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PRÁTICAS DE REGENERAÇÃO DE SOLOS PÓS-INCÊNDIO: ESTUDOS PRELIMINARES
POST-FIRE SOILS REGENERATION PRACTICES: PRELIMINARY STUDIES
PRÁCTICAS DE REGENERACIÓN DE SUELOS POST-INCENDIO: ESTUDIOS PRELIMINARES

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RESUMO

Introdução: Os incêndios florestais alteram significativamente as propriedades do solo, reduzindo a fertilidade, a matéria orgânica e a atividade biológica.

Objetivo: Avaliar práticas de regeneração do solo pós-incêndio em ambientes mediterrânicos, comparando a regeneração natural com diferentes opções de recuperação do solo através da aplicação de material orgânico, o composto.

Métodos: Inicialmente foi feita a caracterização das áreas não queimadas (UB) e queimadas (B), avaliando os efeitos do fogo sobre as propriedades físicas e químicas do solo. Em seguida, as 2 áreas UB e B foram utilizadas para desenvolver diferentes opções de regeneração do solo através da aplicação de compostos produzidos a partir de resíduos urbanos e agroflorestais.

Resultados: O fogo tem um impacto negativo nos solos em termos de aspetos químicos e biológicos. Apesar de preliminares, os resultados mostram que a recuperação de solos queimados com a aplicação de composto mostra-se como uma metodologia importante, que parece melhorar os solos e simultaneamente contribuir para a sustentabilidade da gestão de resíduos urbanos e agroflorestais.

Conclusão: Estes resultados contribuem para o desenvolvimento de estratégias de gestão ecológicas pós-incêndio.

Palavras-chave: biomassa microbiana; composto; regeneração do solo; solos pós-incêndio

ABSTRACT

Introduction: Wildfires significantly alter soil properties, reducing fertility, organic matter, and biological activity.

Objective: To evaluate post-fire soil regeneration practices in Mediterranean environments, comparing natural regeneration with different soil restoration options involving the application of organic material, specifically compost.

Methods: Initially, it was made the unburned (UB) and burned (B) areas were characterized, evaluating the effects of fire on the physico-chemical properties of the soil. Then, the 2 areas, UB and B, were used to develop different soil restoration options through the application of composts produced from urban and agroforestry wastes.

Results: Fire has a negative impact on soils in terms of both chemical and biological aspects. Although preliminary, the results show that the restoration of burnt soils through the application of compost is an important approach, which appears to improve soil quality whilst contributing to the sustainability of urban and agroforestry waste management.

Conclusion: These findings contribute to the development of ecological post-fire management strategies.

Keywords: microbial biomass; compost; soil regeneration; post-fire soils

RESUMEN

Introducción: Los incendios forestales alteran significativamente las propiedades del suelo, reduciendo la fertilidad, la materia orgánica y la actividad biológica.

Objetivo: Evaluar las prácticas de regeneración del suelo tras un incendio en entornos mediterráneos, comparando la regeneración natural con diferentes opciones de recuperación del suelo mediante la aplicación de materia orgánica, el compost.

Métodos: Inicialmente, se realizó la caracterización de las áreas no quemadas (UB) y quemadas (B), evaluando los efectos del fuego sobre las propiedades físicas y químicas del suelo. A continuación, se utilizaron las 2 áreas UB y B para desarrollar diferentes opciones de restauración de suelos mediante la aplicación de compost producido a partir de residuos urbanos y agroforestales

Resultados: El fuego tiene un impacto negativo en los suelos desde el punto de vista químico y biológico. Aunque son preliminares, los resultados muestran que la recuperación de suelos quemados mediante la aplicación de compost se perfila como una metodología importante, que parece mejorar los suelos y, al mismo tiempo, contribuir a la sostenibilidad de la gestión de residuos urbanos y agroforestales.

Conclusión: Estos hallazgos contribuyen al desarrollo de estrategias ecológicas de manejo post-incendio.

Palabras clave: biomasa microbiana; compost; regeneración del suelo; suelos post-incendio

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INTRODUCTION

Nowadays, there is an increasing effort for raising global awareness about the importance of soils in order to ensure food security, to improve agricultural and environmental planning and monitoring, and to establish effective and sustainable land management policies to counteract soil degradation. However, understanding the effects of fire on the soil system is a major issue required for managing natural landscapes for ecosystem restoration purposes. Wildfires can affect soil properties and nutrient cycling; thus, a proper restoration practice can stabilize and mitigate negative effects.

