

RESEARCH

Open Access



Improving soybean (*Glycine max* (L.) Merr.) growth and soil health with Gyttja biochar: insights into plant biochemical attributes and soil chemical properties

Vedat Beyyavaş^{1*}

Abstract

Background Soil degradation and nutrient deficiencies often limit soybean productivity and soil health. Biochar has emerged as a sustainable soil amendment to improve crop growth and soil health. Gyttja biochar is an innovative soil amendment with high organic matter and balanced nutrient contents compared to conventional biochar. Nonetheless, the ability of gyttja biochar to improve soybean growth and soil health is poorly investigated. Therefore, this study investigated the role of gyttja biochar in improving soybean growth and soil chemical health.

Methods A greenhouse pot experiment was conducted using soil amended with gyttja-derived biochar at four concentrations [0.0% (control), 1.5%, 3.0%, and 4.5%] to infer their impacts on growth and biochemical attributes of soybean [*Glycine max* (L.) Merr.], and soil chemical health. Growth parameters (plant height and biomass) and plant biochemical attributes (e.g., chlorophyll index, stomatal conductance, proline, malondialdehyde contents, and antioxidant enzyme activity) were analyzed. Post-harvest soil samples were analyzed for chemical properties including pH, electrical conductivity, and activities of catalase, urease, and dehydrogenase enzymes.

Results Gyttja biochar significantly improved soybean growth and biochemical attributes compared to the control treatment. Growth traits were significantly increased (plant height by 20.9%, root length by 29.2%, and plant weight by 84.9%) with 4.5% concentration, and leaves showed greater chlorophyll index. Biochar-treated plants also exhibited increased antioxidant enzyme activities and lower oxidative stress indicators, reflecting improved plant health. Soil pH and electrical conductivity improved by 5.9% and 33.2%, respectively. Soil enzyme activities significantly increased, and urease activity nearly doubled compared to the control.

Conclusion Gyttja-derived biochar significantly improved soybean growth, biochemical attributes, and soil chemical health. These results indicate that converting gyttja sediment into biochar could improve crop productivity and soil fertility, providing an environmentally friendly approach to enhance agroecosystem health. Future research should include long-term, multi-season field trials to validate these results under varied environmental conditions, assess economic feasibility, and evaluate the effects of gyttja biochar across diverse soil types and soybean genotypes.

*Correspondence:
Vedat Beyyavaş
vbeyyavas@harran.edu.tr

Full list of author information is available at the end of the article



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Keywords Gyttja Biochar, Plant growth enhancement soil amendment, Sustainable agriculture, Soil enzymatic activity

Introduction

Gyttja is an organic-rich sediment that develops in aquatic ecosystems, especially in lakes and wetlands. Gyttja (means 'slime' in Swedish) was described in 1862 by Swedish scientist Hampus von Post and subsequently investigated as a soil conditioner in agriculture. Gyt-tja consists of degraded flora and fauna, along with fine mineral particles [1]. It develops in low-oxygen environments where organic matter accumulates and undergoes delayed decomposition [2]. Generally, it comprises 30–40% calcium carbonate (CaCO_3) and 40–50% organic materials [3]. Gyttja accumulates under water's surface due to the deposition of suspended particles from water column and surface runoff from the catchment area. Gyt-tja has potential uses in agriculture as it improves soil health and fertility because of its unique properties and elevated organic matter content [4]. Moreover, gyttja is a nutrient-dense organic silt that must be eliminated to access coal in coal-fired thermal power plants [5]. Gyt-tja is prevalent in the Afşin-Elbistan coal basin in Turkey with total reserves of 4.8 billion tons. Gyttja serves as soil conditioner due to its higher organic matter content, low toxic element concentration, high humic acid content, and compliance with organic fertilizer regulations [3, 6]. The effects of gyttja on soil properties and plant growth have been investigated in several studies [7, 8].

Gyttja has significant potential for improving crop production and soil health [8–11]. It improves soil structure by promoting aggregation and reducing bulk density [5]. Improved soil aeration and water retention with gyttja application result in better root growth [12]. Furthermore, cation exchange capacity of soil is improved by the application of gyttja, resulting in increased nutrient retention and release [12]. Plants may use the gyttja's organic matter content as a reservoir for slow-releasing nutrients [10]. Gyttja has several benefits; however, effects may vary depending on the soil composition and the quantity applied. To maximize its efficacy as a soil conditioner, it must be managed carefully and considered in relation to the specific soil conditions.

Biochar is a carbon-dense byproduct of biomass pyrolysis, which is extensively used as a soil amendment to enhance soil fertility and promote crop growth [13–17]. Biochar incorporation into soil improves soil structure, porosity, and water retention, while creating a highly porous surface that adsorbs nutrients and provides refugia for beneficial bacteria [18]. These characteristics often result in improved plant growth. Biochar incorporation into soil improves activities of soil enzymes essential for soil health and nutrient cycling [19, 20]. Nevertheless, the

impact is dependent upon the kind, quantity and application rate of biochar, as well as soil characteristics. Biochar contains various nutrients, such as nitrogen, phosphorus, and organic carbon, which may enhance microbial development and enzyme synthesis [21]. Biochar enhances urease activity in soil as it contains significant amounts of nitrogen. Soil nitrogen cycling is affected by increased urease activity because urea is broken down into ammonia at a quicker rate [22]. Dehydrogenase plays a critical role in microbial respiration, often exhibits enhanced activity with the addition of biochar. Biochar provides ample organic matter and energy for soil microbes, hence promoting their metabolic functions and increasing dehydrogenase activity [23]. Catalase activity is often increased in biochar-amended soils owing to enhanced microbial populations and associated oxidative processes. Organic matter and nutrients in biochar may improve microbial resistance and catalase activity [24]. For example, the incorporation of corncob biochar increased plant height, biomass, and yield of soybean in both greenhouse and field conditions [25].

Although raw gyttja is rich in organic matter and nutrients that promote plant growth and improve soil health, converting gyttja into biochar has unique benefits. Pyrolysis converts the unstable organic compounds into a stable aromatic carbon structure, significantly decreasing microbial degradation rates and extending the advantages of soil amendment [26, 27]. Consequently, transforming gyttja into biochar significantly enhances its agronomic and environmental advantages relative to raw gyttja. Nevertheless, most of the biochar research has concentrated on conventional feedstocks (such as wood or agricultural residue) [14, 17], while the potential of unconventional materials like gyttja remains barely investigated. Gyttja is abundant in Turkey, with an estimated reserve of around 4.8 billion tons in the Afşin–Elbistan region [9]. Gyttja biochar exhibits unique physicochemical characteristics principally attributable to its sedimentary origin compared to traditional biochar produced from common feedstocks like wood, agricultural wastes, or animal manure. Furthermore, gyttja biochar is rich in CaCO_3 , greatly enhancing its alkalinity and liming potential, thereby providing superior capacity for soil pH adjustment and increased nutrient availability compared to plant-based biochar [8, 11].

Soybean [*Glycine max* (L.) Merr.] is a key crop, which significantly impacts global food security. Global soybean production exceeded 340 million metric tons, reflecting 1,200% growth since 1960s [28]. The global soybean industry is projected to reach 278 billion US\$ by 2031

compared with 155 billion US\$ in 2023 because of extensive growth in soybean production [29]. Turkey mostly imports soybean to meet domestic demand [30]. Furthermore, soybean imports are predicted to reach 3.1 million metric tons between 2023 and 2024 [30]. While soybean is a significant component of world agriculture because of its high protein and oil contents, its contribution to Turkey's agricultural sector is just developing. Despite strategic growing circumstances, soybean yield is extremely low in the country. The major reason for low cultivation area and yield is that farmers prefer cultivating crops that provide more profits. Gyttja biochar has significant potential for improving soybean production in Turkey by improving soil health, and nutrient availability while also offering environmental advantages. Nevertheless, different concentrations need to be tested for improving growth and productivity.

