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Investigation of the Effects of Biochar, a Pyrolysis Product of Waste Filter Coffee, on Germination of Grass and Basil Plants

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Abstract

This study focuses on the production of biochar via pyrolysis for the sustainable recycling of agricultural waste and the investigation of its effects on plant germination. The plant species selected for this study were basil (*Ocimum basilicum*) and grass (*Lolium perenne*). The present study investigates the soil-improving properties of biochar derived from filter coffee waste. In the experimental process, coffee waste was subjected to pyrolysis at specific temperatures, and the resulting biochar was analysed in terms of its physical and chemical properties. The resulting biochar was then mixed with soil at varying ratios to assess its effects on the germination and growth performance of basil and grass seeds. The application of 15% biochar resulted in the highest plant height (15 cm), although the fresh weight remained below that of the control. In the case of basil, plant development was only observed in the control group, while no growth occurred in any of the biochar-amended treatments. These results indicate that the effect of coffee waste-derived biochar on plant growth may vary depending on the plant species. While biochar applications enhanced soil water retention capacity, enriched organic matter content, and supported grass growth, they appeared to inhibit basil germination. In this context, it was demonstrated that biochar could potentially contribute to both agricultural waste management and sustainable agriculture when applied under suitable conditions.

Keywords: Filter coffee, Pyrolysis, Biochar, Plant germination

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INTRODUCTION

Coffee is one of the most widely consumed beverages globally, yielding a considerable volume of solid waste in its consumption. This waste, consisting of coffee husks, pulp, mucilage, silver skins, and spent coffee grounds, originates from various stages of coffee processing, including harvesting, roasting, and brewing (Lee et al., 2023). Coffee grounds, which are characterized by their high organic matter content and biodegradable structure, present considerable potential for recycling (Wu, 2015). The increasing consumption of coffee results in a significant amount of waste, with spent coffee grounds being a notable byproduct. These grounds can be repurposed into a variety of valuable products (McNutt & He, 2019)

The current practice of discarding spent coffee grounds has been shown to contribute to environmental issues, including potential soil degradation, due to the presence of tannins and caffeine and the generation of greenhouse gases in landfills (Arya et al., 2021). It is important to note that used filter coffee waste still contains a high amount of solids. Its composition depends on factors such as brewing method, growing conditions, and coffee type, but the composition of coffee is typically characterized by the presence of certain compounds (Mussatto et al., 2011). The primary component of spent coffee grounds, comprising about 50% of its dry weight, is polysaccharides, including cellulose and hemicellulose (Ballesteros et al., 2015). In addition, coffee grounds also contain health-related compounds such as phenolics, melanoidins, diterpenes, xanthines, and carotenoids. Additionally, spent coffee grounds have been found to be rich in organic compounds like fatty acids, lignin, and sugars, making it a valuable biodegradable material (Campos-Vega et al., 2015).

The potential of spent coffee grounds to function as a versatile resource has been demonstrated in a number of areas, including agriculture and material science (Bomfim et al., 2022; McNutt & He, 2019). It is evident that the environmental management of such waste is inadequate and effective methods must be developed. It is therefore imperative to explore sustainable applications for spent coffee grounds in order to mitigate environmental harm and foster a circular economy (Rivera & Ortega-Jiménez, 2019). In the context of the perpetual global demand for energy, the sustainable production of coffee presents opportunities for the utilisation of waste through combustion processes.

Pyrolysis is a thermochemical process that breaks down biomass at elevated temperatures in the absence of oxygen, resulting in the formation of gaseous, liquid, and solid by-products such as biochar (Amenaghawon et al., 2021). This technique allows for the transformation of organic waste into useful energy sources and materials, while also offering advantages like carbon sequestration and improved soil quality (Lee et al., 2010). The addition of biochar to soil has been associated with enhanced water-holding capacity, increased organic matter, and stimulation of microbial populations (Atkinson., 2018). Among the major thermochemical techniques for biomass conversion, pyrolysis plays a key role in generating solid (char), liquid (bio-oil), and gaseous (syngas or biogas) outputs along with other value-added compounds. Biomass pyrolysis can be further categorized based on the decomposition of its primary components, such as cellulose, hemicellulose, lignin, and whole wood (et al., 2010).

Figure 1 illustrates the overall process of biomass pyrolysis and the resulting products.

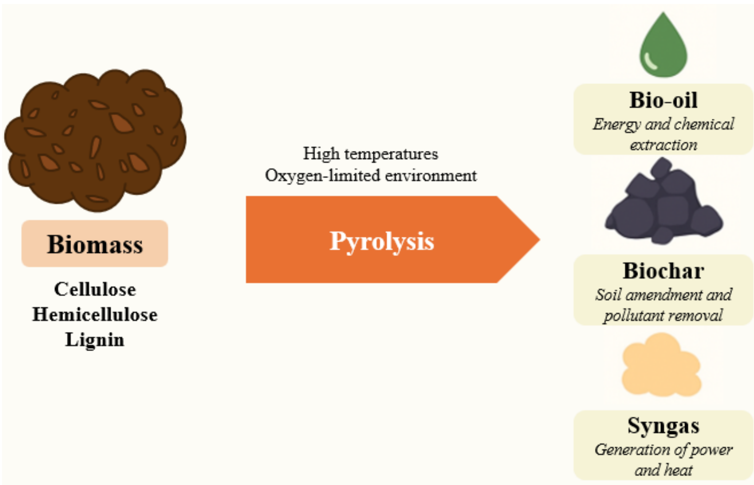


Figure 1. Overview of biomass pyrolysis and its main products: bio-oil, biochar, and syngas.

