*Malaysian Journal of Soil Science 2026 Vol. 30: 177-191*
*Received 12/12/2025; Revised 10/5/2026; Accepted 14/7/2026; Online 12/8/2026*

# Soil Restoration in Semi-arid Mediterranean Forests of *Pinus halepensis* and *Tetraclinis articulata* using Spent Mushroom Substrate

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## ABSTRACT

*Forests play a central role in terrestrial ecosystems by regulating hydrological and climatic cycles, preserving biodiversity, and providing environmental ecosystem services. Soil, a limited and non-renewable resource, is essential for plant production, carbon sequestration, regulation of biogeochemical cycles, and maintenance of edaphic fertility. However, its degradation, particularly in arid and semi-arid regions, poses a major environmental challenge, linked to climate change through a vicious cycle of greenhouse gas emissions and vulnerability to extreme events. Ecological restoration approaches are emerging as key tools, with forest restoration recognized for curbing biodiversity loss, enhancing climatic resilience, and improving soil quality. This study evaluates the potential of spent mushroom substrate (SMC), an organic amendment derived from agricultural waste rich in nutrients, to restore degraded forest soils. The objective is to analyze its impact on the physical and chemical properties of the soil, as well as on ecological restoration processes, by comparing the responses of monospecific and mixed forest stands one year after application. The results show significant improvements: increases in organic carbon, total nitrogen, organic matter, moisture, electrical conductivity, water retention, and porosity; decreases in pH, C/N ratio, bulk density, and permeability. These changes enhance nutrient availability and soil structure, promoting plant recovery.Spent mushroom substrate appears as a promising tool for the ecological restoration of degraded forest soils, improving edaphic health and forest resilience, while aligning with circular economy principles.*

**Keywords**: Soil restoration, monospecific forest, mixed forest, Physico-chemical properties, spent mushroom substrate

## INTRODUCTION

Forests represent an essential element of the terrestrial system, playing a decisive role in maintaining fundamental ecological functions. They ensure the preservation of biodiversity, participate in climate regulation, and provide a wide range of ecosystem and economic services essential to humanity (Trumbore *et al.,* 2015). However, on a global scale, anthropogenic and climatic pressures increasingly threaten them. In the Mediterranean basin, forests have historically played a vital role in the development of local societies. Exploited for timber, grazing, non-timber forest products, or soil protection, they have always been valued for their many uses (FAO, 2016; Allam *et al.,* 2019; Dahmani *et al.,* 2023). Nevertheless, this overexploitation generates major environmental impacts, contributing to the progressive degradation of forest ecosystems in the region.

In Algeria, the national forest heritage, mainly concentrated in the northern regions of the country, covers an estimated area of 4,149,400 hectares. This area is distributed as follows: 1,329,400 ha of natural forests, 1,844,400 ha of maquis, 972,800 ha of reforestation, and approximately 3,000 ha of grasslands (DGF, 2018). Over the last decade, nearly fires, reflecting the growing vulnerability of forest ecosystems to recurrent disturbances, have affected 320,409 hectares of forests. This dynamic has manifested in an alarming regression of forest cover in recent years. This degradation of forest ecosystems is not limited to the loss of vegetation cover but is also accompanied by a progressive alteration of soils, which constitute the fundamental support of these environments. Soil, a non-renewable resource on the human time scale, forms the foundation of agricultural and forest systems. It is essential for food production, plant growth, carbon storage, and the regulation of biogeochemical cycles (Trasar *et al.,* 2016; Lehmann *et al.,* 2020). Its degradation, particularly in arid and semi-arid zones, represents a major environmental and socio-economic challenge today (Zouidi *et al.,* 2018). Maintaining soil quality, especially in agricultural and forest environments, is now one of the most urgent challenges of the 21st century (Zouidi *et al.,* 2019; Santorufo *et al.,* 2021).

Climate change is a major factor in environmental degradation in the Mediterranean region, where temperatures have increased by about 1.3°C over the last century, exceeding the global average (Solomou *et al.,* 2017). This evolution is accompanied by a modification of the rainfall regime, an intensification of droughts, and increased vulnerability of forest ecosystems (Trumbore *et al.,* 2015; IPCC, 2021). Among the most visible impacts are forest fires, whose frequency, severity, and duration have increased, directly linked to global warming (Zhang *et al.,* 2024; Jones *et al.,* 2024; Matougui and Zouidi, 2025).

Faced with these challenges, restoration strategies have become essential. Ecological restoration, defined as the process of assisting the recovery of degraded ecosystems, seeks to restore ecological integrity while taking into account social, cultural, and economic dimensions (Gann *et al.,* 2019). In this perspective, the restoration of forest soils is today one of the key solutions to curb biodiversity loss, strengthen climatic resilience, and improve soil health (Yue *et al.,* 2017). In response to the global urgency, the United Nations Decade for Ecosystem Restoration (2021–2030) was launched to strengthen regeneration efforts and achieve the Sustainable Development Goals (SDGs), as well as the post-2020 biodiversity targets (Reyers and Selig, 2020; Strassburg *et al.,* 2020; Edrisi and Abhilash, 2021). It aligns with the commitments of the United Nations Convention to Combat Desertification (UNCCD) and the Kunming-Montreal Global Biodiversity Framework, emphasizing the importance of sustainable land management (Bouramdane, 2025).