Despite extensively reported benefits associated with raw gyttja, the impacts of gyttja biochar on plant morphological characteristics, activities of stress enzymes, and functions of soil enzymes have been explored less [5, 7, 10, 11]. Furthermore, the effects of gyttja-derived biochar on soybean growth and related biochemical processes are poorly studied. While previous studies have examined raw gyttja's function as a soil conditioner, no studies have investigated its biochar form. This study addresses this critical knowledge gap by investigating the dose-dependent effects of gyttja biochar on soybean morphological traits, antioxidant enzyme activities, and key soil chemical and enzymatic properties.

Materials and methods

Experimental site

This study was conducted in a greenhouse at Faculty of Agriculture, Harran University, Şanlıurfa Turkey. Raw

gyttja sediment was collected from Afşin-Elbistan thermal power plant in the coal basin of Kahramanmaraş. The soil used in the study was collected from Osmanbey Campus, Harran University, Sanliurfa, Turkey (37° 10' 14" N latitude and 39° 00' 14" E longitude). Soil was collected at a depth of 0–30 cm and analyzed for physiochemical properties using standard soil analysis procedures. The soil physiochemical properties are given in Table 1. The soil had a clay texture, indicating considerable water-holding capacity. The soil was slightly alkaline with moderate electrical conductivity, indicating low salinity. The lime content was significantly high, suggesting a substantial amount of calcium carbonate. The concentrations of organic matter and total nitrogen were low, indicating low inherent fertility. The concentrations of available potassium and phosphorus suggested moderate-to-low nutrient availability, stressing the need for supplementary soil amendments to improve soybean production. The soil had enough secondary nutrients, including calcium and magnesium, while micronutrients such as iron, copper, and manganese (were at low to moderate concentrations (Table 1).

Gyttja biochar

The collected raw gyttja sediment was air-dried, crushed and sieved to <2 mm particle size before pyrolysis. Biochar was produced via slow pyrolysis using a high-temperature furnace (CM Furnaces Inc., Bloomfield, New Jersey, USA) equipped with conventional resistive heating components. The biochar was prepared by pyrolyzing gyttja sediment in the furnace under controlled inert conditions. The furnace was purged continuously with nitrogen gas flowing at a rate of 0.7 standard m³/h (normalized to 101 kPa and 21 °C) and maintained at a constant absolute pressure of 212 kPa. Heating was carried out at a controlled rate of approximately 10 °C min⁻¹, gradually increasing to the final pyrolysis temperature of 450 °C, at which the material was held for a residence time of 60 min. Following cooling in an inert environment, the produced gyttja biochar was pulverized and sieved through a 2 mm mesh for consistent soil application. The composition of the obtained biochar is shown in Table 2.

The characteristics of gyttja biochar highlight its potential as an efficient soil amendment. The low moisture content (4.12%) indicates that it is stable, reducing the likelihood of microbial deterioration. The biochar had a volatile matter content of 13.45%, indicating intermediate thermal stability, while its elevated fixed carbon content of 55.45% suggests significant potential for long-term carbon sequestration. The ash concentration of 6.12% is acceptable, indicating the availability of vital minerals that may improve soil fertility. The elemental analysis indicated significant contributions to nutrition cycling.

Table 1 Physiochemical properties of the soil used in the experiment

Soil characteristics	Unit	Value
Sand	%	19.20
Silt		30.10
Clay		50.70
pH	-	7.78
Electrical conductivity	ds m ⁻¹	0.81
Lime	%	10.16
Organic matter		0.91
Total nitrogen		0.38
Calcium		0.82
Available potassium	mg kg ⁻¹	175.22
Available phosphorus		4.23
Magnesium		298.70
Iron		2.98
Copper		0.81
Manganese		0.41

Table 2 Composition of Gytija Biochar prepared and used in the study

Parameter	Unit	Value
Moisture content	(%)	4.12
Volatile matter		13.45
Fixed carbon		55.45
Ash content		6.12
Hydrogen (H)		2.45
Nitrogen (N)		1.31
Phosphorus (P)		0.92
Potassium (K)		2.32
Calcium (Ca)		2.11
Magnesium (Mg)		1.45
Iron (Fe)		0.95
Zinc (Zn)	mg kg ⁻¹	141.12
Copper (Cu)		15.28
Manganese (Mn)		21.75
pH	-	8.32

The hydrogen level (2.4%) signifies elevated aromaticity, associated with biochar's structural stability, while the nitrogen content (1.3%) offers a reasonable supply of plant-available nitrogen. Essential macronutrients, including phosphorus (0.9%), potassium (2.32%), calcium (2.11%), and magnesium (1.45%), highlight the ability of biochar to enhance soil nutrient profile. Moreover, trace minerals like iron (0.95%), zinc (141.12 mg/kg), copper (15.28 mg/kg), and manganese (21.75 mg/kg) provide essential micronutrients vital for plant development. These characteristics demonstrate that produced gytija biochar has a balanced chemical composition, rendering it appropriate for improving soil fertility and nutrient availability, and promoting sustainable agricultural practices.

Treatments

The collected soil was passed through a 2 mm sieve and then filled into plastic pots (5 kg per pot). Afterwards, 0, 8, 16 and 24 g (control, 1.5%, 3% and 4.5% respectively) gytija biochar was mixed with the soil. Five seeds of soybean genotype 'Gapsoy-16' developed by GAP Agricultural Research Institute Şanlıurfa, Turkey were sown in each pot and pots were irrigated until field capacity. The seeds were obtained from GAP Agricultural Research Institute Sanliurfa, Turkey. The pots were arranged according to completely randomized design with three replications. Each replication had two pots and all plants in each replication were harvested for data collection. The experiment was terminated once the plants reached flowering stage (45 days after sowing). Data relating to plant growth, biochemical attributes, soil enzyme activities and soil properties were collected at harvesting. Data was collected from all plants in each replication and averaged across replications for analysis.

Data collection

Data relating to morphological attributes, i.e., plant height, stomatal conductance, chlorophyll index (SPAD values), root length and weight, plant weight and activities of soil enzymes, i.e., catalase, urease, and dehydrogenase were collected. Similarly, malondialdehyde, hydrogen peroxide (H₂O₂), and proline contents in soybean plants and activities of ascorbate peroxidase, peroxidase and catalase enzymes were recorded. Although no abiotic stress was imposed during the study, activities of antioxidant enzymes were measured, since biochar may improve the physical and chemical properties of soil and influence plant metabolic processes under normal environments. These changes might affect the ratio of reactive oxygen species to antioxidant defense. The assessment of the impacts of gytija biochar on plant health and oxidative metabolism is facilitated by measuring the activities of antioxidant enzymes. Soil chemical properties, i.e., soil reaction (pH) and electrical conductivity (EC) were determined after harvesting.

Growth traits

Plant height, root length and weight and plant biomass were recorded for all the harvested plants from each pot in each replication. The lengths of all plants were measured with the help of meter rod and averaged across replication. The plants were uprooted carefully, debris was removed by washing the roots, divided into roots and shoots and then root length and weight and shoot fresh biomass were recorded. The shoots were dried in an oven for 72 h at 65 °C and dry biomass production was recorded.

Leaf stomatal conductance (mmol m⁻² s⁻¹) and chlorophyll index

Leaf stomatal conductance was measured using a portable leaf porometer (Decagon Devices, Pullman, WA, USA), according to the methods described by Long and Bernacchi [31] and Pérez-Harguindeguy et al. [32]. Measurements were conducted on fully grown, healthy leaves under stable environmental conditions. The chlorophyll index (SPAD values) was measured using a portable chlorophyll meter (Minolta SPAD 502, Konica Minolta, Tokyo, Japan), in accordance with the standard methods established by Markwell et al. [33]. Measurements were conducted on healthy, fully grown leaves under stable environmental conditions.

Leaf proline, hydrogen peroxide and monoaldehyde contents

Leaf proline content was determined by following Bates et al. [34]. Leaf samples (0.5 g) were homogenized in 10 ml of 3% sulfosalicylic acid. Following centrifugation at 12,000 rpm for 15 min, 2 ml of supernatant was mixed

with 2 ml of glacial acetic acid and 2 ml of acid ninhydrin solution. Samples were incubated at 80 °C for 1 h, immediately cooled, and proline was extracted by adding 4 ml toluene. Absorbance was spectrophotometrically measured (Shimadzu UV-1800, Japan) at 520 nm using a toluene blank as a reference.