The use of biochar in soil provides advantages such as increased water retention capacity, organic carbon storage, and support for microbial activity.(Yadav et al., 2023) These properties have made biochar an important material for sustainable agriculture (Lehmann & Joseph, 2015). Biochar has been demonstrated to possess notable properties that contribute to the enhancement of soil quality.(Ding et al., 2017; Kalus et al., 2019; Yadav et al., 2023; Zhang et al., 2022) The process has been shown to enhance the physical, chemical and biological characteristics of the soil, thus increasing agricultural productivity. For example, the highly porous structure of biochar increases water retention capacity in sandy soils, while improving air circulation in clay soils (Li et al., 2021). Additionally, the alkaline pH characteristics of biochar can balance the pH of acidic soils, positively affecting plant growth (Chan & Xu, 2009). Biochar also impacts the chemical properties of soil by increasing cation exchange capacity, which helps nutrients remain in the soil for a longer period (Kavitha et al., 2018). Furthermore, by enhancing organic carbon storage capacity, biochar plays a significant role in combating climate change (Lorenz & Lal, 2014). Moreover, biochar has been identified as a critical component in the effective management of waste. It is an efficient method of recycling agricultural and urban biomass waste, including coffee grounds, corn stalks, and forestry residues (Xiong et al., 2017). This approach not only diverts organic waste from landfills but also converts it into a valuable resource for energy and soil enhancement (McNutt & He, 2019).

Recent studies have shown that the response of plants to biochar varies significantly depending on species and amendment dose. Sensitive horticultural crops such as basil (*Ocimum basilicum*) have exhibited variable germination and growth responses to different types of biochar (Gámiz et al., 2021; Nocentini et al., 2023; Wang et al., 2021). In particular, biochars produced from feedstocks rich in organic compounds or pyrolyzed at low temperatures have sometimes been associated with phytotoxic effects, including delayed germination and reduced root elongation (Buss et al., 2016; Hale et al., 2012). For example, Nocentini et al. (2023) reported that total or high substitution of peat with biochar in basil pot experiments resulted in seedling death within a few days of transplantation, likely due to increased pH and electrical conductivity of the growing media. Similarly, Gámiz et al. (2021) demonstrated that residual allelopathic compounds in biochar derived from agricultural residues could negatively affect seedling development in basil. However, the influence of biochar characteristics (particularly those derived from different feedstocks and pyrolysis conditions) on seed germination and early plant development is still not fully understood. Understanding these effects is crucial for optimizing biochar application rates and ensuring that its use does not cause phytotoxic effects on sensitive crops.

In this study, the effects of varying application rates of biochar on the germination and early growth performance of grass (*Lolium perenne*) and basil (*Ocimum basilicum*) were examined, with the aim of evaluating its potential as a sustainable soil amendment derived from coffee waste. By comparing two species with different sensitivities, this research aims to provide insights into both the beneficial and inhibitory effects of coffee waste-derived biochar on plant germination and growth.

MATERIALS AND METHODS

Experimental Materials and Sample Preparation

The present study utilized filter coffee residues collected from local coffee shops as the primary material. Since the residues originated from brewed filter coffee, the coffee grounds correspond to medium-grind size particles (approximately 500–800 µm). The waste filter coffee was air-dried and stored in sealed containers until it was used in the experiments.

The soil samples used for the plant germination tests were sourced from agricultural fields surrounding the research facility. The pH values were measured using a pH meter (Jenway 3040 Ion Analyzer), after being mixed by a magnetic stirrer for 10 min . The pH values of the soil samples were determined in a water suspension 1:2.5 sample: solution ratio and in KCl 0.1 N. The Thermo Flash 2000 Elemental Analyzer (The Central Research Laboratory of Bursa Technical University has employed this as an external service) is used for conducting the elemental analysis.

The plant species selected for this study were basil (*Ocimum basilicum*) and grass (*Lolium perenne*), chosen for their rapid germination and growth characteristics, which make them suitable for short-term experiments (Zhou et al., 2016; Javaid et al.,2022).

