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Effects of Gyttja and Gyttja-Derived Biochar on Soil Biological Properties and the Growth of Common Bean (*Phaseolus vulgaris* L.)

Murat TUNÇ [1], Ferhat UĞURLAR [2*]
[1] Harran University, Faculty of Agriculture, Department of Field Crops, Şanlıurfa
[2] Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Şanlıurfa
[*] Corresponding author: ferhatugurlar@gmail.com

Abtract

The use of organic amendments is crucial in revitalizing soil fertility and ensuring long-term agricultural sustainability. Gyttja, a mineral- and organic-rich sediment, and its biochar form offer promising potential to improve soil health and plant performance. This study investigated the effects of raw gyttja and gyttja-derived biochar on soil biological properties and the growth performance of common bean (*Phaseolus vulgaris* L.) under semi-controlled greenhouse conditions. Treatments included three application rates (10, 20, and 30 t ha^{-1}) of both gyttja and biochar, along with an unamended control. Results showed that gyttja significantly enhanced shoot and root lengths, SPAD values, and urease activity, indicating improved nitrogen cycling and plant nutritional status. In contrast, biochar applications were more effective in increasing biomass accumulation, root elongation, and dehydrogenase activity, reflecting enhanced microbial respiration. Correlation analysis revealed strong associations between physiological plant responses and soil enzymatic activity. The findings underscore the complementary contributions of gyttja and its biochar to soil enrichment and plant development. Their joint use could serve as an effective method for boosting crop yields and rehabilitating poor or degraded soils.

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1. Introduction

The global agricultural sector is under increasing pressure due to population growth and climate change. This situation heightens the need for sustainable agricultural practices and calls for the development of innovative approaches to maintain and enhance soil fertility. Soil fertility is directly related not only to its physical and chemical properties but also to its biological richness and organic matter content (Aytenew and Bore, 2020; Javed et al., 2022). Organic matter is fundamental to sustaining a healthy soil ecosystem through its critical functions in enhancing soil structure, augmenting water retention capacity, and facilitating nutrient bioavailability (Hoffland et al., 2020; Singh et al., 2020; Cotrufo and Lavallee, 2022). However, many agricultural lands lack sufficient organic matter, limiting these properties and, consequently, hindering plant growth and agricultural productivity (Voltr et al., 2021; Gerke, 2022). To address these deficiencies, various organic amendments are preferred, and they are being evaluated as potential soil enhancers in research (Liu et al., 2022; Garbowski et al., 2023). As an illustration, derived from the buildup of organic and mineral materials in prehistoric lake basins, gyttja is characterized by its abundant organic matter and considerable levels of lime. In Turkey's Afşin-Elbistan Thermal Power Plant basin, an estimated 4.8 billion tons of gyttja, a byproduct of lignite mining, presents a low-cost and abundant resource for agricultural soil improvement (Saltalı, 2015). By enhancing properties such as moisture retention, pH balance, soil aggregation, and nutrient holding capacity, gyttja serves as an effective treatment for soils with low fertility and organic content (Korkmaz et al., 2021; Saltalı et al., 2023). The need to transform organic residues into a more stable carbon form and long-lasting form has led to the development of biochar (Ighalo et al., 2023). Biochar is a carbon-rich material produced by pyrolyzing various organic materials, such as agricultural residues, wood waste, and biomass, at high temperatures (Seow et al., 2022; Sieradzka et al., 2022). Converting organic matter into biochar is valuable not only for its soil-enhancing properties but also for its potential in carbon sequestration, thereby contributing to climate change mitigation (Arif et al., 2020; Lehmann et al., 2021). Biochar's resistance to natural breakdown in soil ensures its long-term persistence, thereby enhancing soil organic carbon levels over time (Han et al., 2020; Navarro-Pedreño et al., 2021). This stability allows biochar to function as a long-term carbon sink, thereby mitigating carbon emissions from soil systems (Luo et al., 2023). Furthermore, biochar's ability to balance soil pH, improve electrical conductivity (EC), enhance water retention, and support microbial activity positions it as a sustainable alternative with lasting benefits (Murtaza et al., 2021; Bolan et al., 2022). Gyttja, with its high organic matter and mineral content, shows promise as a soil enhancer, yet its full potential, particularly when converted into biochar, remains unexplored. Biochar derived from gyttja may offer a more durable solution, improving soil aggregation, nutrient availability, and microbial functionality. Therefore, the objective of this research is to examine the effects of gyttja and its derived biochar on the biological properties of phosphate-enriched soils and the growth performance of common bean (*Phaseolus vulgaris* L.). By examining the effects of different doses of gyttja and biochar on plant growth and soil health, this research aims to provide insights into sustainable strategies for enhancing soil productivity. This research fills an important knowledge gap regarding the role of gyttja-based amendments in enhancing soil health and strengthening agricultural resilience.