The MDA content was quantified by following the method described by Weisany et al. [35]. Leaf samples (0.1 g fresh weight) were homogenized with 5 ml of 0.1% trichloroacetic acid (TCA). The homogenates were centrifuged at 12,000 rpm for 15 min at 4 °C. Supernatant aliquots (1 ml) were combined with 4 ml of 0.5% thiobarbituric acid (TBA) formulated in 20% trichloroacetic acid (TCA). The reaction mixture was incubated in a water bath at 95 °C for 30 min, rapidly cooled in an ice bath, and then centrifuged for 10 min at 12,000 rpm. The absorbance was measured spectrophotometrically at 532 nm, with non-specific absorbance at 600 nm subtracted.

The concentration of H₂O₂ was determined using the methodology proposed by Loreto and Velikova [36]. Leaf samples (0.5 g fresh weight) were homogenized in 5 ml of 1% TCA. Following centrifugation at 12,000 rpm for 15 min at 4 °C, 0.75 ml of supernatant was mixed with 0.75 ml of 10 mM potassium phosphate buffer (pH 7.0) and 1.5 ml of 1 M potassium iodide (KI). Absorbance was quantified at 390 nm, and H₂O₂ concentrations were determined using a standard curve.

Activities of antioxidant enzymes in plants

The activity of ascorbate peroxidase (APX) was assessed by employing the methodology of Nakano and Asada [37]. Leaf tissues (0.5 g) were homogenized in ice-cold 50 mM phosphate buffer (pH 7.0) supplemented with 1 mM EDTA and 1 mM ascorbate. Following centrifugation at 12,000 rpm for 15 min, the enzyme assay was conducted by mixing 0.1 ml of enzyme extract with 50 mM phosphate buffer, 0.1 mM H₂O₂, and 0.5 mM ascorbate. The reduction in absorbance was measured at 290 nm.

The catalase (CAT) activity was assessed according to the methodology of Kraus and Fletcher [38]. The enzyme was extracted by homogenizing 0.5 g of leaf tissue in 50 mM phosphate buffer (pH 7.0) at 4 °C, thereafter, centrifuged at 12,000 rpm for 15 min. The reaction mixture (3 ml) included enzyme extract (0.1 ml) and 50 mM phosphate buffer with 15 mM H₂O₂. The response was observed by quantifying the reduction in absorbance at 240 nm at 30-second intervals for a duration of 2 min.

Peroxidase (POD) activity was quantified by following Maehly and Chance [39]. Leaf samples (0.5 g fresh weight) were homogenized in 50 mM phosphate buffer (pH 7.0) and centrifuged at 12,000 rpm for 15 min. The test mixture (3 ml) included enzyme extract (0.1 ml), phosphate buffer (50 mM, pH 7.0), guaiacol (20 mM), and H₂O₂ (20 mM). POD activity was assessed by measuring

the increase in absorbance at 470 nm at 30-second intervals for a duration of 2 min.

Activities of soil enzymes

The dehydrogenase activity in the soil was determined by spectrophotometric measurement of TPF (triphenyl formazan) at 485 nm of the color formed after incubation of soil samples with TTC (triphenyl tetrazolium chloride) solution at 25 °C for 24 h [40]. Similarly, urease activity was determined by the color intensity of the filtrate obtained by incubation of soil samples with 10% urea and sodium phenolate solution at 37 °C [41]. Catalase activity was assessed using the volumetric approach described by Johnson and Temple [42]. Five g of fresh soil samples were put in a flask and treated with 5 mm of 3% H₂O₂. The flask was immediately sealed, and the amount of released oxygen gas was quantified volumetrically after a 3-minute incubation at an ambient temperature.

Statistical analysis

One-way analysis of variance (ANOVA) [43] was used to analyze collected data for each trait. Prior to conducting ANOVA, the data were assessed for normality [44] and homogeneity of variances, which indicated a normal distribution. Hence the data satisfied the normality assumption of ANOVA. Post-hoc comparison was performed using Tukey's Honest Significant Difference (HSD) test at the 95% confidence level ($p < 0.05$) where ANOVA denoted significant differences among treatments. Pearson correlation was computed among the measured traits to observe their relationship. All statistical analyses were performed by using SPSS statistical software version 21.0 [45].

Results

Plant growth traits

All measured plant (except chlorophyll index, H₂O₂ and proline content and ascorbate activity) and soil traits were significantly affected by different gytja biochar concentrations included in the study (Table 3).

The highest plant height was recorded for 4.5% gytja biochar concentration (35.33 cm), representing a 20.9% increase compared to the control (29.20 cm) (Fig. 1a). Increasing biochar concentrations exerted beneficial impact on plant biomass. Plant biomass improved by 44.78%, 57.31%, and 84.92% with 1.5%, 3.0% and 4.5% biochar concentrations, respectively compared to control (Fig. 1b). The application of 1.5%, 3.0% and 4.5% biochar concentrations improved root length by 23.94%, 29.22%, and 28.17%, respectively, in comparison to the control (Fig. 1c). All biochar concentrations significantly improved root weight compared to the control group. The improvement was 19.12%, 48.91%, and 64.15% for 1.5%, 3.0% and 4.5% biochar concentrations, respectively.

Table 3 Analysis of variance for different growth and biochemical attributes of soybean plants and soil pH, EC and enzyme activities

Traits	SOV	DF	SS	MS	F value	p value
Plant traits						
Plant height	BD	3	76.93	25.64	3.26	0.008
	Error	8	62.87	7.86		
Stomatal conductance	BD	3	5232.42	1744.14	18.07	0.001
	Error	8	772.29	96.54		
Chlorophyll index	BD	3	46.59	15.53	1.82	0.222 ^{NS}
	Error	8	68.38	8.55		
Root length	BD	3	136.54	45.51	10.98	0.003
	Error	8	33.15	4.14		
Root weight	BD	3	15.83	5.28	7.23	0.011
	Error	8	5.84	0.73		
Plant weight	BD	3	21.32	7.11	7.25	0.011
	Error	8	7.84	0.98		
MDA content	BD	3	4.84	1.61	11.21	0.003
	Error	8	1.15	0.14		
H ₂ O ₂ content	BD	3	1.26	0.42	1.07	0.415 ^{NS}
	Error	8	3.15	0.39		
Proline content	BD	3	10.37	3.46	3.39	0.075 ^{NS}
	Error	8	8.16	1.02		
Ascorbate activity	BD	3	1.29	0.43	0.91	0.481 ^{NS}
	Error	8	3.77	0.47		
Peroxidase activity	BD	3	11.36	3.79	7.14	0.012
	Error	8	4.24	0.53		
Catalase activity	BD	3	0.16	0.05	4.08	0.050
	Error	8	0.11	0.01		
Soil traits						
Catalase activity	BD	3	6067.67	2022.56	65.95	<0.0001
	Error	8	245.33	30.67		
Urease activity	BD	3	401.64	133.88	218.65	<0.0001
	Error	8	4.90	0.61		
Dehydrogenase activity	BD	3	100.33	33.44	54.99	<0.0001
	Error	8	4.87	0.61		
pH	BD	3	0.33	0.11	19.37	0.001
	Error	8	0.05	0.01		
EC	BD	3	12192.33	4064.11	140.95	<0.0001
	Error	8	230.67	28.83		

The bold values in p value column denote that the relative traits were significantly altered by applied biochar doses, whereas *NS* represents non-significant effect of biochar doses on corresponding traits

SOV Source of variation, BD Biochar doses, DF Degree of freedom, SS Sum of squares, MS Mean squares

Root weight increased with increasing biochar concentrations, and the highest value was recorded for 4.5% dose (Fig. 1d). Although biochar treatments had a non-significant impact on chlorophyll index (SPAD values), the highest value (36.1) was recorded with 4.5% gytja biochar, indicating a 12.5% increase relative to the control (Fig. 1e). Stomatal conductance increased from 66.56 in the control treatment to 127.23 with 4.5% biochar, indicating a 91.2% improvement. The longest root length (36.7 cm) was recorded with 3% biochar, indicating a 29.2% increase relative to the control (Fig. 1f).