Pyrolysis Process and Biochar Production

In order to conduct pyrolysis process at 500 °C, waste filter coffee samples were first dried in a laboratory oven at the target temperature (105°C), aiming to remove their moisture content. After reaching a constant weight, 50 grams of the dessicated coffee residue were placed into a fixed-bed stainless steel reactor, which had an internal diameter of 8 cm and an approximate volume of 3 litres. After reaching a constant weight, 50 grams of the desiccated coffee residue were placed into a fixed-bed stainless steel reactor with an internal diameter of 8 cm and an approximate volume of 3 litres. The sample mass (50 g) was selected to ensure a uniform bed height and effective heat transfer within the laboratory-scale system. The reactor was custom-fabricated for experimental purposes and does not correspond to a commercial brand or model. Further design and operational details of the reactor can be found in a previous work (Ongen et al., 2018). Pyrolysis experiments were conducted under controlled laboratory conditions at target temperature of 400 °C with a heating rate of approximately 20 °C/min. The heating rate of the system was controlled by using an electrical panel, while rock wool insulation was employed around the reactor to minimize heat losses. To maintain an inert atmosphere during the pyrolysis process, nitrogen gas (N_2) was continuously introduced into the system at a flow rate of approximately 1.5 L/min. The duration of the pyrolysis was set to 4 hours, as preliminary trials with different residence times (ranging from 2 to 5 hours) indicated that this condition yielded the highest fixed carbon content. In order to prevent gas leakage, pure graphite and graphite-lead spiral gaskets were used at the connection points between the reactor body and the lid. The reactor was equipped with a gas inlet line for the introduction of nitrogen and a gas outlet line located in the lid of the reactor for the discharge of synthesis gas formed during pyrolysis. The internal temperature of the reactor was monitored using a thermocouple. To condense volatile organic compounds present in the synthesis gases, the outlet stream was passed through two consecutive cooling columns, and the resulting condensates were collected in conical flasks attached to these columns.

Characterization of Biochar

The moisture and solids content of the samples were determined according to the ASTM E1756-08 standard method. For this procedure, the samples were placed in crucibles and dried in an oven at 105 °C until a constant weight was achieved (typically around one hour). The percentage of moisture was then calculated using Equations (1). A Memmert brand oven was employed for this experimental procedure.

$$Moisture\ content\ by\ weight\ (\%) = \frac{(A-B)}{A} \times 100 \quad (1)$$

where,

A= The weight of the test sample (g)

B = The weight of the sample after drying at 105°C (g)

Scanning Electron Microscopy (SEM) was employed to examine the surface morphology and porosity of the biochar. The SEM analyses were carried out by the Central Research Laboratory of Recep Tayyip Erdoğan University as an external service.

The determination of ash content and loss on ignition was performed as a part of proximate analysis, which is commonly applied to solid fuels and biomass to characterize their fundamental properties. In this procedure, the samples were placed in ceramic crucibles and heated in a furnace at 550 °C for 120 minutes, followed by cooling to 105 °C. The remaining residue was recorded as ash, representing the inorganic fraction of the sample, while the weight loss corresponds to the combined release of moisture and volatile matter. This procedure was carried out in accordance with ASTM D7348 (Standard Test Methods for Loss on Ignition of Solid Combustion Residues). The obtained ash and weight loss in combustion values were then calculated using Equations (3) and (4).

$$Weight\ loss\ on\ combustion\ (\%) = \frac{(C-D)}{C} \times 100 \quad (3)$$

$$Ash\ content\ by\ weight\ (\%) = \frac{D}{C} \times 100 \quad (4)$$

where,

C= The weight of the test sample (g)

D = The weight of the sample after burning at 550°C (g)

The calorific value of biochar is an important parameter that indicates its energy content and combustion potential. This value represents the amount of heat energy released during the complete combustion of a specific amount of biochar in the presence of oxygen. The calorific value is typically measured as the Higher Heating Value (HHV) or Lower Heating Value (LHV); this distinction depends on whether the heat obtained from the condensation of water vapor in exhaust gases is considered. At constant volume and a reference temperature of 25°C, the Higher Heating Value (HHV) of a solid biofuel is determined using a bomb calorimeter. In this study, this measurement was carried out using the IKA C200 bomb calorimeter, which allows for the measurement of the high heating value (HHV) of solid samples. The biochar sample placed in the calorimeter is completely combusted in an excess oxygen environment. The heat released during combustion is measured by the temperature change in the water within the calorimeter. This temperature change is then used to calculate the energy content of the biochar. The calorific value provides important information about the energy potential of biochar, which is essential for evaluating its suitability as a fuel or energy source in various industrial processes. In the context of biochar obtained from waste coffee, knowing its calorific value helps assess its viability as an alternative energy source. Additionally, it is a critical parameter for evaluating the efficiency of the pyrolysis process, as it can influence the overall energy balance in waste-to-energy systems.

Elemental analysis is a technique used to determine the elemental composition of samples, focusing on the primary elements such as carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). This method quantifies the percentage of these elements in the sample, which is essential for understanding the chemical composition of the material. The analysis is typically conducted using two primary methodologies: combustion analysis and instrumental techniques employing elemental analysers. In this study, the Thermo Flash 2000 Elemental Analyzer (The Central Research Laboratory of Bursa Technical University has employed this as an external service) is used for conducting the elemental analysis. This device is widely used to measure the content of carbon, hydrogen, nitrogen, sulfur, and oxygen in both organic and inorganic samples, often referred to as CHNS/O analysis. During the process, the sample undergoes combustion, converting it into carbon dioxide, water, and other gaseous byproducts. The analyzer then detects the gases produced to determine the composition of the sample. In this study, Elemental Analysis is used to measure C, H, N values of soil and biochar samples.

Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed to identify the functional groups present in the biochar (ASTM E 1252). The measurements were carried out at the Central Research Laboratory (MERLAB) of Istanbul University-Cerrahpasa.

Plant Germination Experiments

The experiments were conducted separately for grass and basil, using 500 ml of soil per pot in each case. Three treatment groups were prepared for each plant: soil only (control), soil with 10% (v/v) biochar (50 ml biochar per 500 ml of soil), and soil with 15% (v/v) biochar (75 ml biochar per 500 ml of soil). For each treatment, including the control, two replicate pots were prepared. After mixing the soil and biochar, the pots were irrigated and conditioned for 15 days to allow stabilization of the mixtures. Following this conditioning period, grass and basil seeds were sown. The pots were then irrigated and maintained in a controlled environment at 25 °C, and germination was monitored for 20 days. The pH values of the soil mixtures were measured both at the end of the 15-day conditioning period (before sowing) and at the end of the 20-day germination period. All plant-related measurement results are reported as mean values.

RESULTS AND DISCUSSION

Soil characterisation

The pH and elemental composition of the soil used in the experiments are presented in Table 1. The soil exhibited a slightly acidic character, with a pH in the range of 5.5–6.0. Elemental analysis indicated that the soil contained 10.08% carbon, 0.26% nitrogen, and 9.56% hydrogen. These values suggest that the soil had a moderate level of organic matter, providing a suitable medium for plant growth and for evaluating the effects of biochar amendment.

Table 1. Soil pH and Elemental Analysis Results

Parameter	Value
pH	5.5–6
C %	10.08
N %	0.26
H %	9.56

Biochar characterisation

The percentages of moisture and solid matter contents are presented in Table 2. The energy values of the biochar after pyrolysis are presented in Table 3.

Table 2. Results of Moisture content and Solid Matter

Sample	Moisture content (%)	Solid matter (%)
Raw	8.28	91.72
Pyrolysis product biochar at 500°C	2.13	97.87

Table 3. Energy values of biochar after Pyrolysis

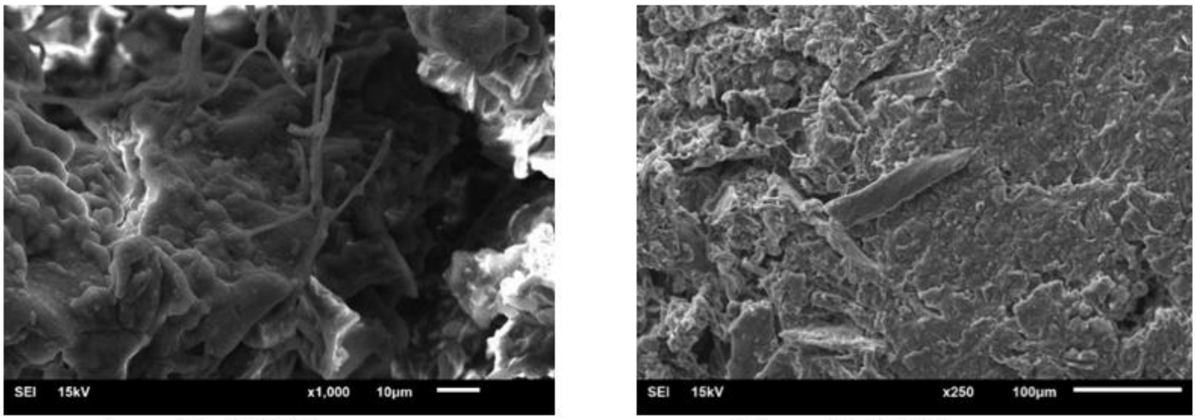
Sample	Energy value (cal/g)
Waste filter coffee	5121
Pyrolysis product biochar at 500 ºC	6970

Table 4 presents the elemental composition of waste filter coffee and the biochar produced through pyrolysis at 500 °C, including the measured percentages of carbon, hydrogen, and nitrogen.

Table 4. Elemental Analysis Results

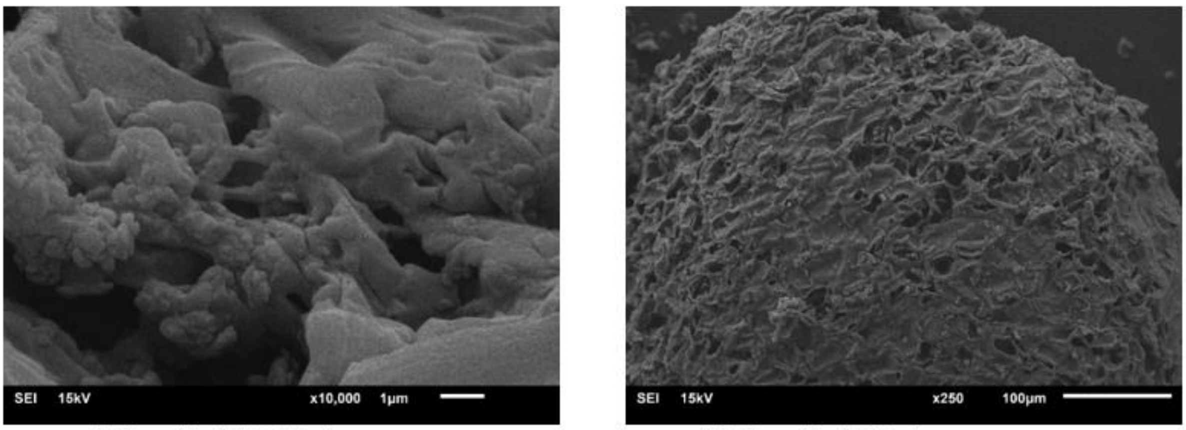
Sample	Carbon (%)	Hydrogen (%)	Nitrogen (%)
Waste filter coffee	50.87	6.87	2.295
Pyrolysis product biochar at 500 ºC	81.53	2.592	1.613