In Portugal, wildfires are a frequent and severe environmental problem. Due to a combination of climatic conditions, land-use practices, and rural exodus, thousands of hectares burn every year, causing major ecological and socio-economic damage. This reality highlights the urgency of studying wildfire impacts on soil and improving post-fire recovery strategies in fire-prone regions. Soil regeneration is essential to restore ecosystems affected by wildfires, which can cause significant soil degradation, erosion, and nutrient loss. Although post-fire strategies are needed to address local soil and hydrological conditions to prevent further degradation, integrating sustainable practices such as agroforestry and leveraging microbial symbiosis can facilitate long-term recovery and conservation. Research gaps in post-fire soil regeneration practices include the long-term effectiveness of techniques, optimal combinations of methods, and the recovery of soil biological properties. There is a limited understanding of how local conditions affect restoration success, and the role of biochar and organic amendments needs further exploration. The impact of climate change on regeneration strategies also requires more investigation, alongside comprehensive cost-benefit analyses. Additionally, new monitoring technologies, such as remote sensing, can improve efficiency. Finally, integrating local communities into regeneration efforts is underexplored, highlighting the need for more inclusive and region-specific solutions. Moreover, challenges in scaling and standardizing the restore practices remain and require robust evaluation frameworks.

This study aims to evaluate the consequences of fires on the soil properties by monitoring their physico-chemical and biological parameters. The main purpose was to define strategies to achieve soil restoration after wildfires with the application of different composts, pre and post characterization. The initial phase of the work was dedicated to evaluating the effects of fire on the soil. Followed by the application of two types of compost as restoration practices, and the assessment of the effects of these composts on the soil selected. It will be possible to increase knowledge of soil restoration through the application of organic materials, besides the rise of waste valorization.

1. THEORETICAL FRAMEWORK

In the Mediterranean Basin, changes in climate and fire regime (increased recurrence and severity) reduce ecosystem services after fires, which are linked to changes in soil biota, by increasing soil degradation and losses in plant diversity (Moya et al., 2019). High burn severity limits natural vegetation recovery and reduces biological soil functionality. Soil resources cannot be renewed within a human's lifetime. Therefore, it is fundamental to address future global challenges such as climate change, water scarcity, loss of biodiversity, human health, and food security. Post-fire impacts on soil degradation depend on the fire history, environmental conditions of the area, and human management. Burned land, without organic matter, does not produce aggregates, and the soil loses its porosity. Thus, rainwater does not penetrate the soil surface and eventually runs down, eroding fields and pastures. With less porosity, soil ventilation is reduced, chemical reactions slow, some important minerals for nutrition become toxic, the plant metabolism becomes slow, and vegetation grows poorly and weakly. Under such conditions, crop productivity is poor, even with high fertilization. Soil dynamics depend not only on physico-chemical properties, but also on micro-fauna and microbiological health because the return of vegetation after a fire is directly impacted by the activity of these organisms. These organisms are responsible not only for the decomposition of organic matter and the formation of humus, but also for closing the biogeochemical cycles, which ensures that essential nutrients are available for plants. Some types of post-fire interventions are: salvage logging, site preparation (e.g. ripping), mulching (e.g. with straw), seeding, erosion barriers application, and channel treatments (Pereira et al., 2018). However, some interventions can increase soil degradation: salvage logging, which is carried out in the period immediately after a fire, and site preparation can lead to soil degradation (e.g., soil compaction, aggregate stability, organic matter loss, and reduction of carbon sequestration) and have negative impacts on the vegetation recuperation capacity (Slesak et al., 2015). On the other hand, mulching practices, using organic additives, reduce soil degradation (Pereira et al., 2018).

Overall, post-fire management options can trigger or reduce soil degradation in burned areas. Soil restoration and protection are urgent, but their ecological suitability can only be achieved using methods that improve the natural ecosystem. Mulching has a high capacity to reduce overland flow and soil erosion and to increase some major cation nutrients. It can modulate nitrogen transformation during the critical winter–spring period following fire events, contributing to soil stabilization and diminishing nutrient leaching (Fernández-Fernández et al., 2022).