Plant biochemical attributes

Different gytja biochar concentration significantly influenced malondialdehyde (MDA) content, and activities of peroxidase (POD) and catalase (CAT) enzymes; however, hydrogen peroxide (H₂O₂) and proline contents, and ascorbate peroxidase (APX) activity remained unaffected in this regard (Table 3). The MDA content significantly decreased with increasing biochar concentration (Fig. 2a). The application of 1.5%, 3.0%, and 4.5% biochar reduced plant MDA content by 17.34%, 35.08%, and 24.60%, respectively (Fig. 2a). The H₂O₂ contents and APX remained non-significant (Fig. 2b and d). The control treatment resulted in the lowest proline contents,

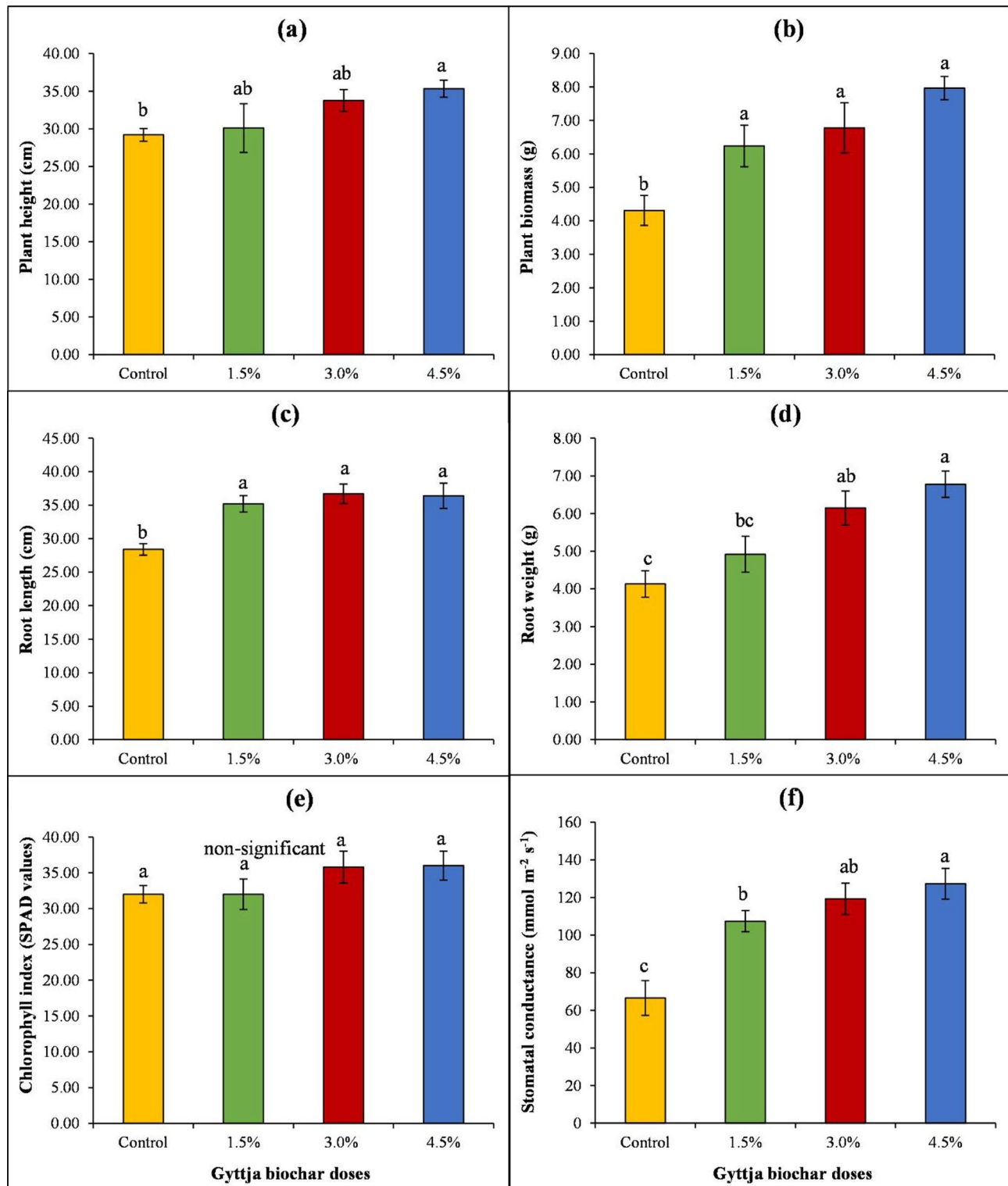


Fig. 1 The influence of different gytija biochar concentrations on plant height (a), plant biomass (b), root length (c), root weight (d), chlorophyll index (e) and stomatal conductance (f) of soybean plants. The data presented are means \pm standard errors of means ($n=3$). The means having different letters are statistically different from each other ($p < 0.05$)

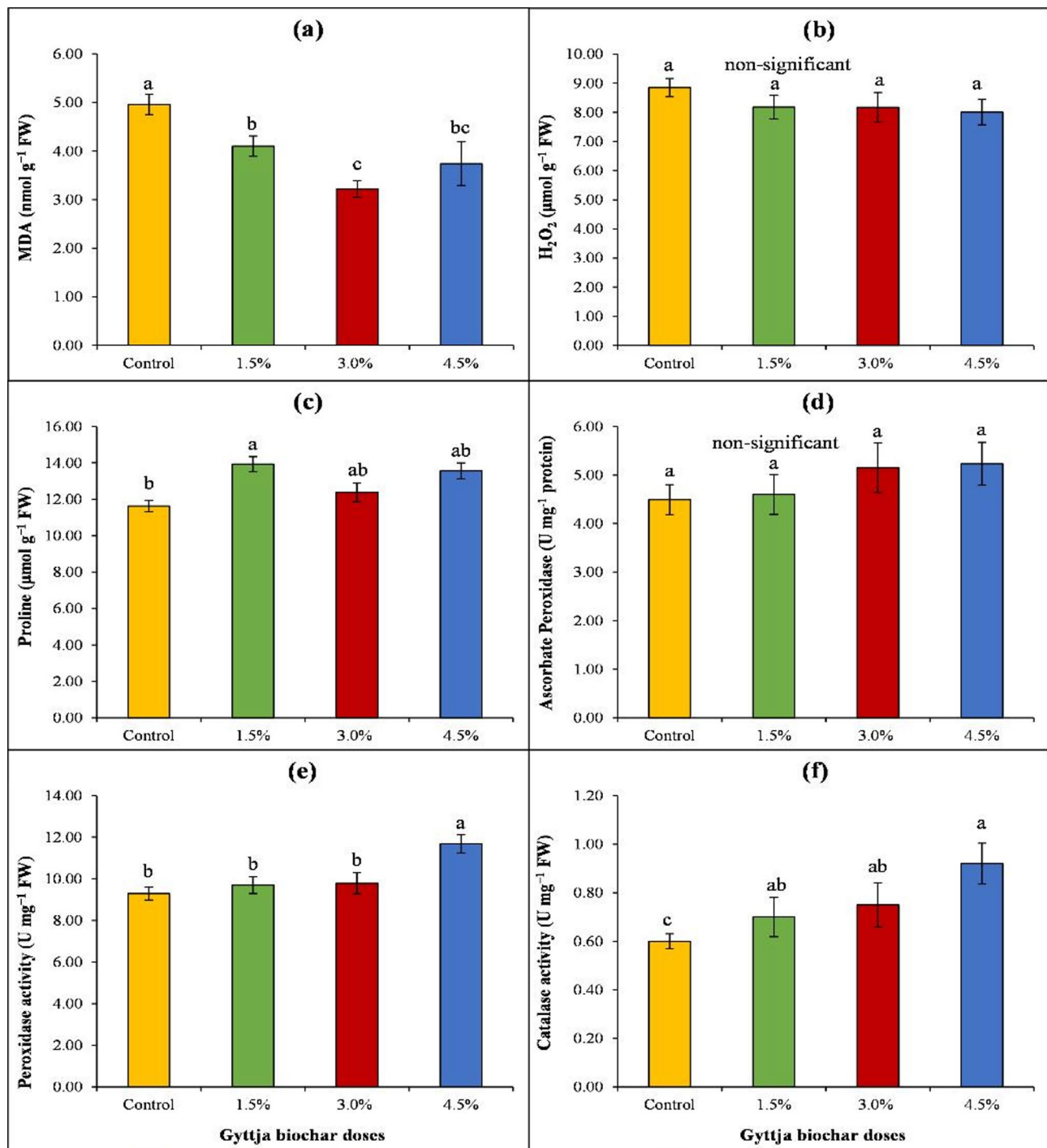


Fig. 2 The influence of different gyttyja biochar concentrations on malondialdehyde (a), hydrogen peroxide (b) and proline contents (c), and activities of ascorbate peroxidase (d), peroxidase (e) and catalase (f) enzymes in soybean plants. The data presented are means \pm standard errors of means ($n=3$). The means having different letters are statistically different from each other ($p < 0.05$)