Figure 2 shows the scanning electron microscope (SEM) images of raw filter coffee waste. Figure 3 shows the SEM images of the biochar obtained from the waste after the pyrolysis at 500 °C.



a) magnified 1000 times b) magnified 250 times

Figure 2. SEM images of raw waste filter coffee



a) Magnified 10.000 times b) Magnified 250 times

Figure 3. SEM images of biochar obtained from waste filter coffee after pyrolysis at 500°C

Analysis of SEM pictures of raw coffee waste shows that its surface exhibits a non-porous, polymeric structure. SEM photos of biochar produced under different conditions show that its porosity has increased. The resulting biochar is evident to have a rough, porous and hollow exterior. The carbonisation process at high temperatures expands the pores and disrupts the polymeric structure of the raw material, removing volatile compounds from the waste coffee.

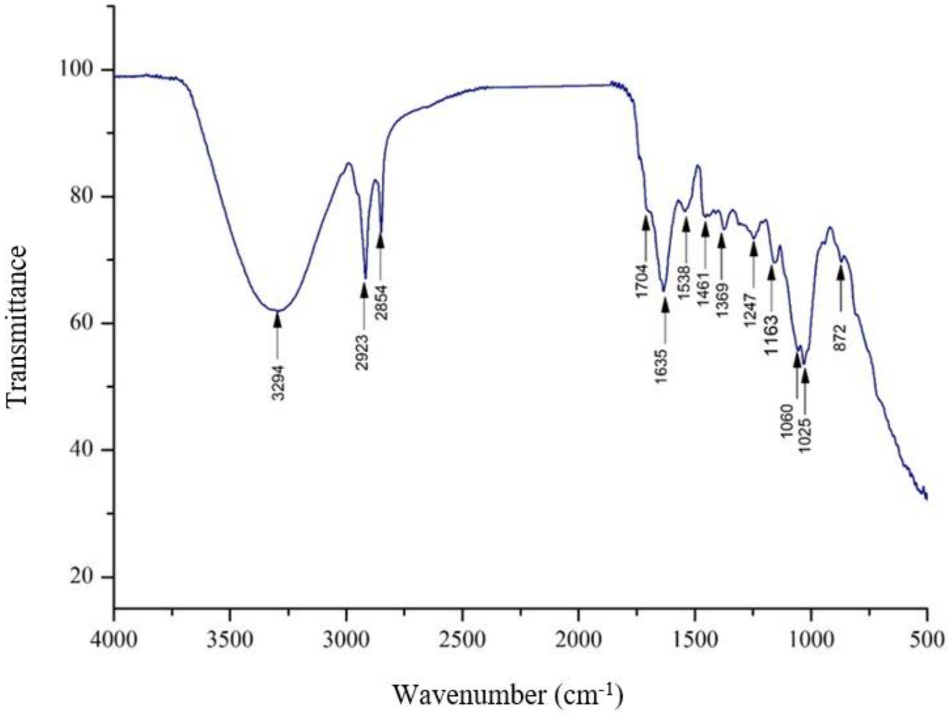


Figure 4. FTIR Spectra of waste filter coffee

Coffee typically contains approximately 1-2% caffeine. As shown in Figure 4, the stretching vibrations observed at 2923 cm⁻¹ and 2854 cm⁻¹ are attributed to the presence of caffeine within the coffee matrix (Barrios- Rodriguez et al., 2021). Additionally, chlorogenic acids constitute around 5-10% of coffee content. The distinct absorption bands at 1704 cm⁻¹ and 1635 cm⁻¹ in the spectrum correspond to ester functional groups present in the structure of these acids. Moreover, the characteristic C–N stretching vibrations of tertiary amines, originating from compounds such as caffeine, theobromine, and theophylline, are typically observed in the 1350-1200 cm⁻¹ region. In this case, however, a prominent peak appears at 1247 cm⁻¹. Depending on storage conditions, coffee may also contain 2-5% moisture, with the O–H stretching vibration of water molecules observed at 3294 cm⁻¹ in the FTIR spectrum (Barrios- Rodriguez et al., 2021).