2. Material and Methods

This study was conducted under semi-controlled greenhouse conditions at the Faculty of Agriculture, Harran University, Şanlıurfa, Türkiye. The soil used in the experiment was collected from the phosphate deposits of the Kasrik basin in Mazıdağı, Mardin, which includes both active mining areas and phosphate-processing facilities

(Figure 1A). The Yunus-90 common bean cultivar was selected as the test plant. Gyttja, obtained from the Afşin–Elbistan Thermal Power Plant basin, was characterized before use, and its key properties are presented in Table 1. Biochar was produced from gyttja through pyrolysis at 500 °C for 4 hours (Figure 1B).

Table 1. General properties of gyttja

pH	EC ($dS\ m^{-1}$)	Lime (%)	Organic matter (%)	Humic acid (%)	Total N (%)
7.70	2.13	38.8	42.1	35	0.22

Plastic pots were filled with air-dried soil amended with three application rates of gyttja (4, 8, and 12 g kg^{-1} soil) and three rates of gyttja-derived biochar (4, 8, and 12 g kg^{-1} soil). A control treatment without amendment was also included. Three bean seeds were sown in each pot, and after germination, excess seedlings were removed so that only one plant remained per pot. The experiment consisted of 21 pots in total, corresponding to seven treatments with three replicates each.

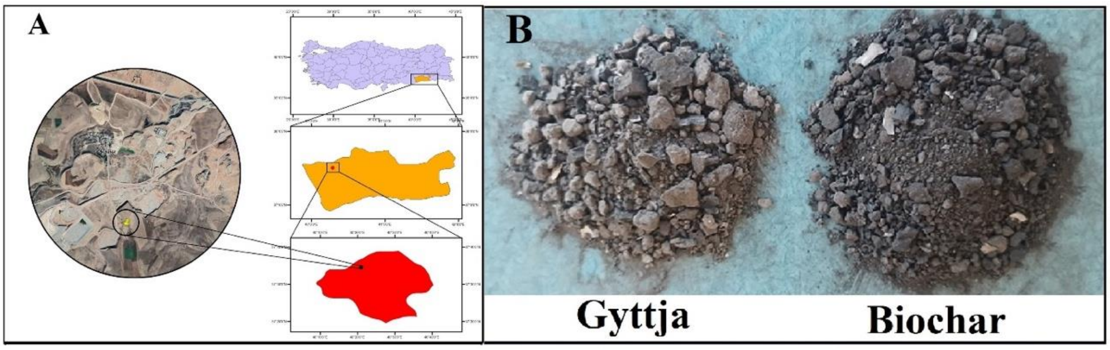

Figure 1. The area where soil samples were collected, (B) gyttja and gyttja-derived biochar

2.1. Measurement of plant and root length

Plant height was measured to the nearest millimeter from the soil surface to the highest point of the plant. After harvesting, roots were carefully washed, and primary root length was measured from the root collar to the root tip.

2.2. Measurement of shoot and root fresh weight

Harvested plants were washed with distilled water to remove soil residues and gently blotted dry. Shoots and roots were separated and weighed immediately using an analytical balance to determine fresh biomass.

2.3. Leaf physiological measurements

Leaf physiological parameters, including chlorophyll content and stomatal conductance, were used as physiological indicators of plant response. The chlorophyll content was measured directly on leaves using a portable SPAD meter (Minolta SPAD-502). For each plant, three leaves were randomly chosen for measurement, and the mean of these readings was recorded as the SPAD value. Stomatal conductance measurements were conducted between 11:00 and 15:00 using a leaf porometer (Decagon SC–1), according to the procedure described by Ben-Gal et al. (2009). Measurements were taken on one selected leaf per plant, and results were recorded in mmol $m^{-2}\ s^{-1}$.