whereas remaining biochar doses resulted in the similar proline contents (Fig. 2c). The 4.5% concentration significantly improved POD activity relative to control (Fig. 2e). Moreover, all biochar concentrations significantly influenced CAT activity, with the most pronounced effect observed for 4.5% concentration. The 1.5%, 3.0%, and

4.5% application rates increased CAT activity by 17.64%, 25.96%, and 50.08%, respectively (Fig. 2f).

Soil traits

Soil pH, EC, and activities of soil enzyme activities were significantly affected by different gyttyja biochar

concentrations. The highest catalase activity in soil was noted for 4.5% concentration (Fig. 3a). Application of 1.5%, 3.0%, and 4.5% concentrations enhanced urease activity by 22.81%, 58.70%, and 97.01%, respectively compared to control (Fig. 3b). Likewise, 1.5%, 3.0%, and 4.5% concentrations improved soil dehydrogenase activity by 2.89%, 15.81%, and 34.71%, respectively, in comparison to the control. The most significant rise was recorded for 3.0% and 4.5% concentrations (Fig. 3c). Soil pH increased by 2.55%, 4.57%, and 5.91%, respectively with the application of 1.5%, 3.0%, and 4.5% biochar concentrations, respectively compared to control (Fig. 3d). Similarly, the increase in soil EC for 1.5%, 3.0%, and 4.5% biochar concentrations was 9.50%, 20.09%, and 33.13%, respectively (Fig. 3e).

A strong positive correlation was observed between plant height, stomatal conductance, chlorophyll index, root length, root weigh, and overall plant biomass, suggesting that gytjtja biochar enhanced plant growth traits. Soil enzymatic activities, including catalase, urease, and dehydrogenase also exhibited positive correlations with plant growth traits, highlighting the role of biochar in promoting soil health and nutrient cycling. Notably, soil pH and EC were positively correlated, indicating a shift in soil chemistry due to biochar amendments. Stress-related markers (MDA and H_2O_2) demonstrated an inverse relationship with growth traits, suggesting that biochar applications mitigate oxidative stress in plants. Additionally, proline, ascorbate peroxidase, and catalase activities in leaves showed significant correlations, emphasizing their role in stress response mechanisms (Fig. 4). These findings collectively suggest that gytjtja biochar enhances plant growth by improving soil enzymatic activities while reducing oxidative stress, thereby contributing to overall plant resilience and productivity.

PH=plant height, SC=stomatal conductance, CI=chlorophyll index, RL=root length, RW=root weight, PB=plant biomass, CAT=catalase activity in soil, URE=urease activity in soil, DHG=dehydrogenase activity in soil, pHS=soil pH, EC=soil EC, MD=malonaldehyde contents in leaves, H_2O_2 , hydrogen peroxide contents, PRO=proline concentration in leaves, ASCO=ascorbate peroxidase activity in leaves, CATP=catalase activity in leaves.

Discussion

The application of gytjtja biochar significantly improved growth and biochemical traits of soybean, with the most significant improvements recorded for the highest concentration included in the study. All biochar-treated plants had better plant height, biomass, and leaf chlorophyll content compared to the control treatment. The highest biochar dose (4.5%) led to the most significant improvements in plant height and shoot dry weight. In

contrast, the moderate biochar concentration (3.0%) yielded slightly lower yet significant improvements, while the lowest dose (1.5%) also produced noticeable improvements compared to the control. The findings complement earlier studies indicating that biochar enhances legume growth and nodulation. Suppadit et al. [13] documented an increase in nodule count, plant height, dry biomass, and nutrient absorption in soybeans following the application of quail-litter biochar. The positive impact of gytjtja biochar on soybean growth in the current study indicates both direct and indirect advantages.

The application of biochar likely mitigated nutritional deficiencies by increasing nutrient availability and enhancing soil conditions for soybean growth. Increased leaf chlorophyll and photosynthetic activity in biochar-treated plants suggest improved nutritional status (e.g., increased N and Mg availability for chlorophyll synthesis) along with improved water absorption, which promoted growth. Previous studies have demonstrated that biochar improves plant water uptake (transpiration), hence facilitating nutrient absorption by roots [46]. Biochar applications may indirectly improve root growth and functioning by modifying the soil physical structure (e.g., porosity, water retention) and increasing nutrient bioavailability [47, 48]. The results of the current study indicated no growth inhibition at the highest concentration, suggesting that 4.5% gytjtja biochar could be used for improving soybean growth. The dose-dependent response of plants aligns with literature suggesting that the effects of biochar differ based on application rate and type.

Besides improvements in root traits and biomass production, gytjtja biochar also improved other physiological and biochemical indices of plant performance. Soybean plants treated with biochar exhibited increased stomatal conductance, which probably enhanced CO_2 assimilation and growth. The activities of essential antioxidant enzymes, i.e., superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) were altered by the incorporation of biochar. The plants in control treatment exhibited moderate SOD and CAT activities likely indicating baseline scavenging of reactive oxygen species (ROS). Biochar application at 3.0% and 4.5% resulted in a modest increase in SOD and CAT activities, although POD activity decreased. Despite no stress imposed in the current study, these changes indicate that biochar created a more beneficial, less oxidative environment for the plants. The same phenomenon has been observed under abiotic stress conditions. For example, Anwar et al. [49] indicated that biochar application might enhance CAT and SOD activity in plants while decreasing POD, therefore mitigating oxidative damage during heavy metal stress. The slight elevation in SOD and CAT activities indicate an enhanced antioxidant capacity