However, the impacts of mulching on the quality and quantity of soil organic matter (SOM), as well as on vegetation recovery, remain poorly studied (De la Rosa et al., 2019; Keizer et al., 2019). Since SOM is the most functional fraction of many soils and, hence, a widely used indicator of soil health and quality, it is important to increase the knowledge of this interaction. Restoring soils using stabilized organic wastes, such as compost, as an amendment, it is not only sustainable but also accelerates the recovery of the burned soils ecosystem by correcting unbalanced physico-chemical and microbiological parameters, while compost or residues serve as microorganisms inoculation (Vaz-Moreira et al., 2008). Moreover, post-fire soil compost addition can stimulate microbial recovery and enhance soil enzymatic activities, accelerating ecological succession and vegetation establishment (Jiménez-Morillo et al., 2020; Wang & Fu, 2020). Moreover, the use of compost contributes to closing the circular economy loop. So, composting is a key process within circular economy framework~~s~~, as it enables the biotransformation of organic waste into stable, nutrient-rich amendments. Its application in post-fire landscapes has shown particular relevance, since wildfires often cause severe depletion of soil organic matter, nutrient volatilization, and loss of microbial activity (Jiménez-González et al., 2016). By incorporating compost or similar organic amendments, essential macronutrients such as nitrogen, phosphorus, and potassium are replenished, while soil structure and water retention capacity are improved (Cellier et al., 2012; Guerrero et al., 2001). Recent findings also highlighted that compost amendment type and frequency of application can determine long-term effects on nutrient cycling and plant community composition in fire-impacted grasslands (Anthony et al., 2024).

Nevertheless, most studies involving fire impacts on soil properties in ecosystems have evaluated the effect of short-term rehabilitation techniques on soil erosion and runoff, while others have examined how biotic components respond to long-term restoration activities. Few studies show an integrated physical, chemical, and biological assessment of long-term restoration techniques.

Regarding the influence of meteorological conditions, some studies report that the precipitation/runoff ratio shows an increase in runoff immediately after the fire, which mainly affects the concentration of suspended sediments (Cerdà & Lasanta, 2005). In addition to precipitation, whose influence on fires is well established, the main meteorological variables relevant to fires are the temperature, air humidity, and wind. However, there are few studies that address the trilogy: post-fire soil restoration techniques, meteorological conditions, and soil quality.

2. METHODS

2.1 Study Area and Restoration Practices

In the region of Viseu (Bodiosa parish), Portugal, where fires destroy a significant area every year, a burned (B) area of approximately 0.5 ha and a nearby unburned (UB) area of the same dimensions (used as a control), were selected to ensure the same climate and land conditions. The burned (B) area is located at 40°43’18´´N latitude and 8°00´23´´W longitude, and the unburned (UB) area is located at 40°43’49´´N latitude and 7°57´53´´W longitude. These landscapes were used to develop soil recovery options by spreading organic materials, urban waste (UW), and agroforestry waste (AFW) composts. For both composts, an average of 5kg/m^2. A non-spread area was used as a control. Thus, each study area (B and UB) was therefore divided into three subareas characterized by: no compost, UW compost, and AFW compost treatments.

Soil samples were collected at two time points: initial sampling (t0) in January 2023 and post-treatment sampling (t1) in January 2025. Composts were applied in June 2024, and t1 sampling was conducted six months after application (24 months after t0).

2.2 Soil and Compost Characterization

The first soil sampling was made in January 2023 to characterize the study areas in terms of environmental conditions and physical and chemical properties of the soil. Composite soil samples were collected at two different depths (0-2 cm and 15-20 cm) in the B and UB areas. At each site, five subsamples were collected following a zigzag pattern, combined, and homogenized to form a composite sample.

The environmental conditions, measured with a Krestel weather meter, included temperature, relative humidity, the heat index, the dew point, the wet bulb temperature, atmospheric pressure, and wind speed.

Parameters such as moisture content, total organic matter (TOM), total organic carbon (TOC), ash, pH, and electric conductivity (EC) were determined. At time t1 (January 2025), the microbial biomass, the Growth index (GRI), and the Germination index (GI) were also measured. Characterization was carried out following the standard methods. The microbial biomass was determined following the chloroform fumigation–extraction method described in Amaral and Abelho (2016). Subsamples of freshly sieved soil were fumigated with ethanol-free chloroform (CHC_3) in the dark for 24 h and extracted with 70 mL of 0.5 M K_2SO_4 solution for C and N determination. Dissolved organic C and N were determined according to Tinsley (1950) and the Kjeldahl nitrogen method, respectively. Phosphorus was extracted by adding 30 mL of 0.5 M sodium bicarbonate ($NaHCO_3$; pH 8.5) and was quantified by colorimetry using the Acid Ascorbic Method for Phosphorus (4500-P) from Standard Methods for examination of water and wastewater (APHA, 1998). Microbial biomass C, N, and P were assessed as the difference between the fumigated (soil and intracellular organic elements) and the non-fumigated samples (soil organic elements).

The Growth index (GRI) and Germination index (GI) were used to evaluate according to EN 16086-1:2011. Both tests were made using tomato seeds.