2.4. Soil enzyme activities

Activities of soil enzymes such as catalase, urease, and dehydrogenase were evaluated to determine the biochemical responses of soil to the treatments. Catalase activity was determined using the method developed by Beck (1971), which measures the enzyme's ability to decompose hydrogen peroxide (H_2O_2) into water and oxygen. The released oxygen was measured, with enzyme activity calculated as ml O_2 per minute per gram of oven-dried soil. The analysis of urease activity was conducted using the procedure outlined by Tabatabai and Bremner (1972). Soil samples were treated with a urea substrate and incubated at 37 °C for one hour. After incubation, the amount of ammonia produced from urea hydrolysis was measured colorimetrically at 578 nm. Dehydrogenase activity was evaluated using TTC as the substrate, according to the protocol by Tabatabai (1982). Soil samples were incubated with TTC and glucose at 25 °C in the dark for 24 hours. After incubation, the resulting formazan was extracted using methanol and measured spectrophotometrically at 485 nm.

2.5. Measurement of soil ph and electrical conductivity (EC)

Soil pH and EC were measured in a 1:2.5 soil-to-water suspension. Samples were shaken for 30 minutes before pH was measured with a calibrated pH meter. EC was determined using a conductivity meter on the same extract.

2.6. Data analysis

The experiment was conducted using a randomized complete block design with three replications. Prior to analysis, the assumptions were evaluated using the Levene test for homogeneity of variances and the Shapiro–Wilk test for normality. Following these diagnostics, a one-way analysis of variance was performed, and differences among treatments were identified using Tukey's multiple comparison test. In addition, Pearson's correlation analysis was conducted to determine the relationships among the measured variables. All statistical analyses were carried out using the JMP Pro 13 software, whereas all graphical visualizations were produced in Python using standard scientific libraries (e.g., Matplotlib, Seaborn) to ensure high-resolution, reproducible, and customizable data representation.

3. Results and Discussion

3.1. Effects of gyttja and biochar on plant growth

The application of gyttja and biochar produced clear and statistically significant differences in plant growth, physiological traits, soil chemical characteristics, and soil enzyme activities, as supported by the graphical data. Shoot length varied substantially among treatments ($F=27.92$; $P<0.01$), with the G3 treatment forming a distinct upper group in Figure 2A, where letters indicate significant differences ($P<0.01$). The increase in shoot length under G2 may be associated with the higher contribution of humic and fulvic substances, which are known to stimulate cell elongation and nutrient uptake (Canellas et al., 2015; Gerke, 2022). Humic substances enhance membrane permeability and root exudation, which may indirectly promote shoot elongation (Nardi et al., 2021). In contrast, shoot fresh weight displayed a different pattern, with B1 producing the highest biomass (Figure 2B). This effect may reflect the ability of biochar to improve soil water-holding capacity, microbial habitat structure, and root-zone aeration (Bolan et al., 2022; Agegnehu et al., 2017). Biochar pores can protect roots from intermittent drying and create stable microsites for nutrient retention, which are often associated with higher fresh biomass (Lehmann et al., 2011). The divergence between shoot length (higher under G2) and shoot biomass (higher under B1) suggests that gyttja and biochar influence plant growth through partially different physiological pathways. Root traits also showed distinct responses. Root length increased strongly under B1 and G2 treatments ($F=8.75$; $P<0.01$), as shown in Figure 2C, while root fresh weight peaked under B1 and B2 (Figure 2D). These results align with the notion that biochar improves subsurface physical conditions, particularly by reducing bulk density and increasing soil porosity (Glaser et al., 2001; Laird et al., 2010). Enhanced porosity facilitates deeper and more branched root systems, which in turn improve nutrient acquisition (Prendergast-Miller et al., 2014). The relatively high variation in root biomass under B2–B3 may also indicate a dose-responsive effect, as moderate-to-high biochar levels often show the strongest influence on root morphological development (Wan et al., 2023; Liu et al., 2025). In parallel, gyttja likely contributed through increased nutrient availability, especially nitrogen and phosphorus, which are essential for early root growth (Khan and Kwot, 2024). The complementary patterns of responses highlight the distinct pathways through which organic amendments modulate root–soil interactions.