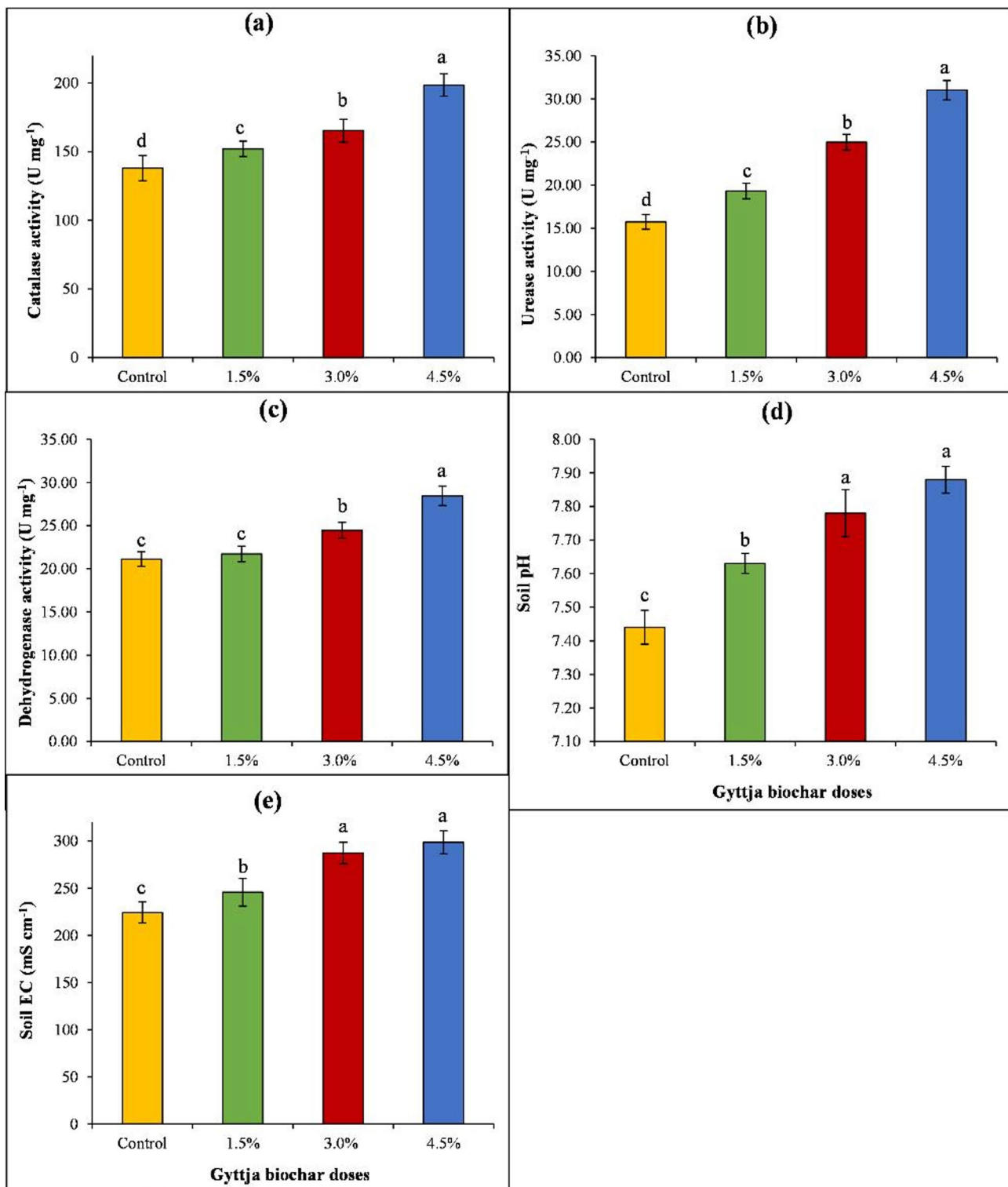


Fig. 3 The influence of different gytija biochar concentrations on the activities of catalase (a), urease (b), and dehydrogenase (c) enzymes in soil and soil pH (d) and EC (e). The data presented are means \pm standard errors of means ($n=3$). The means having different letters are statistically different from each other ($p < 0.05$)

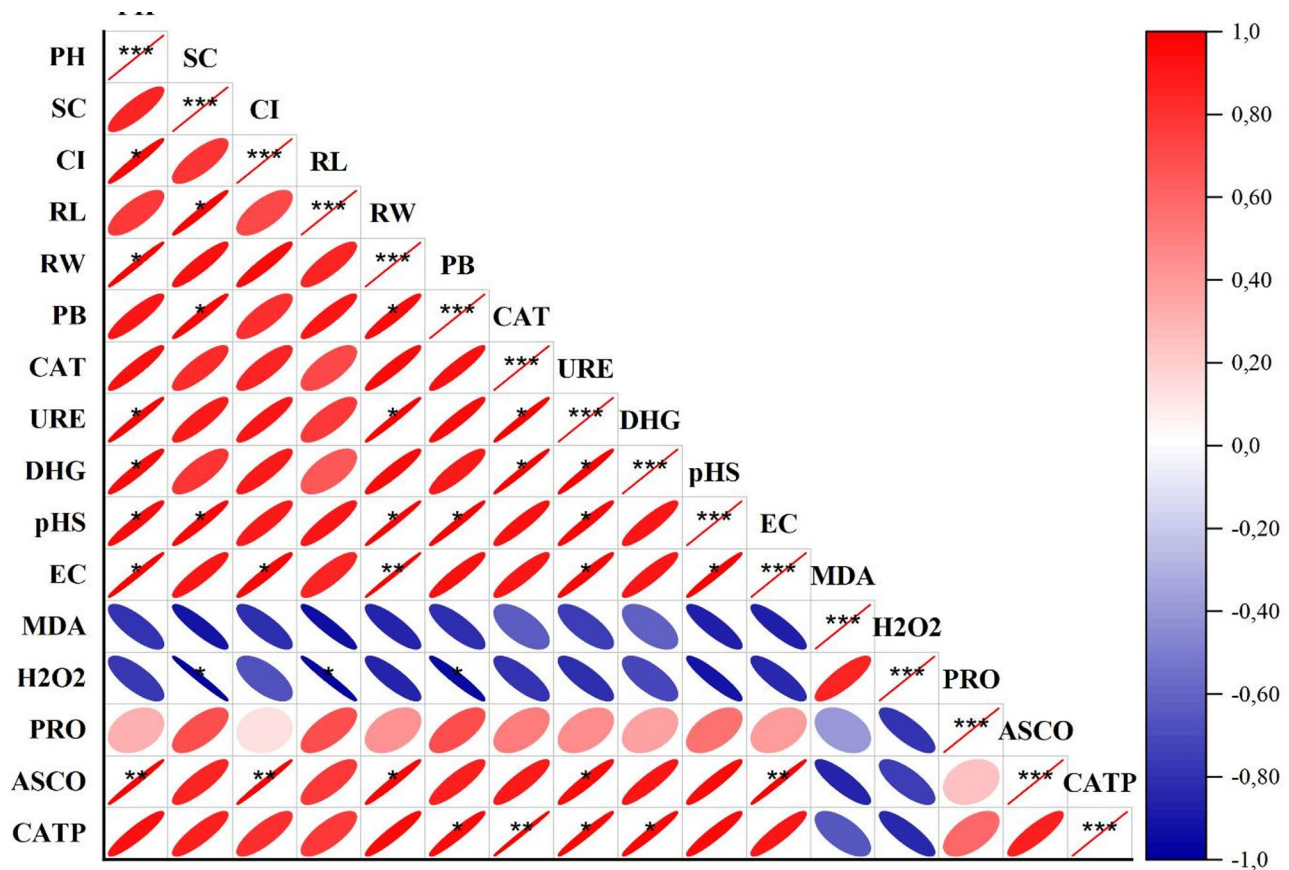


Fig. 4 Correlation among different growth and biochemical attributes of soil and soybean plants grown under varying concentrations of gytija biochar

or increased metabolic activity of the healthier biochar-treated plants. In contrast, the slight decrease in POD activity at high biochar concentrations may indicate that biochar-amended plants experienced less oxidative stress, since POD typically increases in reaction to stress-induced ROS. This hypothesis is supported by earlier studies indicating that biochar may mitigate Cd toxicity, enabling plants to reduce excessive production of antioxidant enzymes [47, 49]. The biochar-treated soybean plants exhibited reduced oxidative stress and enhanced redox balance, consistent with their improved growth. Consequently, gytija biochar not only stimulated soybean growth and photosynthesis by enhancing nutrition but also facilitated the maintenance of oxidative homeostasis.

The incorporation of gytija biochar improved soil chemical attributes and biological activity, hence promoting plant growth. All biochar concentrations improved soil pH and EC compared to the control, with the most significant improvements seen at 4.5%. The application of 4.5% biochar increased pH by 0.4–0.6 units relative to the control, whereas 1.5% and 3.0% biochar increased pH by 0.2–0.3 units. The ash content of gytija biochar

and its possible enrichment in basic cations (Ca_2^+ , Mg_2^+ , K^+) indicate a liming effect. Recent study indicated that incorporation of raw gytija into acidic soils increased pH, calcium carbonate content, organic matter, and available phosphorus [9]. Soils treated with biochar probably had better nutrient profile which enhanced soil nutrient availability. Biochar's stable carbon probably improved soil organic carbon, which improved fertility and carbon sequestration over time. Higher soil organic matter enhances soil structure and moisture retention, perhaps benefiting soybean roots. In brief, gytija biochar improved soybean performance by decreasing soil acidity and augmenting nutrient availability.