Compost from the urban organic waste recovery plant (UW), as well as compost produced from agroforestry waste (AFW), were used in the restoration practice. The two composts used in the assays were also characterized to evaluate their quality as indicated in the Ordinance nº185/2022 (2022) for corrective organic. The standards used were: EN 13038:2011 for Electrical conductivity

(EC); EN 13037:2011 for pH; EN 13040:2008 for Moisture content, TOM and Ashes content, and EN 13650:2001 for Nutrients and heavy metals. Total organic carbon (TOC) was achieved by dividing TOM by 1.8 (Jiménez and Garcìa, 1992). All analyses were made in triplicate.

3. RESULTS AND DISCUSSION

3.1 Environmental characterization of the study areas

The soils from both areas under study are classified as Cambisols, developed over a dominant lithology of granitoids (Inácio et al., 2008). The UB area is predominantly covered by forest, representing the typical vegetation of the region prior to fire disturbance. They are represented in Figure 1.

Figure 1 – Unburned (A) and burned (B) study areas in the region of Viseu (Map data: Google Earth, January 2023)

A shows a polygonum characterized by a continuous tree and shrub cover, typical of a forested area. The vegetation canopy appears dense, with a heterogeneous distribution of medium-sized trees and understory shrubs. This configuration corresponds to forest or scrubland occupation, likely dominated by Mediterranean *sclerophyllous* species (e.g., *Quercus coccifera*, *Cistus* spp., *Pistacia lentiscus*) or conifer plantations depending on the local context. From a land use perspective, this area aligns with CORINE Land Cover (CLC) class 3.1.2 (Coniferous forest) or 3.2.2 (Scrub and/or herbaceous vegetation associations), depending on the exact floristic composition. The high canopy density indicates limited anthropogenic disturbance, indicating the land use as forestry, biodiversity conservation, or extensive silvopastoral systems. Figure 1. B, representing the B area, exhibits markedly different characteristics, as a result of previous rural fires and further ecological disturbances, even with proximity to rural housing and access roads. The area is dominated by open land with sparse, low vegetation cover. The soil surface is partially exposed, with herbaceous and shrubby species scattered irregularly. The absence of a continuous arboreal canopy and the visual presence of degraded patches indicate that. In terms of forestry occupation, it can be classified as non-forest land with incipient vegetation recovery. According to CORINE Land Cover categories, it is best described as 3.3.1 (Transitional woodland-shrub) or 3.3.2 (Bare rock / sparsely vegetated areas), depending on the regeneration trajectory.

The success of post-fire soil recovery largely depends on climatic factors such as rainfall, temperature, and wind patterns. Thus, weather conditions can influence the restoration of soil after fire events. During the two samplings, the weather conditions measured in the B and UB areas show some differences, also reflecting the season characterized by weather patterns and temperatures (Table 1). In the burned zone, in January 2023, the temperature was 17.7 °C, with a relative humidity of 47.1%. The heat index was recorded at 15.8 °C, the dew point at 5.3 °C, and the wet bulb temperature at 11.5 °C. Atmospheric pressure in this area was 978.8 mb, at an altitude of 289 m. The wind speed was measured at 1.6 km/h. In contrast, the unburned zone had a lower temperature of 12.7 °C, with a higher relative humidity of 57.4%. The heat index was 13.8 °C, the dew point was 6 °C, and the wet bulb temperature was 10.1 °C. Atmospheric pressure was 970.1 mb at a higher altitude of 362 m. The wind speed in this area was 2.8 km/h. Although the environmental conditions reflect the winter weather, the data highlight environmental variations between the two areas, particularly in temperature, humidity, and atmospheric pressure, which may influence the local conditions of the soil.

Table 1 - Meteorological Conditions in Burned *vs.* Unburned Zones at the sampling periods

	12 January 2023		06 January 2025	
Parameter	**Burned Zone**	**Unburned Zone**	**Burned Zone**	**Unburned Zone**
Temperature (°C)	17.7	12.7	12.9	12.3
Relative Humidity (%)	47.1	57.4	67.0	77.6
Heat Index (°C)	15.8	13.8	13.1	10.4
Dew Point (°C)	5.3	6.0	7.5	7.2
Wet Bulb Temperature (°C)	11.5	10.1	9.9	9.5
Atmospheric Pressure (mb)	978.8	970.1	959.2	949.3
Wind Speed (km/h)	1.6	2.8	1.8	1.6

The atmospheric data may have some variation in meteorological conditions, even in the winter; however, it is important to note that in the days preceding January 6, 2025, there was an episode of intense rainfall. The differences between the two areas are also a consequence of the different typology of vegetation and land occupation. The burned zone presented a higher temperature, a lower relative humidity, and related parameters, compared to the unburned zone. This combination, due to the absence of trees, reflects a warmer and drier atmosphere. The wind speed has no trend, but it was weak, suggesting reduced air circulation. Overall, the atmospheric conditions during the two sampling periods highlight a warmer, drier environment in the burned zone, in contrast with the cooler, more humid conditions in the unburned zone.