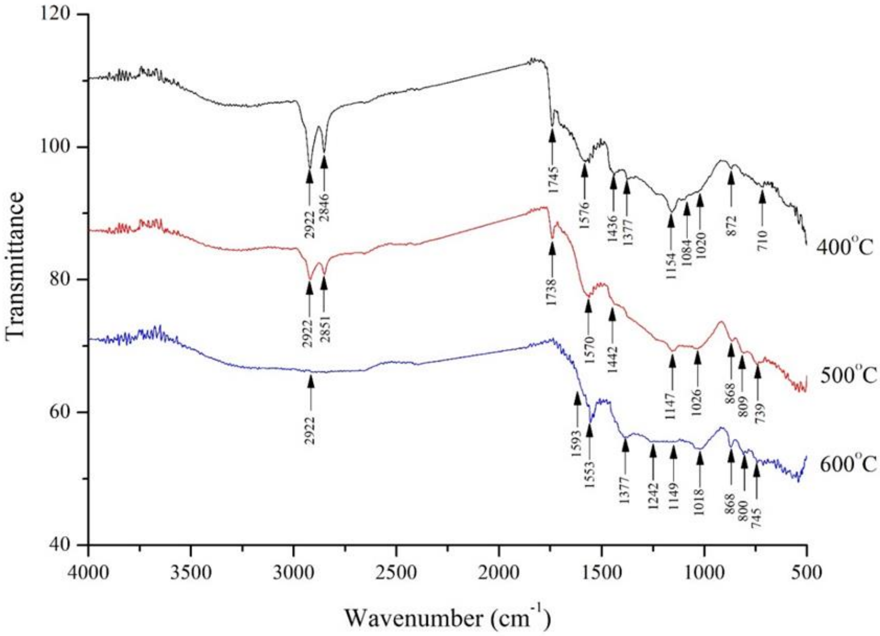


Figure 5. FTIR Spectra of the final structure at different pyrolysis temperature

Examining Figure 5 reveals that the stretching vibrations observed at 2922 cm⁻¹ and 2846 cm⁻¹ (shifting to 2831 cm⁻¹ at 500 °C) are due to the presence of caffeine in the coffee. Additionally, due to the ester groups present in chlorogenic acids and certain functional groups derived from caffeine, a spectral band appears in the 1750–1550 cm⁻¹ range, especially at 1745 cm⁻¹, which shifts to 1738 cm⁻¹ at 500 °C. (Barrios- Rodriguez et al., 2021). The bands located in the 1300–1150 cm⁻¹ region are also associated with the structural components of chlorogenic acids that weakens at 500 °C. (Briandet et al., 1996). This suggests that the related organic compounds are decomposed and volatilized atthe pyrolysis temperature.

Plant Germination Experiments

As a result of the elemental analyses of the biochars, the biochar with the highest carbon content was the one obtained through pyrolysis at 500 °C. Therefore, this biochar was used in the plant growth experiments. Figure 6 shows the pots that were prepared and the growing plants. Table 5 presents the measurement results of germinated plants. Figure 7 shows the photographs of germinated plants.

a) Soil mixed with biochar and left to be conditioned

b) Plants after regular irrigation

Figure 6. The pots that were prepared and the growing plants

Table 5. Growth characteristics of grass and basil plants cultivated in soil and biochar mixtures and pH values of at the end of the germination period

Mixtures and planted plants in pots	**Root Length (cm)**	**Plant Height without Roots (cm)**	**Total Plant Height (cm)**	**Rooted Weight (g)**	**Number of Leaves (pieces)**	**pH values of at the end of the germination period**
Grass(soil)	3.5	10.5	14	0.0749	5	6
Grass (%10 biochar) (20ml)	2	10	12	0.0261	5	6
Grass (%15biochar) (30ml)	2.5	12.5	15	0.0502	5	6
Basil (soil)	4	7	11	0.3555	1	6
Basil (%10)	-	-	-	-	-	6
Basil (%15)	-	-	-	-	-	6

In this study, the growth performance of grass and basil plants cultivated in soil media enriched with biochar was evaluated. Within the scope of the experiment, a comparative analysis was conducted by measuring parameters such as root length, stem length (excluding root), total plant height, fresh weight, and number of leaves in plants grown in the control group (soil only) and in those cultivated with the addition of 10% and 15% biochar. In the control group, where grass was grown in soil only, the following measurements were recorded: root length, 3.5 cm; stem length, 10.5 cm; and total plant height, 14 cm. This plant had a fresh weight of 0.0749 g and five leaves. In the group with a 10% addition of biochar, the grass plant had a root length of 2 cm, a total height of 12 cm and a fresh weight of 0.0261 g, and exhibited weaker overall development compared to the control group. In the medium containing 15% biochar, the measurements were 2.5 cm for root length, 12.5 cm for stem length, and 15 cm for total height. The fresh weight was 0.0502 g. Although this group exhibited the greatest height, its weight remained lower than that of the control group (Table 5).