Ecological restoration of soils aims to restore the health and functions of degraded soil ecosystems through methods such as adding organic matter, planting vegetation (cover crops, willows, indigenous species), and implementing sustainable land management practices. These techniques improve soil structure, fertility, and water retention capacity, while promoting biodiversity and reducing erosion (Dahmani *et al.,* 2023).

Faced with the need to restore degraded soils and reduce dependence on conventional inputs, the valorization of organic waste appears as a strategic pathway. Spent mushroom substrate, also called spent mushroom compost, is a major by-product of edible mushroom cultivation. It is a residual mixture composed of the culture substrate and the casing soil remaining after harvest. For every kilogram of mushrooms produced, about 5 kg of SMS are generated, representing a considerable volume of residues to manage (Nakatsuka *et al.,* 2016; Carpio *et al.,* 2023). Historically, this co-product has been considered waste, contributing to environmental problems, including possible soil contamination, air and water pollution (Kaushal *et al.,* 2020; Lam *et al.,* 2019). This negative perception has posed a major challenge to the mycological industry, which is now seeking sustainable solutions for the management and valorization of these organic residues.

Although long considered waste, spent mushroom substrate (SMS) proves to be a resource of high agronomic value. It has notable richness in organic matter and mineral micronutrients, making it an attractive material for various applications (Ravlikovsky *et al.,* 2024). These characteristics have led to growing interest in its use as an alternative fertilizer or soil amendment (Alves *et al.,* 2022; Ravlikovsky *et al.,* 2023).

In recent years, research on the integration of SMS in agriculture, particularly as an organic amendment, has intensified (Udom *et al.,* 2016). Current studies mainly aim to optimize the valorization of this co-product to reduce health risks, promote waste recycling, support agricultural economy, and contribute to the sustainable development of the mycological sector (Pérez Chávez *et al.,* 2019; Mahari *et al.,* 2020; Ravlikovsky *et al.,* 2025).

In the context of our study, we wished to examine the impact of spent mushroom substrate (SMS) on the rehabilitation of degraded forest soils under a semi-arid climate. To do this, we selected two predominant forest species in our area: Aleppo pine and thuja. The main objective of this research is to valorize organic waste from mushroom cultivation by using it as an organic amendment in an ecological and sustainable perspective. The study aims to evaluate the impact of this amendment on the physico-chemical properties of forest soils, as well as its effectiveness in ecological restoration processes. Particular attention is paid to comparing edaphic and ecological responses between monospecific and mixed stands, through the analysis of treatment effects one year after its application.

## MATERIALS AND METHODS

### *Presentation of the study area*

In this study, three forests in Tiaret province (western Algeria) were selected as experimental sites due to their ecological contrasts (Fig.1). The first site, located in the commune of Frenda, corresponds to a monospecific stand of Aleppo pine (*Pinus halepensis*). The second, also located in Frenda, consists of a mixed stand associating Aleppo pine (*Pinus halepensis*) and Barbary thuja (*Tetraclinis articulata*). The third site, implanted in the commune of Mechraa Sfa, is dominated by a monospecific stand of Barbary thuja (*Tetraclinis articulata*).All these sites are located in a semi-arid climate zone, characterized by low rainfall and high interannual variability, conditions typical of inland Mediterranean ecosystems.

### *Climate of the region*

From a climatic point of view, the meteorological data recorded at the Ain Bouchekif station reveal that the first three study areas are subject to a seasonal regime of the HAPE type. Over the period 1984–2022, the average minimum temperatures drop to 1.06°C in January, while the average maximum temperatures reach 35.03°C in summer, reflecting a strong annual thermal amplitude. Annual precipitation varies considerably with an average annual rainfall of about 350 mm. The average annual relative humidity is around 63.5%, which reflects an overall dry climate, but with some interannual variability. According to Emberger's pluviometric quotient (1954), the Tiaret region is classified in the lower semi-arid bioclimatic stage with a cool winter. This classification is corroborated by the ombro-thermal diagram analysis, which highlights a marked drought period extending from May to October, characteristic of semi-arid Mediterranean climate zones.