3.2 Soil resilience to rural fires - Pilot Study Results

Compost from the urban organic waste recovery plant (UW), as well as compost produced from agroforestry waste (AFW), were used in this work. The options followed the proximity principle, meaning that the composts selected were produced in nearby facilities using waste from local management systems. Special emphasis was given to agroforestry waste, since it originates from the forestry clearing aimed at fire prevention. These natural additives prevent the use of synthetic fertilizers and, on the other hand, contribute to the recycling of urban and agroforestry wastes and to a circular economy framework.

With the purpose of studying the effects of the addition of compost on the recovery of burned soils, soil samples were collected. Figure 2 shows the results for physical and chemical characterization of the UB and B soils without compost addition, considered as the control. These data make it possible to understand the effect of time on soil recovery (from January 2023 (t0) until January 2025 (t1)).

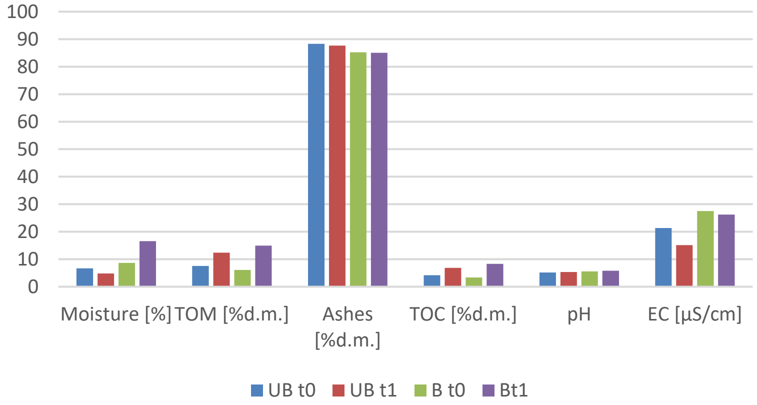

Figure 2 – Physico-chemical characterization of control soils: UBt0 – unburned/time zero; Bt0 burned/time zero; UBt1 – unburned/24th months; Bt1 – burned/24th months

Overall, the soil samples exhibited a similar profile, with low moisture content for both samples; only Bt1 reached values higher than 15%. It should be noted that rainfall occurred prior to the second sampling, and that areas with higher vegetation cover may have influenced soil water content leaching processes, potentially affecting the samples. The moisture content is dependent on the climatic conditions, and it plays a crucial role in soil fertility, as it affects nutrient availability, microbial activity, and overall plant growth. In this case, the TOM values ranged between 6 and 15%$_{d.m.}$, with the Bt1 reaching the highest value again. Both soils had an acidic pH, ranging between 5.2 and 5.8, a characteristic of a majority of Portuguese soils according to Ramos et al. (2017). Low values of EC were also registered, with the highest value of 27 µm/cm registered for soil B at the time t0. The content of ashes of the soil decreases, along with their electrical conductivity, and the organic matter increases. Ortega et al. (2023) described higher values for pH and EC parameters for burned and unburned soils in the Mediterranean area.

Soil pH is a critical indicator of chemical soil quality, with acidic character correlated with the organic matter content. Organic matter plays a key role in buffering soil acidity, improving cation exchange capacity, and sustaining microbial biomass activity. Consequently, adequate physico-chemical characteristics facilitate nutrient solubilization, enhance microbial activity, and support optimal plant physiological processes. After two years, both soils (UB and B) showed an increase in organic matter, the pH remained stable, and the EC content decreased slightly.

The two composts used (AFW and UW) to the restoration practice were characterized. The moisture ranged between 57% and 24.1% for AFW and UW composts, respectively, suggesting an adequate moisture level for compost use. The TOM ranged between 53 and 49%$_{d.m.}$ for AFW and UW composts, respectively. The pH of both composts was 8, indicating a slight alkalinity. The EC for AFW was 410 µS/cm, and for UW compost was 4326 µS/cm. This content may influence nutrient availability for plants. Concerning nutrients, potassium was found at 0.7 and 1.5%$_{d.m.}$, and magnesium at 0.29 and 1.10%$_{d.m.}$, for AFW and UW composts, respectively, contributing to plant nutrition. These results show that composts contain significant amounts of essential nutrients.