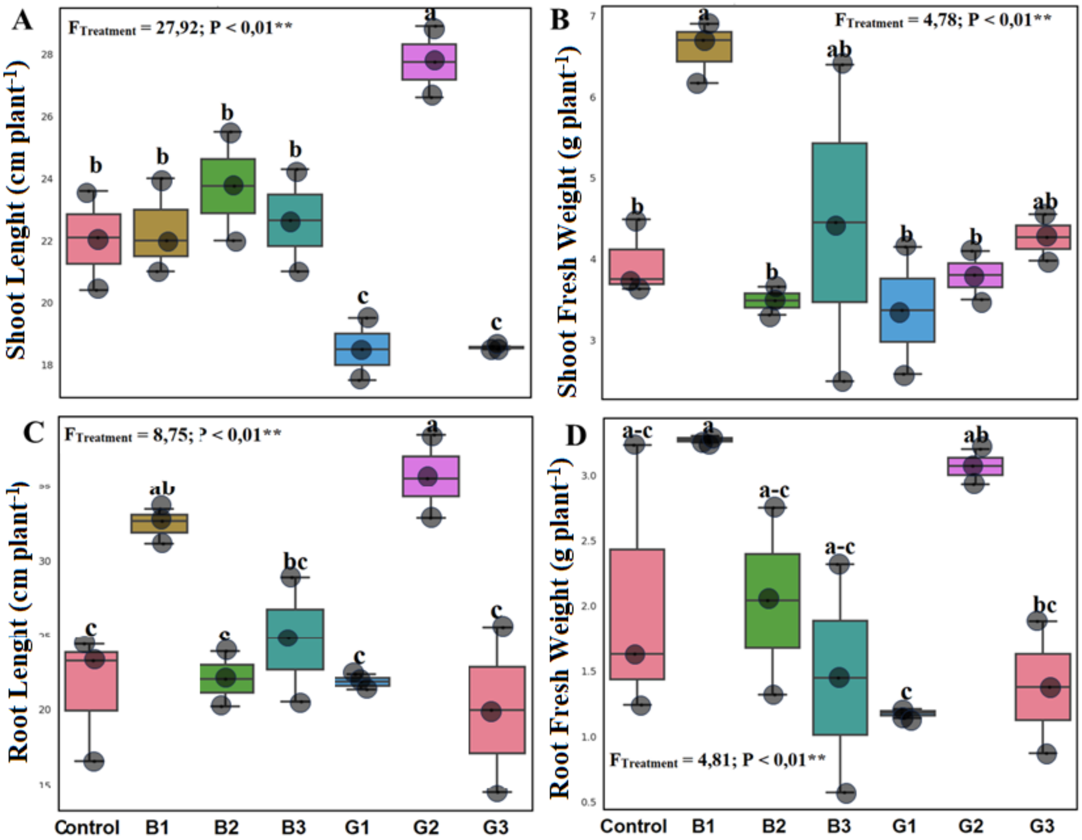

Figure 2. Plant height [A], shoot fresh weight [B], root length [C], and root fresh weight [D] of bean plants treated with different doses of Gyttja (G) and biochar (B)

3.2. Physiological responses of common bean

Physiological parameters were also markedly affected. SPAD values varied significantly across treatments (F=10.07; P<0.01), with the highest values in the control and G2 groups (Figure 3A). Although the control unexpectedly produced high SPAD values, G2's similarly high readings may indicate that moderate gyttja levels supported nitrogen mineralization and chlorophyll biosynthesis (Tian et al., 2022; Beyyavaş, 2025). Gyttja, being rich in organic N fractions, may have released nitrogen gradually, leading to enhanced chlorophyll content. Stomatal conductance showed its maximum under G1 (F=4.09; P<0.01), as seen in Figure 3B, suggesting that biochar improved water availability or root hydraulic conductance, leading to more open stomata. Biochar-mediated increases in stomatal conductance have been documented in other legume studies, where enhanced soil moisture and root activity supported gas exchange (Semida et al., 2019; Liu et al., 2022; Chen et al., 2023).