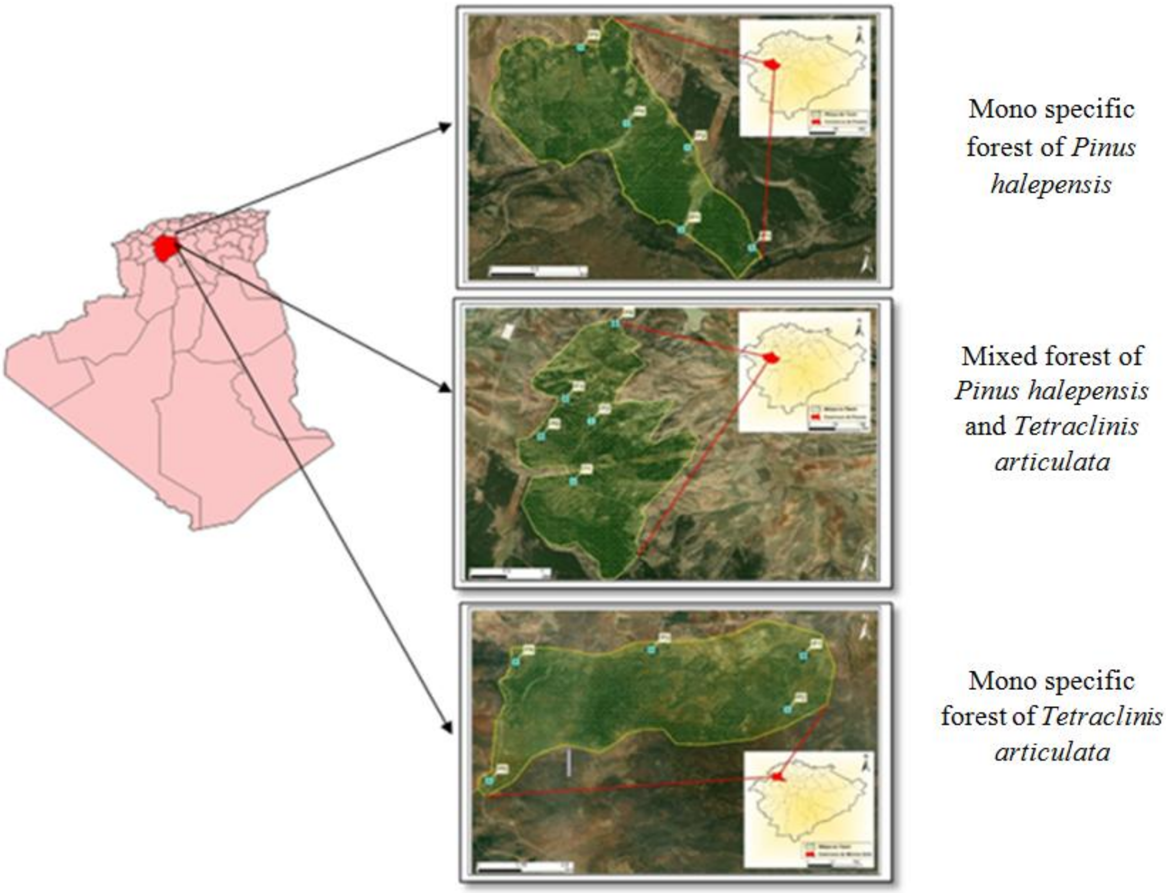


**Figure1.** Presentation of the experimental forests of the study area.

***Setting up the in situ experimentation of sampling sites before and after compost addition***

In each of the studied areas (monospecific forests and mixed forest), soils were sampled in May 2023. On each forest plot of 500 m², spaced at least 5 km apart, five samples were collected in the first 20 centimeters of soil, for a total of 100 samples. No plot had a depth greater than 30 cm above the rocky substrate. The sampling campaign took place over a week, and the samples were immediately stored at 4°C before analysis. They were then sieved at 2 mm for the determination of soil physico-chemical properties.

After soil characterization, two plots were randomly selected in each forest for restoration trials. On each of these plots, three subplots were installed and amended with spent mushroom substrate (SMS). Each subplot covered an area of 5 m², protected by a metal grid fixed on a flat surface, with a minimum distance of 2 m between subplots. The applied doses refer to recommendations established by the literature, indicating that optimal inputs depend on the initial soil conditions and the properties of the residue. In general, the most effective doses vary between 15 and 30 t/ha (dry weight) (IUCN). Furthermore, Lele et al. (2016) showed that an input of 15 t/ha of biochar significantly improves available carbon, phosphorus, and potassium contents. In our study, the spent mushroom substrate was applied as mulch (surface deposit) in March 2023, at a dose equivalent to 17 t/ha, or 1.7 kg/m².

***Composition of the spent mushroom substrate used***

The physico-chemical characterization of spent mushroom substrate (SMS) from the cultivation of edible Agaricus bisporus conducted in this study revealed the following values:

pH = 7.64, N = 2.17%, OM = 78.5%, organic C (OC) = 36.71%, EC = 3.48 mS·cm⁻¹, and moisture (H%) = 65.28%. These results fall within the ranges of values reported by several authors. Indeed, Catal *et al.* (2018) observed a pH of 6.8, a nitrogen content (N) ranging from 1.5 to 3%, organic matter (OM) varying from 60 to 85%, and electrical conductivity (EC) ranging from 1 to 3 mS·cm⁻¹. Similarly, according to Širić *et al.,* (2022), Ahlawat and Sagar (2007), Catal and Peksen (2020), Corral-Bobadilla et al. (2019), and Aiduang *et al.* (2025), the SMS parameters generally fall within the following intervals: pH = 5.02–8.05, EC = 4–6.5 dS·m⁻¹, OM = 66–98%, N = 0.92–2.75%, and OC = 23.40–54.30%. Thus, the values obtained in the present study are generally in agreement with those reported in the literature. The pH of 7.64 indicates a slightly alkaline substrate, consistent with the observations of Širić *et al.* (2022) and Aiduang *et al.* (2025), who mention maximum values around 8.05. The measured electrical conductivity of 3.48 mS·cm⁻¹ is close to the upper limit reported by Catal *et al.* (2018) (1–3 mS·cm⁻¹) and slightly lower than the values indicated by Širić *et al.* (2022) and Corral-Bobadilla *et al*. (2019) (4–6.5 dS·m⁻¹), suggesting moderate salinity favorable for agricultural reuse. The organic matter content (78.5%) lies at the heart of the ranges reported by all studies (60–98%), while the nitrogen content (2.17%) and organic carbon (36.71%) correspond respectively to the intervals of 0.92–2.75% and 23.40–54.30% described by Ahlawat and Sagar (2007), Catal and Peksen (2020), and Aiduang *et al.* (2025). These results confirm that the studied SMS exhibits physico-chemical properties comparable to those reported in the literature, demonstrating its organic richness and high agronomic potential for use as an amendment or in composting.

***Physico-chemical analyses of the soil (before and after treatment)***

The physico-chemical properties of the soils were analyzed according to standardized protocols to ensure the comparability and reliability of the results. The pH was measured in two media: in distilled water (pH $H_2O$) and in a 2 M potassium chloride solution (pH KCl), after an equilibration time of 40 minutes, thus making it possible to assess both the current and potential reaction of the soil. The electrical conductivity (EC, expressed in µS·cm⁻¹), an indicator of soil salinity, was determined in distilled water following the same protocol as for pH $H_2O$. The water holding capacity (WHC, %) was evaluated using the formula: WHC = [(Saturated soil weight – Dry weight) / Dry weight] × 100. The gravimetric water content (% of dry mass) was determined by drying at 105 °C for 24 hours, a method allowing the quantification of the current soil moisture. The organic matter content was estimated by determining organic carbon according to the method of Baize (2000), based on the oxidation of carbon by potassium dichromate in a sulfuric medium, in accordance with the method of Anne (1945). The total nitrogen content of the soil is determined by digesting the sample with sulfuric acid and a catalyst to convert organic nitrogen into an ammoniacal form. A blank is used as a reference, and the percentage of nitrogen is calculated from the titrated volumes, the normality, and the mass of the sample. The calcium carbonate ($CaCO_3$) content was determined using the Bernard calcimeter (Aubert, 1978), in order to assess the level of calcareousness, which strongly influences nutrient availability and pH. The real density (Rd) was measured using the pycnometer method (Mathieu *et al*. 2003), while the bulk density (Bd) was determined using the cylinder method (Gballou and Gnahoua, 1989). These two parameters allowed the calculation of porosity (P%) using the formula: P% = (1 − Bd / Rd) × 100, providing an indirect estimate of the pore space available for water and air in the soil. Permeability (K), which reflects the capacity of the soil to transmit water, was measured in the laboratory using a graduated cylinder containing sieved soil (< 2 mm) up to 100 ml, completed with distilled water up to 200 ml. After 12 hours of settling, the remaining water height (h) was measured, and permeability was calculated using the formula: K = 0.857 × h. This simple method allows for a quick classification of soils according to their relative permeability. Finally, the particle-size distribution of fine particles was determined by sedimentation using the Robinson pipette method (Aubert, 1978), separating three fractions: sands (2000–50 µm), coarse silts (50–2 µm), and clays (< 2 µm).

***Statistical analysis***

A two-factor analysis of variance (ANOVA) was performed for each physical property of the soil in order to evaluate the effects of the type of forest, the treatment, and their interaction. The statistical model included the main effects of the two factors studied (Type of forest × Treatment), as well as their interaction. This method makes it possible to simultaneously test the independent influence of each factor on the measured variables, while also examining whether the effect of one depends on the level of the other.

## RESULTS AND DISCUSSION

Spent mushroom substrate (SMS), an organic waste used for mushroom cultivation, is primarily rich in lignocellulose, carbohydrates, lipids, proteins, residual mycelium, and nutrients (N, P, K) (Gong *et al.,* 2019). The main components of the original substrate (MS) in which mushrooms are grown include fermented straw (barley, corn, wheat) with bovine or poultry manure, peat, gypsum, urea, and water (Grujić *et al.,* 2015).

***Effect of spent mushroom substrate on the physical properties of forest soils***

The application of spent mushroom substrate induced significant changes in the physical properties of forest soils (**Table 1**). The results show a clear improvement in parameters related to soil structure and hydrodynamic behavior after this treatment. Indeed, moisture, total porosity, water-holding capacity, and permeability show significant increases, reflecting better water retention and higher aeration of the profile. At the same time, a notable decrease in bulk density is observed, indicating a loosening of the soil and enrichment in organic matter provided by the substrate. In contrast, particle-size fractions (sand, silt, and clay) do not show significant variation, confirming that the treatment does not affect texture, which remains an intrinsic property of the soil. Overall, these results highlight the effectiveness of spent mushroom substrate in improving the dynamic physical properties of the soil, thereby contributing to enhancing its capacity for the restoration of degraded forest ecosystems.