The analysis of heavy metals revealed the presence of Zn with 81.2 and 483.4 mg/kg$_{d.m.}$, Cd with 0.46 and 2.2 mg/kg$_{d.m.}$, Ni with 4.37 and 25.4 mg/kg$_{d.m.}$, Cu with 38.4 and 227.9 mg/kg$_{d.m.}$, Pb with 24.0 and 85.6 mg/kg$_{d.m.}$, Cr with 27.1 and 42.7 mg/kg$_{d.m.}$, for AFW and UW composts, respectively. According to the Ordinance nº 185/2022, composts may be classified into four classes: I, II, IIA, and III, based on their heavy metal content. Based on compost characterization, AFW is a class I, while UW compost is classified as class IIA. Both are within acceptable limits for compost used in agriculture. However, the AFW compost is restricted to arboreal and shrub agricultural crops, namely orchards, olive groves, vineyards, and forestry species.

The effect of compost applications to promote soil restoration is illustrated in Figure 3, which shows soil characteristics six months after compost application, for control and amended soils.

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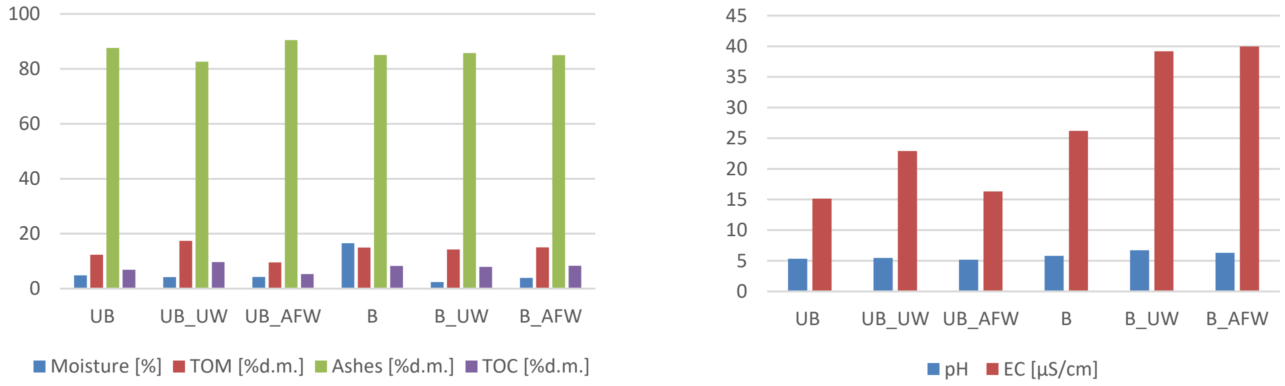

Figure 3 – Physico-chemical soils characterization after compost application (UB – unburned; UB_UW – unburned with compost from urban waste; UB_AFW – unburned with compost from agroforestry waste; B – burned; B_UW – burned with compost from urban waste; B_AFW – burned with compost from urban waste)

In the UB soils, the TOM and TOC increased with the UW compost and showed a slight reduction with AFW compost, which was not observed in the burned (B) soils, where no noteworthy differences were found with the addition of either compost. Although the composts showed alkaline behavior, this had only a minor effect with the addition of UW compost in the burned soils. As previously mentioned, the EC values were higher in the B soils, showing the highest content where compost was added (40 µS/cm). In the unburned soils, the AWF compost application did not increase the EC, but a slight increase was found by the UW compost application. It seems that compost application increased soils EC content more noticeably in the B soils.

Along with the proximate analysis (moisture, ashes, and organic matter), the microbial biomass was also assessed (Figure 4). The microbial biomass C is higher (112 mgC/kg) for the UB soils compared with the B soils (31 mgC/Kg), and it has lower amounts in the soils with compost. However, for the microbial biomass P, the behavior is opposite, with the B soil registering 83 mgP/kg, while UB soil reached 11 mgP/kg. In the case of microbial biomass N, the content is similar for both soils, ranging between 2 and 4 mgN/kg for UB soil and B soil, respectively. Overall, fire significantly increased the microbial biomass N and microbial biomass P, but decreased microbial biomass C. These findings were also reported by Palese et al. (2004) and Wang et al. (2012).

