrologia agrícola. Universidade de Évora. https://dspace.uevora.pt/rdpc/bitstream/10174/7233/1/Capitulo7_HidrologiaAgricola_final_Formatado2a.pdf

Santos, J.Q., (2015). Fertilização, Fundamentos agroambientais da utilização dos adubos e correctivos. Publindústria, Lisboa. Hill Laboratories (s.d.). Soil tests and interpretation:

Technical note. Hill Laboratories, Hamilton, New Zealand. Disponível em: https://www.hilllabs.co.nz/media/djdbzzhl/3196v6_technical-note-soil-tests-and-interpretation.pdf

Santos, I. N. (2022). Impacto do fogo controlado na estabilidade da agregação do solo em áreas de matos do Parque Natural de Montesinho, NE Portugal (Dissertação de mestrado, Escola Superior Agrária, Instituto Politécnico de Bragança, Portugal)

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S., & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. Nature, 478(7367), 49–56. https://doi.org/10.1038/nature10386

Seitz, D., Dechow, R., Emde, D., Schneider, F., & Don, A. (2025). Improved broad-scale modelling of soil organic carbon dynamics following land-use changes. European Journal of Soil Science. https://doi.org/10.1111/ejss.70159

Six, J., Bossuyt, H., Degryze, S., Denef, K., (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research 79, 7–31. https://doi.org/10.1016/j.still.2004.03.008

Tou, C., Liu, X., Gan, J., Wanek, W., Jones, D. L., Wu, L., & Ma, Q. (2025). Plant residue quality regulates its incorporation into soil aggregates and organic carbon stabilisation. Geoderma, 460, 117407. https://doi.org/10.1016/j.geoderma.2025.117407

University Corporation for Atmospheric Research (UCAR). (2007). Biogeochemical cycles. https://scied.ucar.edu/learning-zone/earth-system/biogeochemical-cycles

Wang, F., Tong, Y. A., Zhang, J. S., Gao, P. C., & Coffie, J. N. (2013). Effects of various organic materials on soil aggregate stability and soil microbiological properties on the Loess Plateau of China. Plant, Soil and Environment, 59(4), 162–168. https://doi.org/10.17221/567/2012-PSE

Wang, H., Boutton, T. W., Xu, W., Hu, G., Jiang, P., & Bai, E. (2015). Quality of fresh organic matter affects priming of soil organic matter and substrate utilization patterns of microbes. Scientific Reports, 5, 10102. https://doi.org/10.1038/srep10102

Wang, S., Liang, X., Luo, Q., et al. (2012). Fertilization increases paddy soil organic carbon density. Journal of Zhejiang University-Science B, 13, 274–282. https://doi.org/10.1631/jzus.B1100145

Waring, B., & Bradford, M. A. (2024). Legacy effects constrain soil restoration trajectories. Global Change Biology, 30, e17082. https://doi.org/10.1111/gcb.17082

Wu, B., Bai, T., Yu, W., Zhu, T., Li, D., Ye, C., Liu, M., & Hu, S. (2025). Soil pH and precipitation controls on organic carbon retention from organic amendments across soil orders: A meta-analysis. Soil Biology and Biochemistry, 207, 109819. https://doi.org/10.1016/j.soilbio.2025.109819

Xu, J., Li, Y., & Li, L. (2025). A comprehensive review of the effects of organic amendments on soil health and fertility: Mechanisms, greenhouse gas emissions, and implications for sustainable agriculture. Agronomy, 15(12), 2705. https://doi.org/10.3390/agronomy15122705