**Table 1**. Variation in soil physical properties before and after compost application in the different forest types studied.

| Parameters | Pine Before | Pine After | Mixed Before | Mixed After | Thuja Before | Thuja After | F-value | *P-value* |
|---|---|---|---|---|---|---|---|---|
| Moisture (%) | 15.20 ± 0.95 | 18.20 ± 0.68 | 3.86 ± 1.39 | 6.81 ± 1.47 | 5.63 ± 1.52 | 9.83 ± 0.41 | 220.31 | <0.001 *** |
| CR | 2.44 ± 0.57 | 3.57 ± 0.80 | 1.76 ± 0.43 | 2.22 ± 0.43 | 2.01 ± 0.25 | 2.77 ± 0.49 | 7.34 | 0.0086 ** |
| Dr | 5.21 ± 0.06 | 5.12 ± 0.04 | 6.01 ± 0.06 | 5.81 ± 0.11 | 5.12 ± 0.06 | 5.01 ± 0.02 | 182.44 | <0.001 *** |
| Bulk density | 1.14 ± 0.02 | 1.08 ± 0.03 | 1.23 ± 0.03 | 1.13 ± 0.02 | 1.10 ± 0.01 | 1.03 ± 0.03 | 28.79 | <0.001 *** |
| Porosity (%) | 78.19 ± 0.36 | 78.96 ± 0.51 | 79.53 ± 0.41 | 80.56 ± 0.50 | 78.45 ± 0.28 | 79.40 ± 0.62 | 12.67 | 0.0011 ** |
| Sand (%) | 62.58 ± 3.38 | 58.47 ± 0.38 | 60.22 ± 1.81 | 59.44 ± 0.94 | 61.78 ± 2.19 | 60.08 ± 1.21 | 9.18 | 0.0049 ** |
| Silt (%) | 23.76 ± 3.82 | 27.26 ± 1.06 | 26.85 ± 1.11 | 27.81 ± 0.48 | 25.66 ± 2.00 | 27.79 ± 0.63 | 6.77 | 0.0112 * |
| Clay (%) | 13.45 ± 0.32 | 14.27 ± 1.11 | 12.92 ± 0.87 | 12.63 ± 0.77 | 12.56 ± 0.45 | 12.13 ± 0.79 | 4.21 | 0.0285 * |
| Permeability | 49.40 ± 0.23 | 40.44 ± 0.33 | 51.31 ± 0.27 | 45.02 ± 0.55 | 50.71 ± 0.20 | 42.73 ± 0.31 | 124.41 | <0.001 *** |

Note:Averages ± standard deviations. The *p value* of independent test is presented with its significance threshold (* $p < 0.05$; **; $p < 0.01$; ***; $p < 0.001$; ns, not significant).

The two-factor analysis of variance (ANOVA) made it possible to evaluate the effects of forest type (FT), spent mushroom substrate treatment, and their interaction (Int) on soil physical properties. The results showed that forest type has a highly significant influence on most of the properties studied. The F-values associated with FT are high, and the significance levels very low ($p < 0.001$) for moisture, bulk density, porosity, permeability, water-holding capacity (WHC), and drainage (Dr). These differences reflect a significant spatial variability of soils according to local ecological conditions (floristic composition, vegetation cover, organic matter content, etc.). In contrast, soil texture (sand, silt, clay) shows non-significant results, confirming that particle size remains stable and specific to each soil.

Regarding the treatment effect, it is overall highly significant ($p < 0.001$) for hydrophysical properties such as moisture, porosity, permeability, bulk density, and water-holding capacity. This positive response indicates that the addition of spent mushroom substrate improves soil structure, promotes water retention, and increases hydraulic conductivity. In contrast, textural parameters (sand, silt, clay) do not show significant differences ($p > 0.05$), suggesting that the treatment mainly affects dynamic physical properties rather than mineral composition. Statistically, the results demonstrate that spent mushroom substrate acts as an effective organic amendment, significantly modifying the soil's hydrodynamic properties. The increase in porosity and permeability is accompanied by a reduction in bulk density, which promotes water infiltration and retention while improving air circulation in the profile. These changes are consistent with the expected effects of decomposed organic matter, which favors the formation of stable aggregates and the creation of macropores.

***Effect of spent mushroom substrate on the chemical properties of forest soils***

The two-factor analysis of variance (ANOVA) highlighted highly significant effects of forest type and spent mushroom substrate (SMS) treatment on the majority of the chemical parameters studied. Soil pH varies greatly according to forest type ($F = 21.51$, $p < 0.001$) and also shows a very significant response to the treatment ($F = 177.26$, $p < 0.0001$), suggesting a slight alkalinization of the soils after substrate application. Electrical conductivity (EC) shows significant differences both between forests ($F = 11.36$, $p < 0.001$) and between treatments ($F = 22.02$, $p < 0.001$), indicating an increase in soluble salts and enhanced soil mineralization after SMS application. Similarly, organic carbon and organic matter display extremely high F-values ($F = 1401.42$, $p < 0.0001$), reflecting a considerable increase in organic matter content following the amendment.