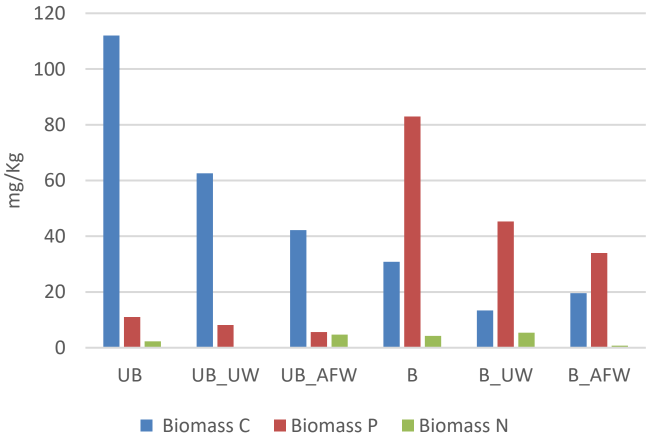

Figure 4 – Microbial Biomass soils characterization after composts application (UB – unburned; UB_UW – unburned with compost from urban waste; UB_AFW – unburned with compost from agroforestry waste; B – burned; B_UW – burned with compost from urban waste; B_AFW – burned with compost from urban waste)

The compost application did not increase microbial biomass. However, the application of UW compost had a slightly positive effect on C and P microbial biomass. This is an important aspect, as microbiological biomass in the soil plays a key role in maintaining the soil health, fertility, and ecosystem functioning. These microorganisms decompose organic matter, releasing essential nutrients like nitrogen, phosphorus, and sulfur back into the soil. This makes nutrients available for plant uptake and acts as a nutrient reservoir, while inhibiting harmful pathogens and reducing the incidence of plant diseases. Fungi and bacteria produce substances that help bind soil particles together, improving soil structure, porosity, and water retention, and stabilize organic carbon in the soil, helping mitigate climate change by storing carbon that would otherwise be released into the atmosphere (Dong et al., 2024). It was expected that the total microbial biomass could increase with the compost addition, but that was not found. Probably this is due to the fact that the compost type affects microbial community response, as compost composition can influence microbial structure and diversity without consistent increases in total biomass (Liu et al., 2022; Shu et al., 2022). The presence of heavy metals or other contaminants in the compost may inhibit microbial growth, explaining the lack of microbial biomass increase. Soil carbon content strongly regulates the relationship between microbial diversity and biomass, with low-carbon soils often exhibiting a higher diversity-to-biomass ratio rather than proportional increases in biomass (Bastida et al., 2021). Therefore, adding compost to carbon-poor soils may not increase microbial biomass unless the carbon is readily available. In addition, environmental factors such as temperature, moisture, pH, and soil aeration strongly influence the microbial activity (Bastida et al., 2021).

To further understand the effect of the compost addition to the soil, it was evaluated whether this application promotes the best conditions for plant growth and enhances ecosystem restoration. Thus, to assess the influence of the two composts on soil restoration and on plant and seed growth, the Growth index (GRI) and Germination index (GI) were analyzed. The results are shown in Figure 5.

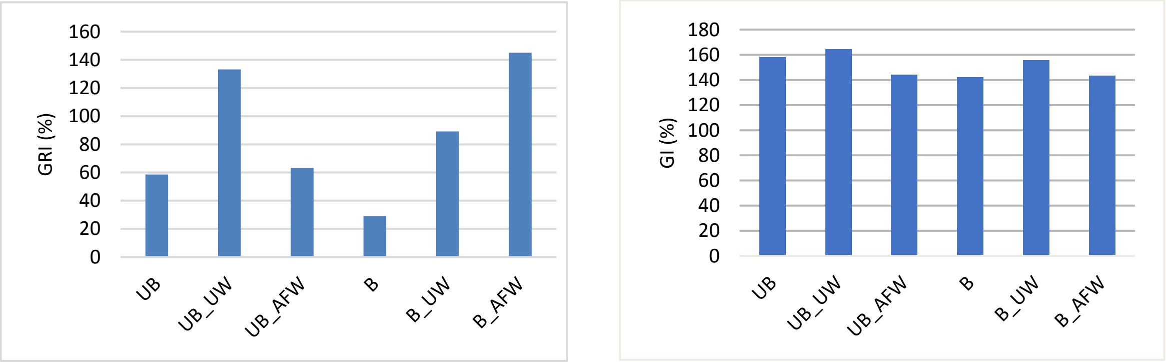

Figure 5 – Effect of compost addition in soil restoration through Growth index (GRI) and Germination index (GI) evaluation (UB – unburned; UB_UW – unburned with compost from urban waste; UB_AFW – unburned with compost from agroforestry waste; B – burned; B_UW – burned with compost from urban waste; B_AFW – burned with compost from agroforestry waste)