Soil amendment with biochar improved soil dehydrogenase activity compared to control soils. The organic carbon substrate and improved habitat offered by biochar might increase the activity or abundance of the soil microbial community. Urease activity, which mineralizes nitrogen was significantly improved in all biochar concentrations. These findings confirm previous research indicating that low-to-moderate biochar enhances soil enzymatic activity [50]. Jiang et al. [50] found that the

incorporation of 2% swine-manure biochar increased soil hydrolase enzymes (e.g., sucrase) by 50–60%, phosphatase and urease by 23–28%, and microbial biomass by 34%. Gytija biochar application in the current possibly supplied nutrients and a microhabitat for microbial colonization. The porous structure of biochar shields microbial cells and extracellular enzymes against degradation while facilitating substrate accessibility. Biochar improves soil moisture retention and aeration, facilitating microbial growth and enzyme production [51]. Biochar improved soil catalase activity in the current study, indicating higher microbial oxidative metabolism. This corresponds with Jiang et al. [50], where 2% biochar enhanced soil catalase by around 50%. Increased enzyme activity in biochar-amended soil indicates a more dynamic soil microbiome facilitating nutrient cycling. Incorporation of biochar improves soil biological activity by offering organic carbon as a nutrient source or mitigating stressors, such as neutralizing acidity and adsorbing toxins [51]. Gytija biochar improved soil health in the current study by increasing chemical fertility and biological activity.

The current study recorded a significant link between biochar application and soil and plant performance. Leaf antioxidant enzymes (e.g., SOD, CAT) exhibited an inverse correlation with soil parameters. Biochar-treated plants demonstrated reduced oxidative stress indicators and small induction of antioxidant enzymes. Soil dehydrogenase activity correlated strongly with soybean shoot and root biomass. Biochar may have benefited plant development by encouraging an active soil microbial community through enhancing nutrient mineralization and plant growth-promoting compounds. Garbuz et al. [51] observed that biochar boosted soil enzyme activity and root growth, promoting soil biology. Biochar-treated soybean plants exhibited larger root systems, which probably increased nutrient absorption and soil enzymatic activity. Biochar improved soil conditions, increasing plant growth, root inputs, microbial substrates, and soil biota.

The current study reports immediate benefits of gytija biochar for soybean growth and soil health; however, it has certain limitations. The experiment lasted for one growing season in pots and focused on the preliminary effects of biochar. The delayed nutrient release of biochar, its long-term benefits to soil structure, and the impacts of nitrogen immobilization or aging might not become apparent within this period. Extended experiments are required to determine if biochar's beneficial effects on soil fertility and crop growth. Secondly, a single soybean genotype was assessed in a greenhouse environment. Different cultivars or field-grown soybeans may have differential responses to biochar, particularly under drought, diseases, or when planted in soil with variable textures

and fertility levels. Extending the findings to several soybean varieties and open-field conditions might enhance generalizability. Testing gytija biochar on other crops or within crop rotation systems may validate those improvements in soil health result in agronomic benefits. The next phases of employing gytija biochar in sustainable agriculture must include field-scale feasibility, economic considerations, and environmental impacts, such as soil water dynamics and greenhouse gas emissions. Overall, gytija biochar is an effective soil amendment for enhancing soybean growth and soil health. Nevertheless, subsequent studies are needed to address the limitations and enhance understanding of biochar's role in agroecosystem resilience.

Conclusion

The use of gytija biochar significantly enhanced soybean growth and soil health. Gytija biochar improved soil characteristics, including pH, EC, and enzyme activities, hence facilitating improved plant growth, characterized by increased height, biomass, and root development. Biochar improved soil health, significantly improving enzyme activities such as dehydrogenase and urease indicating improved nutrient cycling and microbial activity. The observed positive correlations between plant growth traits and soil enzyme activity highlight the interdependence of soil and plant health, with biochar acting as a catalyst for this synergy. Nonetheless, certain limitations must be recognized in this study. The experiment was conducted in a controlled greenhouse environment for a short duration with a single soybean genotype, which constrains the generalizability of the findings. Future studies must involve multi-season field trials utilizing multiple crop varieties, various soil types, and prolonged biochar application periods to evaluate the long-term impacts of gytija biochar.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author's contributions

Conceptualization: VB; Data curation: VB; Formal analysis: VB; Investigation: VB; Methodology: VB; Project administration: VB; Resources: VB; Software: VB; Validation: VB; Visualization: VB; Writing - original draft: VB; Writing - review and editing: VB. All authors read and approved the final manuscript.

Funding

This study received no funding.

Data availability

The data will be available from the corresponding author on reasonable requests.

Declarations

Ethics approval and consent to participate

Not applicable. This is not a clinical study and no patients were involved.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

¹Department of Field Crops, Faculty of Agriculture, Harran University, Şanlıurfa 63050, Turkey