Total nitrogen is also significantly influenced by both forest type ($F = 9.69$, $p < 0.001$) and treatment ($F = 34.03$, $p < 0.001$), with a significant interaction ($p < 0.01$), indicating that the soil nitrogen response partially depends on the forest cover. The C/N ratio, a key parameter of the organic matter cycle, varies significantly between forests ($F = 8.70$, $p < 0.01$) and treatments ($F = 17.95$, $p < 0.001$), with a significant interaction as well ($p = 0.023$), highlighting a combined influence of the substrate and forest type on the carbon-nitrogen balance. In contrast, total calcium carbonate content, although highly variable between forests ($F = 381.89$, $p < 0.001$), is not affected by the treatment ($p = 0.25$), confirming the lithological nature of this property.

Overall, these results (**Table 2**) demonstrate that spent mushroom substrate has a significant and widespread effect on soil chemical properties, mainly by increasing organic matter, carbon, and total nitrogen, while slightly improving pH and electrical conductivity. The absence of a significant interaction for most parameters suggests that this beneficial effect is stable and reproducible across the different forest types studied.

**Table 2:**Comparison of soil chemical properties before and after organic compost amendment in the different forest formations

| Parameters | Pine forest Before | Pine forest After | Mixed forest Before | Mixed forest After | Thuja forest Before | Thuja forest After | F-value | *P-value* |
|---|---|---|---|---|---|---|---|---|
| pH | 8.06 ± 0.07 | 7.05 ± 0.05 | 8.06 ± 0.10 | 7.74 ± 0.22 | 7.97 ± 0.10 | 7.56 ± 0.10 | 32.70 | <0.001 *** |
| CE (µS/cm) | 235.00 ± 35.69 | 278.20 ± 15.66 | 185.80 ± 27.50 | 221.00 ± 27.45 | 194.20 ± 17.77 | 246.80 ± 23.50 | 7.94 | 0.0064 ** |
| Limestone (%) | 20.28 ± 0.86 | 19.96 ± 0.73 | 9.90 ± 0.41 | 9.54 ± 0.39 | 19.52 ± 1.47 | 19.00 ± 1.21 | 229.91 | <0.001 *** |
| OC (%) | 4.07 ± 0.68 | 8.95 ± 0.24 | 4.41 ± 0.17 | 9.93 ± 0.07 | 4.80 ± 0.15 | 9.58 ± 0.49 | 12.20 | 0.0013 ** |
| OM (%) | 7.00 ± 1.17 | 15.39 ± 0.41 | 7.59 ± 0.30 | 17.08 ± 0.11 | 8.26 ± 0.25 | 16.47 ± 0.85 | 12.20 | 0.0013 ** |
| N (%) | 0.35 ± 0.08 | 0.36 ± 0.01 | 0.20 ± 0.07 | 0.39 ± 0.01 | 0.33 ± 0.06 | 0.46 ± 0.02 | 64.59 | <0.001 *** |
| C/N | 12.41 ± 4.15 | 24.68 ± 0.39 | 24.41 ± 8.77 | 25.51 ± 0.43 | 14.79 ± 2.69 | 20.92 ± 2.05 | 19.90 | <0.001 *** |

Note: Averages ± standard deviations. The *p value* of independent test is presented with its significance threshold (* $p < 0.05$; **; $p < 0.01$; ***; $p < 0.001$; ns, not significant).

## *Compost SCU amendment improves soil physical properties in forest ecosystem*

Our results show that the application of SMS compost significantly improves the physical properties of forest soils. A general increase in moisture and water-holding capacity was observed in the restored plots, confirming the beneficial effects of organic amendments on water retention (Huang *et al.*, 2020; Hřebečková *et al.*, 2024). Previous studies have reported substantial increases in water-holding capacity following prolonged application of organic substrates on sandy soils, reaching up to 251% (Lipiec *et al.*, 2021), as well as improved moisture conservation and field capacity in restored soils (Borsali and Zadi, 2014; Cellier *et al.*, 2012; Douaer *et al.*, 2021). These water improvements contribute to better nutrient availability and increase plant tolerance to water stress (Lebrun *et al.*, 2022; Wang *et al.*, 2025).

The application of SMS compost also resulted in a significant decrease in soil permeability, in agreement with the observations of Borsali and Zadi (2014) and Lipiec *et al.* (2021), who showed that compost incorporation reduces excessive drainage in sandy and semi-arid soils, facilitating water retention in the surface horizons. Regarding bulk properties, compost addition reduced both bulk and real density while increasing porosity, corroborating the results of Allam *et al.* (2019), İşler and Kavdır (2024), and OueldLhaj *et al.* (2025). A clear negative correlation was observed between bulk density and porosity, indicating that the reduction of the dense mineral fraction and the improvement of soil structural stability increase the available pore space (Tejada and González, 2007; D'Hose *et al.,* 2012).Improvement of soil structure was also associated with an increase in the proportion of clay and organic matter, promoting aggregation and the storage of organic carbon (Martín *et al.,* 2023; OueldLhaj *et al.,* 2025). Reynolds *et al.* (2020), who observed increased porosity and better structure in soils amended with green waste compost, also confirmed these effects.