In the basil plants grown only in soil (control), a root length of 4 cm, stem length of 7 cm, and a total height of 11 cm were recorded. The fresh weight was 0.3555 g, and one leaf developed. No growth was observed in the biochar-amended groups; therefore, no measurements could be taken (Table 5). The pH values of all soil mixtures, measured both after the 15-day conditioning period and at the end of the 20-day germination period, remained around 6. While germination occurred in the control group, no sprouting was observed in the biochar-amended pots. Similar findings have been reported in the literature, suggesting that this outcome may be linked to multiple environmental and chemical factors. One possible explanation is that biochars derived from coffee waste may introduce stress factors such as high ash content or altered nutrient balance. Although elevated pH levels are often cited as a cause of osmotic stress affecting germination (Glaser et al., 2002; Van Zwieten et al., 2010), this does not appear to be the case here, since pH values were similar across all treatments. Another explanation could be the presence of volatile organic compounds, phenolics, and polycyclic aromatic hydrocarbons (PAHs) in biochars produced at low-to-moderate pyrolysis temperatures, which are known to cause phytotoxic effects (Hale et al., 2012; Buss et al., 2016). In addition, allelopathic compounds naturally present in coffee residues, such as caffeine and chlorogenic acids, may not have been completely degraded during pyrolysis and could have negatively affected germination (Mussatto et al., 2011; Gámiz et al., 2021). Finally, application dose may also play a role, as biochar amendments above 10% (v/v) have been reported to suppress germination and early seedling development (Van Zwieten et al., 2010; Jones et al., 2012). Collectively, these findings suggest that direct application of coffee waste-derived biochar at the tested dosages may adversely affect basil germination.

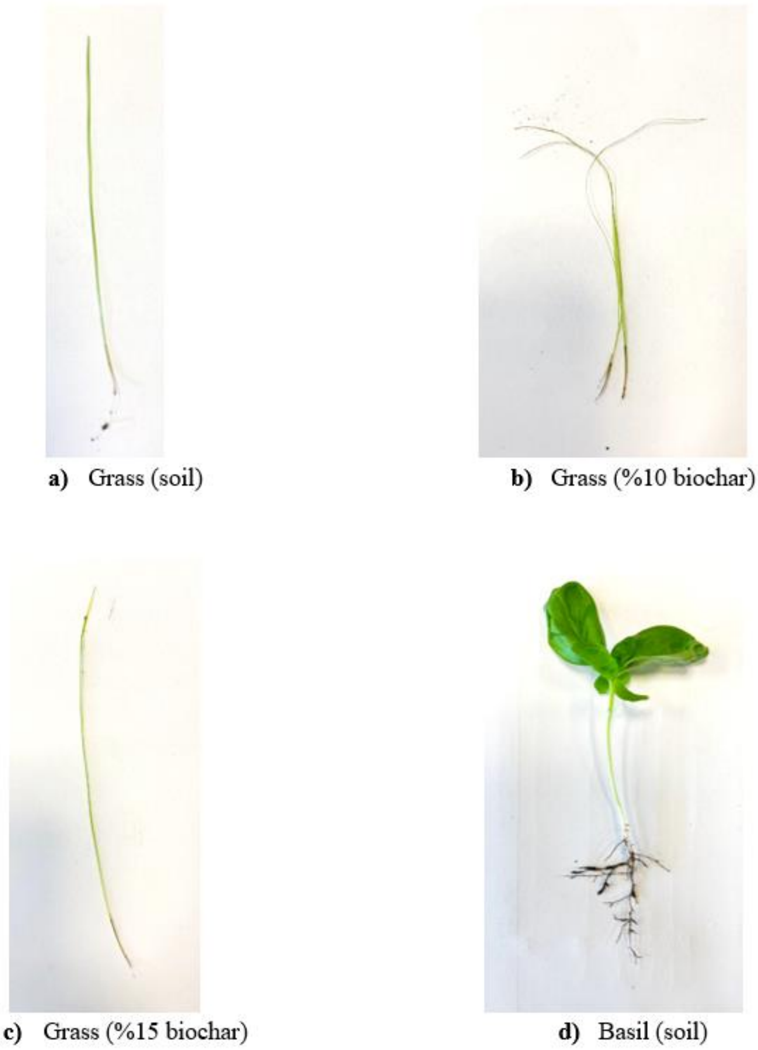


Figure 7. Photographs of germinated plants.

In the case of grass, the maximum total plant height was observed in the groups with 15% biochar. This highlights the significance of not only volumetric growth but also the efficient biomass production. In the case of basil, growth was only observed in the soil group; no germination or development was recorded in other environments containing additive.

In the control group which consisted of soil only, the grass samples exhibited a root length of 3.5 cm, a total plant height of 14 cm, a fresh weight of 0.0749 g, and five leaves per plant. These values were taken as reference. In the 10% biochar application (20 ml), both root length and total height decreased to 2 cm and 12 cm, respectively, while the fresh weight dropped to the lowest value of 0.0261 g. This finding suggests that a low dose of biochar may limit grass development, possibly due to excessive water retention or a nutrient imbalance in the soil.

In the 15% biochar application (30 ml), the total plant height reached the highest value of 15 cm. However, the fresh weight was recorded as 0.0502 g, which is lower than that of the control group. This finding indicates that while biochar may enhance plant height by increasing water retention capacity, it may not provide sufficient nutrient support for biomass production. Similarly, literature reports that the effects of biochar on plant morphology can vary depending on the application rate, soil properties, and plant species (Lehmann et al., 2011; Glaser et al., 2002).

The consistent number of 5 leaves across all grass treatments indicates that leaf formation may be independent of the added materials or may have remained constant throughout the experimental period. This suggests that the number of leaves may serve as a more meaningful indicator for evaluating long-term effects.