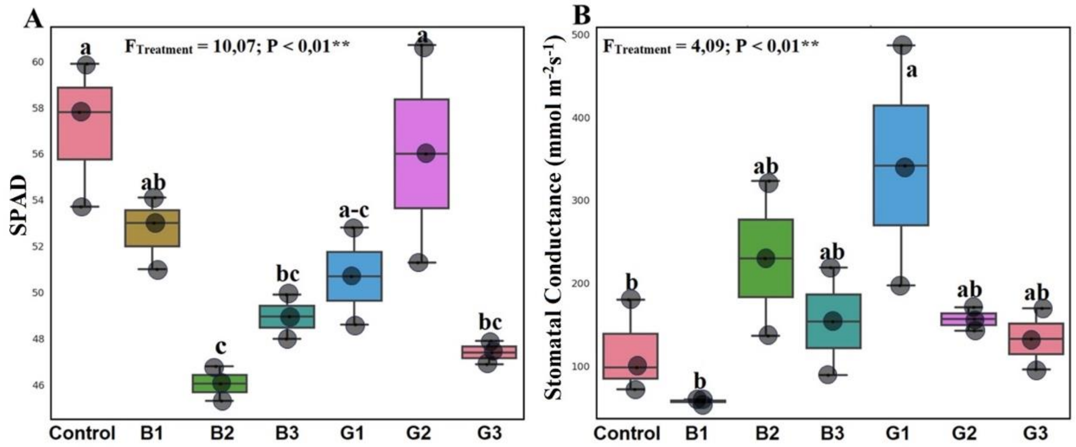

Figure 3. SPAD [A] values and stomatal [B] conductance results of bean plants treated with different doses of Gyttja (G) and biochar (B)

3.3. Changes in soil chemical properties and enzyme activities

Soil chemical properties shifted notably across treatments. Soil pH differed significantly (F=85.03; P<0.01) and followed the expected trend for biochar treatments (Figure 4A). B1 produced the highest pH, consistent with the alkaline nature of many biochars due to ash content and carbonates (Yuan et al., 2011; Saltalı et al., 2023). However, the decrease in pH at higher biochar levels (B3) suggests that the initial liming effect may be influenced by interactions with soil organic matter or microbial activity. EC values showed a pronounced increase under gyttja, particularly in B2 and G3 (F=4833.88; P<0.01), as observed in Figure 4B. Gyttja's soluble salts and mineralized ions likely contributed to this shift, consistent with previous findings on lake-sediment-based soil amendments (Saltalı and Nedirli, 2021). While moderate EC increases can enhance nutrient availability, excessive salinity may suppress microbial activity and limit root growth, a trend also reflected in the negative correlations between EC and several biological parameters.

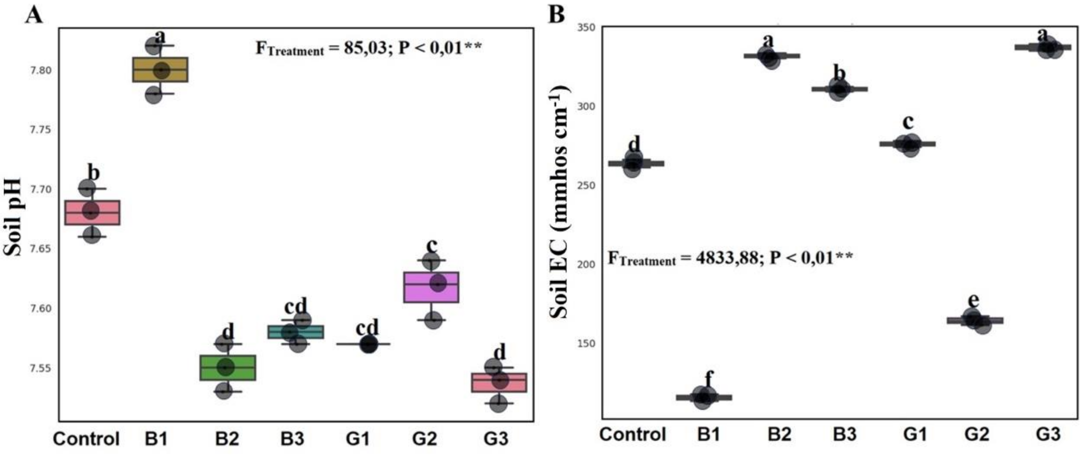

Figure 4. pH [A] and EC [B] results of soils treated with different doses of Gyttja (G) and biochar (B)