Spent mushroom substrate (SMS) represents an effective biofertilizer capable of improving soil fertility and health. Previous studies have shown that SMS can increase nutrient availability, stimulate plant growth, and serve as a partial substitute for mineral fertilizers (Zanella *et al.,* 2018; Chen *et al.,* 2022). The addition of SMS promotes the formation of stable aggregates and improves soil quality while providing a potential pathway for valorizing organic waste (Udom *et al.,* 2016; Majchrowska *et al.,* 2020). The application of SMS compost in degraded forest soils consistently improves moisture, water-holding capacity, density, porosity, and soil structure, contributing to ecological restoration and sustainable soil fertility.

***Chemical responses of forest soils to SCU compost application***

The results obtained demonstrate that the application of spent mushroom substrate (SMS) constitutes an effective organic amendment for the rapid improvement of the chemical fertility of forest soils. The significant increase in organic matter and organic carbon indicates an enhancement of soil organic quality, which is essential for stimulating biological activity, nutrient retention, and aggregate stabilization. The rise in electrical conductivity after treatment suggests a gradual release of nutrients from substrate decomposition, contributing to the enrichment of the soil with minerals available for plants.

The application of SMS compost induced a significant improvement in the chemical properties of forest soils, notably a marked increase in organic matter and organic carbon. Our results show that the organic matter content doubled in a single year of application, rising from 8.6% to 16.34%. This rapid increase highlights the strong capacity of SMS to enrich soils with stable organic compounds. Similar trends have been reported by Zanella *et al.* (2018) and Joniec *et al.* (2022), confirming that prolonged use of spent mushroom substrate (SMS) promotes the accumulation of organic matter and the sustainable recycling of agricultural residues. Lipiec *et al.* (2021) also observed an increase of 102 to 201% in soil organic matter after 20 years of SMS application mixed with poultry manure on sandy soil.

The increase in total organic carbon observed in our samples is consistent with the findings of Borsali and Zadi (2014), Gümüş *et al.* (2017), and Velusami (2022), who showed that the addition of compost or organic substrates significantly improves organic carbon content in various edaphic contexts, including semi-arid soils. The positive correlation observed between organic carbon and organic matter confirms that soil carbon enrichment promotes the improvement of its physico-chemical properties and structural stability (Yazdanpanah *et al.,* 2016; OueldLhaj *et al.,* 2025). This dynamic reflects a better capacity of the soil to store carbon, contributing both to fertility and environmental sustainability.

Furthermore, a significant increase in total nitrogen content was recorded after SMS application, rising from 0.2% to 0.4%. This increase is attributed to the gradual mineralization of organic matter and the release of nitrogen in ammoniacal form, as also observed by Gümüş *et al.* (2017) and Velusami (2022). According to Majchrowska *et al.* (2020), over 90% of nitrogen in surface horizons exists in organic form, making nutrient release gradual and sustainable. Similarly, compost, already partially mineralized, decomposes slowly, ensuring a continuous availability of nitrogen, phosphorus, and potassium (Antil *et al.,* 2011; Pinto *et al.,* 2017).

Our observations also confirm a strong positive correlation between organic matter and total nitrogen content, in agreement with the results of Meysner *et al.* (2006) and Spychaj-Fabisiak *et al.* (2007). This relationship suggests that the increase in organic matter stimulates microbial activity and nitrogen fixation, thereby improving soil and plant nutrition (Mercik *et al.,* 1995). Finally, the gradual release of nutrients from compost decomposition promotes a sustainable improvement of fertility, limiting leaching losses and enhancing soil resilience to water stress.

The application of spent mushroom substrate (SMS) led to a significant decrease in the C/N ratio in restored soils. This result indicates an intensification of organic matter mineralization processes, favoring the rapid release of nutrients available for plants. A narrow C/N ratio indeed reflects an optimal balance between carbon and nitrogen, typical of well-decomposed organic amendments (Becher and Pakuła, 2014; Majchrowska *et al.,* 2020). This behavior is similar to that of farm manure, characterized by a low proportion of carbon relative to nitrogen, which promotes rapid decomposition and nutrient availability (Grimm and Wösten, 2018). Thus, the decrease in C/N ratio after SMS application confirms its efficiency as an organic biofertilizer and its role in improving soil nutrient dynamics.

Regarding soil reaction, a significant decrease in pH was observed in areas treated with SMS. This result aligns with observations by Carpio *et al.* (2023) and Angelova *et al.* (2013), who attributed this acidification to the production of organic acids during microbial decomposition of organic matter. Sundberg *et al.* (2013) also showed that compost application can slightly lower pH due to the release of organic acids during mineralization. Although moderate, this pH decrease contributes to increasing the solubility and bioavailability of several nutrients, particularly in alkaline-prone soils, thus enhancing their uptake by plants (El-Akhdar *et al.,* 2024). Similar trends were reported by OueldLhaj *et al.* (2025), Allam *et al.* (2019), and Alzamel *et al.* (2022), who observed a pH decrease following the accumulation of organic matter and increased microbial activity.