The difference in the GRI for the UB and B soils confirms that the fire had a negative effect on the soil fertility. Overall, the GRI for UB soil registered a higher value than for B soil. Composts showed a positive effect on both soils. However, GRI values varied depending on compost composition. UW compost exhibited the highest positive effect on UB soils, whereas AFW compost was most effective in B soils. This difference may be related to soil properties and nutrient availability, as UW compost often contains a higher proportion of food residues, paper, and green waste, which decompose rapidly and release readily available nutrients (N, P, K), potentially stimulating seed germination and early root development. The AFW compost, derived from woody residues and forestry by-products, tends to have higher lignin and cellulose, which decompose more slowly, reducing immediate nutrient availability. Its composition, rich in lignin, tannins, and polyphenols, during decomposition can release phenolic compounds or organic acids, which are phytotoxic and can reduce germination. Consistent with these characteristics, UW compost, which exhibited higher EC (4326 µS/cm), TOM ($49\%_{d.m.}$), and TOC, showed the strongest positive effect in UB soil, whereas AFW compost, with lower EC (410 µS/cm), TOM ($53\%_{d.m.}$), and TOC, was more effective in B soils. These differences likely reflect a combination of soil properties, nutrient availability, and salinity effects. In contrast, the GI values remained relatively consistent across treatments, ranging from approximately 130% to 160%. The GI values were slightly higher in UB soil compared with B soil. For both soils, the UW compost promoted a higher GI value than the AFW compost. This consistency indicates that seed germination was not significantly affected under any condition tested; however, the compost amendment had a positive effect on the soil, as the germination was higher in amended soils. The highest GI was recorded for UB_UW soil, which is a maturity indicator of this compost, suggesting once again that the nutrient availability was particularly favorable for germination. Differences between treatments were less pronounced for GI compared to GRI, highlighting that germination potential was generally resilient, whereas subsequent growth performance was more sensitive to the treatment applied.

Soil fertility can be improved by adding organic additives, increasing not only the organic matter content, but also moisture retention which in turn improves the biological and chemical properties of the soil. In this study, organic amendments application, such as compost, was applied to improve soil fertility and support microbial recovery, although these methods are less widely used. In Portugal, the regeneration techniques are adapted to the country's Mediterranean climate, with mulching being particularly important. In this study, the effect of the time after the compost's application on the recovery of soil properties was analyzed. For both soils (UB and B), the time had a positive effect on the physico-chemical properties, considering the study period of 24 months. An increase in organic matter was observed, while pH remained stable and the EC decreased slightly. In UB soil, TOM increases with the UW compost application; however, in B soil, this parameter shows a different behavior, similar between the two composts. It appears that 6 months was not sufficient to clearly observe the effects of compost application. Immediately after the application of organic amendments, microbial responses are often influenced by the presence of easily degradable organic compounds and potentially phytotoxic substances, which may temporarily limit biological activity and plant development. However, as time progresses, the degradation of labile compounds and the humification of organic matter contribute to reduced phytotoxicity and improved environmental conditions, promoting microbial diversification and functional stability (Bastida et al., 2021). This temporal progression also enhances nutrient cycling through gradual mineralization processes, supporting increased microbial biomass and enzymatic activity, which are key indicators of soil recovery. Moreover, improvements in biological indicators such as germination responses and microbial respiration over time further demonstrate that soil restoration is not an immediate process but rather a gradual ecological adjustment requiring sufficient time to reach biological stability (Jiba et al., 2024). Therefore, considering temporal variability is essential for accurately assessing soil recovery, as short-term observations may not fully capture the progressive improvements in microbial functionality and soil health. Nevertheless, the use of composts not only represents a circular approach to organic waste management but also appears to be a promising restoration strategy for fire-degraded soils. Future work should focus on monitoring the long-term effects of compost application.

CONCLUSION

Fire negatively impacts soils in terms of both physicochemical and biological properties. It was possible to evaluate that, naturally, the content of ashes of the soil decreases along with electrical conductivity, while organic matter increases. This behavior is pronounced in soils exposed to wildfires. However, after compost application during the study period, no substantial increase in organic matter was observed. Regarding the microbial community, microbial biomass, namely carbon and nitrogen, decreased while phosphorus increased with the addition of compost, particularly in the unburned soil. In the burned soil, compost application lead higher phosphorus content in microbiota, potentially supporting a more diverse microbial community, as P is an essential nutrient for nucleic acids, ATP, and cell membranes. The recovery of burned soils through the application of compost appears to be an effective measure, improving the soil's properties while contributing to sustainable management of urban and agroforestry wastes. Nevertheless, longer monitoring is required to fully assess the effects of compost application.

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AUTHORS' CONTRIBUTION

Conceptualization, E.S. and I.B.; data curation, E.S. and I.B.; formal analysis, E.S. and I.B.; funding acquisition, E.S. and I.B.; investigation, E.S. and I.B.; methodology, B.C. and S.M.; project administration, E.S. and I.B.; visualization, E.S., S.S., S.M. and I.B.; writing – original draft, E.S. and I.B.; writing – review & editing, E.S., S.S., S.M. and I.B.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

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