Received: 31 March 2025 / Accepted: 17 July 2025

Published online: 29 July 2025

References

- Łachacz A, Nitkiewicz M, Pisarek W. Soil conditions and vegetation on gytija lands in the Masurian Lakeland. In: Łachacz A, editor. Wetlands— their functions and protection. Department of Land Reclamation and Environmental Management. University of Warmia and Mazury in Olsztyn; 2009. p. 61–94.
- Myślińska E. Grunty Organiczne i Laboratoryjne metody Ich Badania. Warszawa, Poland: Wydawnictwo Naukowe PWN; 2001.
- Saltali K, Kara Z. Effects of Gytija applications on some chemical properties of acidic soils. *Kahramanmaraş Sütcü İmam Üniversitesi Tarım ve Doğa. Dergisi.* 2022;25:374–9.
- Uslu OS, Babur E, Battaglia ML, Turkaya E, Seleiman MF, Roy R, et al. Effects of gytija applications on hay yield and quality of a rangeland in the Mediterranean region. *Int J Environ Sci Technol.* 2023;20:4139–50.
- Stankevica K, Vincevica-Gaile Z, Klavins M. Freshwater sapropel (gytija): its description, properties and opportunities of use in contemporary agriculture. *Agron Res.* 2016;14:929–47.
- Gulser F, Yilmaz C, Sonmez F. Effects of gytija and chemical fertilizer applications on growing media and pomologic and biochemical properties in pepper (*Capsicum annuum* L.) fruit. *Toprak Bilimi Ve Bitki Besleme Dergisi.* 2014;2:1–5.
- Torun B, Yazici A, Gültekin I, Cakmak I. Influence of gytija on shoot growth and shoot concentrations of zinc and boron of wheat cultivars grown on zinc-deficient and boron-toxic soil. *J Plant Nutr.* 2003;26:869–81.
- Karaca A, Turgay OC, Tamer N. Effects of a humic deposit (gytija) on soil chemical and microbiological properties and heavy metal availability. *Biol Fertil Soils.* 2006;42:585–92.
- Saltali K, Solak S, Özdoğan A, Kara Z, Yakupoğlu T. Gytija as a soil conditioner: changes in some properties of agricultural soils formed on different parent materials. *Sustainability.* 2023;15:9329.
- Korkmaz K, Nur Ergin M, Akgun M, Saltali K. The influence of humic deposit (gytija) application on some selected soil properties and yield-quality of hazelnut in acid conditions. *Agrochimica.* 2021;65:279–93.
- Saltali K, Nedirli A. Phosphorus sorption by Gytija and its effect on the pH value and phosphorus in acidic soils. *Turkish J Agric Forestry.* 2021;45:402–10.
- Vincevica-Gaile Z, Stapkevica M, Stankevica K, Burlakovs J. Testing sapropel (gytija) as soil amendment: Assessment of plant germination and early seedling development. In: Proc. Annual 21st International Scientific Conference Research for Rural Development. 2015. pp. 89–94. https://www2.llu.lv/research_conf/Proceedings/21st_volume1.pdf.
- Egamberdieva D, Wirth S, Behrendt U, Abd_Allah EF, Berg G. Biochar Treatment Resulted in a Combined Effect on Soybean Growth Promotion and a Shift in Plant Growth Promoting Rhizobacteria. *Front Microbiol.* 2016;7:209.
- Jaffar MT, Chang W, Zhang J, Mukhtar A, Mushtaq Z, Ahmed M, et al. Sugar-cane bagasse biochar boosts maize growth and yield in salt-affected soil by improving soil enzymatic activities. *J Environ Manage.* 2024;363: 121418.
- Jaffar MT, Ahmed M, Shi R, Jiang S, Kong Z, Girkin N, et al. Unraveling mechanisms of N₂O emissions and nitrogen cycling: the role of Biochar C:N ratios in loamy and sandy soils. *Appl Soil Ecol.* 2025;207:105950.
- Jaffar MT, Chang W, Ahmed M, Shi R, Liu Q, Girkin N, et al. Mechanistic insights into the role of biochar C:N ratios in modulating greenhouse gas emissions and soil organic carbon fractions in contrasting soil types. *Soil Sci Soc Am J.* 2025. <https://doi.org/10.1002/saj2.70068>.
- Jaffar MT, Zhen S, Han J, Zhang J, Dar A, Mushtaq Z, et al. Orange Peel biochar: an effective amendment to improve the maize resilience by regulating the soil enzymatic activities, nutrient uptake, and ionic homeostasis under salinity stress. *Ind Crops Prod.* 2024;222:120081.
- Atkinson CJ, Fitzgerald JD, Hipps NA. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant Soil.* 2010;337:1–18.
- Khan Z, Zhang K, Khan MN, Zhu K, Hu L. Effects of Biochar persistence on soil physiochemical properties, enzymatic activities, nutrient utilization, and crop yield in a three-year rice-rapeseed crop rotation. *Eur J Agron.* 2024;154:127096.
- Pokharel P, Ma Z, Chang SX. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. *Biochar.* 2020;2:65–79.
- Wang Y, Tian Z, Li X, Zhang M, Fang Y, Xiang Y, et al. Straw-derived biochar regulates soil enzyme activities, reduces greenhouse gas emissions, and enhances carbon accumulation in farmland under mulching. *Field Crops Res.* 2024;317: 109547.
- Zeng L, Zimmerman AR, Huang R. Adsorption of extracellular enzymes by biochar: impacts of enzyme and biochar properties. *Geoderma.* 2024;451:117082.
- Rahmanian M, Khadem A. The effects of biochar on soil extra and intracellular enzymes activity. *Biomass Convers Biorefin.* 2024;14:21993–2005.
- Barbosa FLA, Santos JMR, Mota JCA, Costa MCG, Araujo ASF, Garcia KGV, et al. Potential of biochar to restoration of microbial biomass and enzymatic activity in a highly degraded semiarid soil. *Sci Rep.* 2024;14:26065.
- Liu M, Linna C, Ma S, Ma Q, Guo J, Wang F et al. Effects of Biochar with inorganic and organic fertilizers on agronomic traits and nutrient absorption of soybean and fertility and microbes in purple soil. *Front Plant Sci.* 2022;13:871021.
- Lehmann J, Joseph S. *Biochar for Environmental Management.* Routledge; 2012.
- Sohi SP, Krull E, Lopez-Capel E, Bol R. A Review of Biochar and Its Use and Function in Soil. *Adv Agron.* 2010;105:47–82.
- Siamabele B. The significance of soybean production in the face of changing climates in Africa. *Cogent Food Agric.* 2021;7:1933745.
- Voora V, Bermudez S, Le H, Larrea C, Luna E. Global Market Report: Soybean prices and sustainability. Sustainable Commodities Marketplace Series. 2024. <https://www.iisd.org/system/files/2024-02/2024-global-market-report-soybe-an.pdf>.
- Karabina K. Oilseeds and Products Annual. 2024. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?FileName=Oilseeds%20Annual%20Products%20Annual_Ankara_Turkiye_TU2024-0009.pdf.
- Long SP. Gas exchange measurements, what can they tell us about the underlying limitations to photosynthesis? Procedures and sources of error. *J Exp Bot.* 2003;54:2393–401.
- Pérez-Harguindeguy N, Díaz S, Garnier E, Lavorel S, Poorter H, Jaureguierry P, et al. New handbook for standardised measurement of plant functional traits worldwide. *Aust J Bot.* 2013;61:167.
- Markwell J, Osterman JC, Mitchell JL. Calibration of the Minolta SPAD-502 leaf chlorophyll meter. *Photosynth Res.* 1995;46:467–72.
- Bates LS, Waldren RP, Teare ID. Rapid determination of free proline for water-stress studies. *Plant Soil.* 1973;39:205–7.
- Weisany W, Sohrabi Y, Heidari G, Siosemardeh A, Ghassemi-Golezani K. Changes in antioxidant enzymes activity and plant performance by salinity stress and zinc application in soybean (*Glycine max* L). *Plant Omics.* 2012;5:60–7.
- Loreto F, Velikova V. Isoprene produced by leaves protects the photosynthetic apparatus against ozone damage, quenches ozone products, and reduces lipid peroxidation of cellular membranes. *Plant Physiol.* 2001;127:1781–7.
- Nakano Y, Asada K. Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. *Plant Cell Physiol.* 1981;22:867–80.
- Kraus TE, Fletcher RA. Paclobutrazol protects wheat seedlings from heat and Paraquat injury. Is detoxification of active oxygen involved?? *Plant Cell Physiol.* 1994;35(1):45–52.
- Maehly AC. The Assay of Catalases and Peroxidases. In: *Methods of biochemical analysis.* Hoboken: Wiley; 1954. pp. 357–424.
- Camiña F, Trasar-Cepeda C, Gil-Sotres F, Leirós C. Measurement of dehydrogenase activity in acid soils rich in organic matter. *Soil Biol Biochem.* 1998;30:1005–11.
- Pettit NM, Smith ARJ, Freedman RB, Burns RG. Soil urease: activity, stability and kinetic properties. *Soil Biol Biochem.* 1976;8:479–84.
- Johnson JL, Temple KL. Some variables affecting the measurement of catalase activity in soil. *Soil Sci Soc Am J.* 1964;28:207–9.
- Steel R, Torrei J, Dickey D. *Principles and Procedures of Statistics A Biometrical Approach.* New York: McGraw-Hill; 1997.

44. Shapiro SS, Wilk MB. An analysis of variance test for normality (complete samples). *Biometrika*. 1965;52(3/4):591–611.
45. IBM C, IBM SPSS Inc. SPSS statistics for windows. IBM corp released 2012. Version. 2012;20:1–8.
46. Jiang W, Xu L, Liu Y, Su W, Yan J, Xu D. Effect of Biochar on the growth, photosynthesis, antioxidant system and cadmium content of *Mentha Piperita* 'chocolate' and *Mentha spicata* in cadmium-Contaminated soil. *Agronomy*. 2022;12:2737.
47. Alkharabsheh HM, Seleiman MF, Battaglia ML, Shami A, Jalal RS, Alhammad BA, et al. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. *Agronomy*. 2021;11:993.
48. Murtaza G, Ahmed Z, Usman M, Tariq W, Ullah Z, Shareef M, et al. Biochar induced modifications in soil properties and its impacts on crop growth and production. *J Plant Nutr*. 2021;44:1–15.
49. Anwar T, Qureshi H, Jabeen M, Siddiqi EH, Zaman W, Alharbi SA, et al. Exploring the synergistic benefits of biochar and gibberellic acid in alleviating cadmium toxicity. *Sci Rep*. 2024;14:24196.
50. Jiang Y, Wang X, Zhao Y, Zhang C, Jin Z, Shan S, et al. Effects of biochar application on enzyme activities in tea garden soil. *Front Bioeng Biotechnol*. 2021. <https://doi.org/10.3389/fbioe.2021.728530>.
51. Garbuz S, Mackay A, Camps-Arbestain M, DeVantier B, Minor M. Biochar increases soil enzyme activities in two contrasting pastoral soils under different grazing management. *Crop Pasture Sci*. 2022;74:101–11.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.