In parallel, soil electrical conductivity (EC) experienced a highly significant increase after SMS compost application. This phenomenon reflects the enrichment of the soil in ions and soluble salts released during organic matter decomposition (Angelova *et al.,* 2013; Boudjabi *et al.,* 2019). A similar increase in EC was reported by Carpio *et al.* (2023) and Magdich and Rouina (2020) after organic compost amendment, confirming that the rise in conductivity reflects enhanced availability of dissolved nutrients. According to Arthur *et al.* (2011), EC thus serves as an indirect indicator of the concentration of soluble salts provided by amendments.

Our results also reveal a significant negative correlation between pH and EC, suggesting that acidification of the medium is accompanied by increased ion release in the soil solution. Electrical conductivity also shows a positive correlation with organic matter content, confirming its central role in the gradual release of nutrients and chemical regulation of the soil. These observations, consistent with those of Carpio *et al.* (2023), demonstrate that SMS compost promotes an overall chemical restructuring of the soil, combining nutrient enrichment, better mineral solubility, and long-term improvement of chemical fertility.

**Interactive effects of spent mushroom substrate compost and forest type on the physico-chemical properties of forest soils**

Our results show that the effectiveness of spent mushroom substrate (SMS) compost strongly depends on the forest type, revealing a significant interaction between the amendment and local ecological conditions. In Aleppo pine forests, SMS improved soil moisture, water-holding capacity, and porosity, enhancing structural stability and nutrient availability, consistent with the well-documented effects of organic amendments on sandy and semi-arid soils (Huang *et al.*, 2020; Lipiec *et al.*, 2021). In Thuja forests, the amendment led to a notable increase in organic matter, total organic carbon, and total nitrogen, while reducing the C/N ratio, indicating active mineralization and gradual nutrient release (Zanella *et al.*, 2018; Joniec *et al.*, 2022).

Mixed forests showed more heterogeneous but overall positive responses, particularly in the most degraded plots, where SMS stimulated the growth of dominant tree species and increased understory diversity. These results align with the observations of Merzouki (2025), Bourque (2023), and Moragues-Saitua *et al.* (2023), who highlight the particular sensitivity of mixed forests to continuous organic inputs. Furthermore, the amendment modified electrical conductivity and slightly lowered pH depending on forest type, improving the availability of soluble ions and the solubility of several essential nutrients (El-Akhdar *et al.*, 2024; OueldLhaj *et al.*, 2025).

The effect of the compost also differs according to stand structure. In monospecific plantations, SMS primarily improves the physico-chemical properties of the soil—moisture, organic matter, water-holding capacity, nitrogen availability—but the overall response remains limited by the low root and microbial diversity characteristic of these simplified systems (Berendse *et al.*, 2015; Haghverdi and Kooch, 2019). Conversely, in mixed plantations, the effect of SMS is amplified due to functional complementarity between species, which promotes greater microbial diversity, accelerates nutrient mineralization, and optimizes their uptake through more diverse root systems (Forrester, 2014). Numerous studies show that mixed stands improve soil structuring and ecological resilience, enhancing the effectiveness of organic amendments in terms of fertility and ecosystem stability (Cardinale *et al.*, 2012; Lambers *et al.*, 2008). In this context, SMS application appears to be a particularly effective lever in mixed plantations, where interspecific interactions maximize biological and biogeochemical benefits.

## CONCLUSION

Compost derived from spent mushroom substrate proves to be a sustainable and effective organic alternative for in situ restoration of *Pinus halepensis* and *Tetraclinis articulata* forests in semi-arid areas. Its application significantly improves the physical properties of the soil, notably porosity, bulk density, and water-holding capacity, thus creating a more favorable root environment for the survival and growth of drought-adapted forest species. This improvement also enhances the infiltration of scarce rainfall and reduces moisture loss through evaporation, contributing to the water resilience of the soils.

Chemically, SMS acts as a natural biofertilizer, enriching the soil with essential nutrients for plant growth. Its gradual mineralization ensures slow and continuous release of nutrients, supporting plant growth over multiple cycles and maintaining long-term soil fertility. This slow and steady mode of action makes it particularly suitable for forest systems and low-input soils.

Furthermore, the use of SMS actively contributes to combating forest soil degradation in arid regions. It promotes the sequestration of organic carbon, strengthens soil structure, and stimulates microbial biodiversity, thereby limiting erosion, runoff, and compaction processes. These cumulative effects enhance the ecological resilience of forest ecosystems against climate change impacts, including desertification and productivity loss.

From an environmental perspective, the valorization of this abundant agricultural waste aligns with a circular economy approach, reducing dependence on costly and polluting chemical fertilizers while lowering greenhouse gas emissions associated with their production. Integrating SMS compost into reforestation programs and sustainable forest management strategies offers a promising pathway to restore degraded landscapes, increase forest productivity, and support long-term food security. By simultaneously improving soil fertility, structure, and stability, this approach also contributes to natural vegetation regeneration and wildfire prevention, thereby reinforcing the sustainability of semi-arid terrestrial ecosystems.

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