Soil enzyme activities presented differentiated responses across treatments. Urease activity reached its highest value under G3 (F=813.20; P<0.01; Figure 5A), which may reflect higher nitrogen turnover rates due to gyttja's readily decomposable organic fractions. Urease activity is known to increase in soils with improved organic matter inputs, particularly when microbial biomass is stimulated (Grzyb et al., 2021; D'Agostino and Carradori, 2024). Dehydrogenase activity was highest under B1 (F=17.19; P<0.01; Figure 5C), indicating elevated microbial respiration. This pattern is consistent with studies where biochar increased microbial biomass and enzymatic activity by providing protective habitats and stabilizing organic substrates (Lehmann et al., 2011; Kuzyakov et al., 2009). Catalase activity was highest in control and reduced under gyttja and biochar treatments (Figure 5B), a pattern possibly associated with lower oxidative stress when organic amendments improve soil structure and supply additional substrates (Skivka et al., 2020; Rasheed, 2024). The decline in catalase activity under high-gyttja treatments may also reflect shifts in microbial community composition toward groups with lower catalase expression.

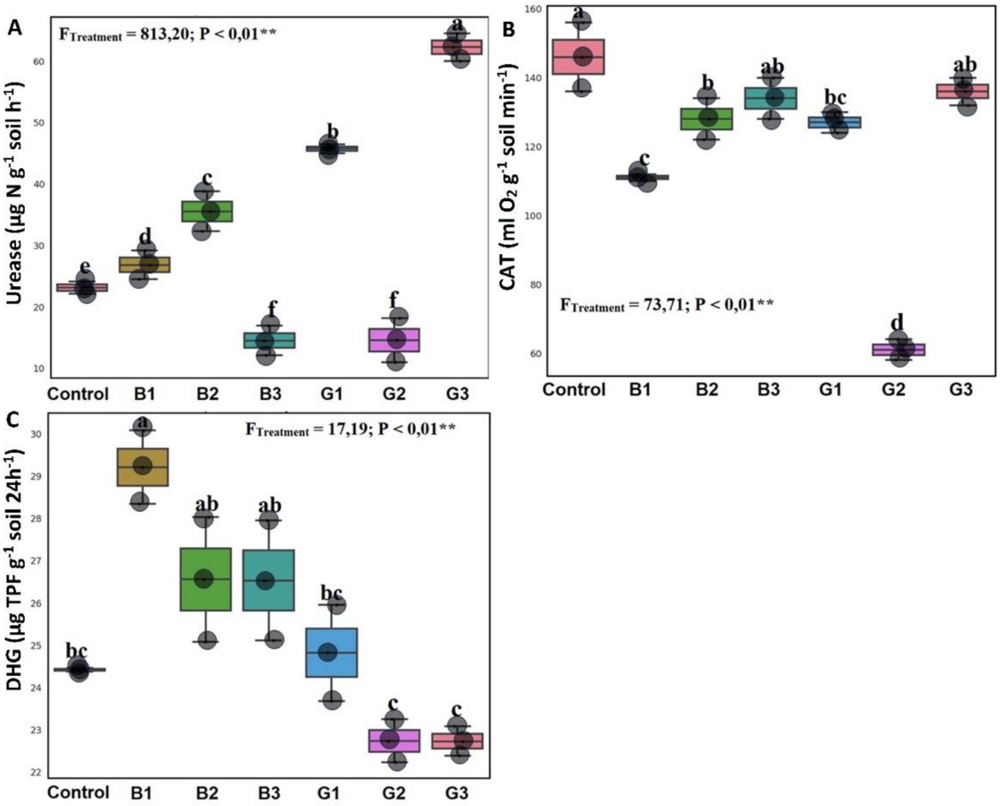

Figure 5. Results of urease [A], catalase [CAT, B], and dehydrogenase [DHG, C] activities in soils treated with different doses of Gyttja (G) and biochar (B)

3.4. Correlation analysis

The correlation analysis revealed several key interactions between plant performance and soil biochemical properties (Figure 6). Plant height showed a positive correlation with SPAD values, indicating that higher chlorophyll content was associated with improved vegetative growth. Soil EC exhibited a strong negative correlation with dehydrogenase activity, suggesting that increased salinity may inhibit microbial respiration and consequently impair soil biological functioning. Urease activity displayed negative correlations with both soil pH and EC, implying that elevated alkalinity and salinity create suboptimal conditions for nitrogen transformation processes. Additionally, the strong positive correlation between root length and root fresh weight demonstrates that treatments promoting root biomass also support greater root elongation, enhancing resource acquisition.

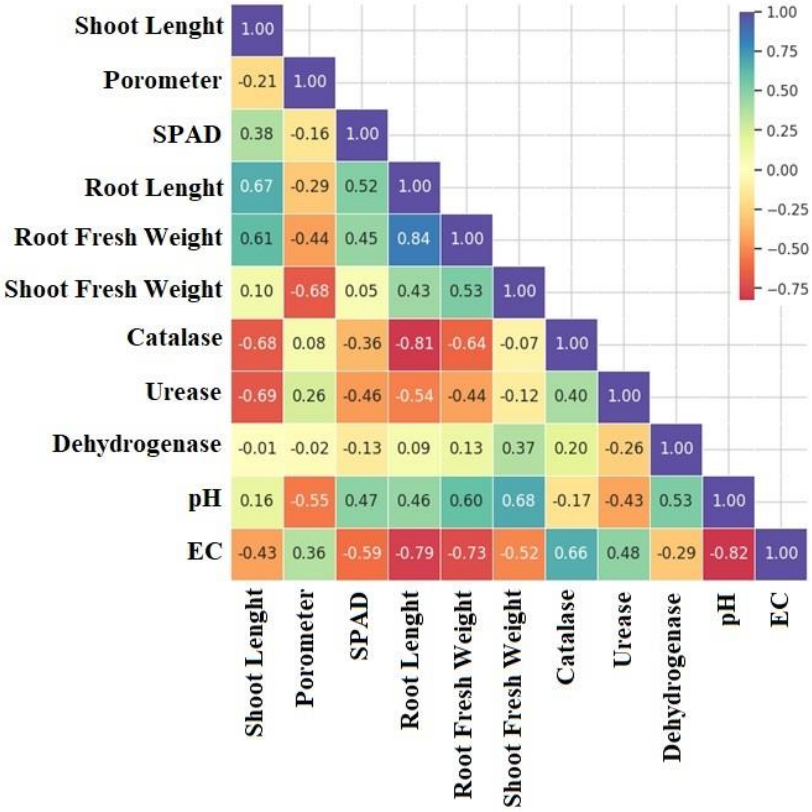

Figure 6. Correlation matrix illustrating the strength and direction of pairwise relationships among all measured variables

4. Conclusion

This study demonstrates that gyttja and its biochar, as two forms of the same organic material, enhance soil fertility, plant growth, and microbial activity through distinct mechanisms. The results indicate that gyttja and its biochar affect plant development and microbial activity in different, dose-dependent manners. Overall, gyttja significantly increased shoot and root length, SPAD values, and stomatal conductance. It also markedly enhanced urease activity, a critical component of the nitrogen cycle. In contrast, the biochar form was more effective in improving shoot and root biomass and promoting dehydrogenase activity. The findings suggest that potential combined applications of gyttja and gyttja-derived biochar represent a promising strategy to improve soil fertility and plant productivity. Future research should focus on optimizing application rates, evaluating long-term effects, and exploring their performance under diverse soil and environmental conditions to advance sustainable agriculture.

Author's Contribution Statement

The conceptualization, methodology, investigation, and data collection were conducted by MT, who also contributed to the manuscript preparation. FU contributed to validation, data interpretation, manuscript writing, and critical revision. The final manuscript has been read and approved by all contributing authors.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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Ethical Committee Approval

This study did not involve human or animal subjects; therefore, ethical approval was not required.

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