In the case of basil, plant development was observed only in the control group (soil only), where the root length was recorded as 4 cm, the total plant height as 11 cm, the fresh weight as 0.3555 g, and the number of leaves as 1. The notably higher fresh weight compared to grass indicates that basil may have a greater capacity for biomass production. However, in other treatments involving biochar, no plant development was observed. This finding suggests two possible explanations for the observed results. Firstly, the additives may have exerted an inhibitory effect on the process of basil seed germination. Secondly, it is possible that the duration of the experiment was inadequate to detect any observable growth. A number of studies have been conducted that demonstrate the capacity of biochar to inhibit the germination of sensitive plant species, a process that has been shown to be facilitated by sudden fluctuations in parameters such as pH and electrical conductivity (Biederman & Harpole, 2013).

The results obtained demonstrate that the effects of soil amendments on plant development vary depending on both plant species and application dose. In grass, the 15% biochar application yielded the most favourable outcomes, while in basil, growth was observed only in the soil-only control group. These findings are consistent with the relevant literature regarding the water retention capacity and structural effects of biochar on soil (Glaser et al., 2002; Lehmann et al., 2011). However, it should also be noted that these additives may suppress germination in certain plant species during the early stages of development.

The findings of this study highlight the importance of using soil amendment materials with careful attention to dosage and plant-specific requirements. Appropriate proportions of biochar have been demonstrated to support root and shoot development, especially in grass species, while potentially having different effects on other species such as basil. Therefore, future applications should include preliminary trials to determine optimal dosages, and amendment strategies should be tailored specifically to each plant type.

CONCLUSION

The experimental results revealed that the morphological development of the grass varied depending on the type and concentration of the applied amendments. Compared to the control group, which was grown in soil alone, applying 15% biochar resulted in the tallest plants (15 cm), although their fresh weight remained lower than that of the control group. This indicates that while biochar may promote vertical growth by improving water retention, it may not provide sufficient nutritional or microbial support for biomass accumulation.

In contrast, the use of 10% biochar appeared to have a negative impact on grass development, as indicated by reduced root length, plant height, and biomass. These findings suggest that the effect of biochar is highly dependent on its dosage, as well as the specific characteristics of the soil and plant species. The physical properties of biochar, such as its high porosity and water-holding capacity, may sometimes lead to suboptimal growing conditions if not appropriately balanced.

For basil, growth was only observed in the control group (soil only). No germination or measurable growth was recorded in any of the groups containing biochar. This implies that basil may be more sensitive to organic soil amendments, and that the conditions provided by these mixtures may have hindered seed germination or early development. It is also possible that the experimental period was insufficient to observe delayed growth.

Moreover, the study demonstrates that spent coffee grounds can be effectively valorized through pyrolysis to produce biochar, which can then be used as a functional soil additive. This contributes to sustainable waste management and supports environmentally conscious agricultural practices by converting organic waste into valuable resources.

In conclusion, this research highlights the importance of applying soil conditioners such as biochar at appropriate dosages and tailored to specific plant species. The findings are consistent with existing literature and show that these organic amendments, when used correctly, can enhance soil quality, improve plant growth, and contribute to sustainable agricultural systems and circular economy principles.

Based on the findings of this study, several recommendations can be proposed to enhance future research efforts and improve the practical applicability of biochar as a soil amendment:

- Conduct Species-Specific and Soil-Specific Optimization Studies: The results clearly demonstrated that different plant species respond differently to organic soil amendments. While grass exhibited positive growth under certain biochar treatments, basil showed no development in any additive-containing media. Therefore, future studies should prioritize optimization of additive dosages and application methods based on both plant species and soil type. Pre-application trials and detailed soil characterization (e.g., pH, salinity, organic matter content) should be incorporated into the experimental design.
- Extend the Duration of Germination and Growth Experiments: In the case of basil, the absence of visible growth in additive-treated soils may be linked to a delayed germination process or initial adaptation challenges. Future studies should consider longer observation periods to allow for the detection of late responses or gradual growth effects that may not become apparent within short experimental timeframes.
- Scale-Up Trials for Real-World Application: While the present study was conducted under controlled conditions, field-scale applications are essential for assessing the practical viability, environmental impact, and economic sustainability of using coffee-derived biochar in agriculture. Such studies would offer valuable insight into long-term performance, nutrient dynamics, and cost-effectiveness.
- Investigating the Influence of Biochar Characteristics on Performance: The quality and behavior of biochar in soil are strongly influenced by its production parameters (e.g., pyrolysis temperature, residence time, activation process). Further research should systematically investigate how these variables affect the physicochemical properties of biochar and, consequently, plant response. This would aid in the development of standardized production guidelines for specific agricultural applications.

- Promote the Integration of Agricultural Waste Valorization in Circular Economy Strategies: This study supports the notion that spent coffee grounds, which are widely available as urban organic waste, can be transformed into value-added products. Municipalities and agricultural sectors should be encouraged to invest in small-scale pyrolysis units and composting initiatives to incorporate such waste streams into local circular economy models, reducing landfill dependency and improving soil health.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

All of the authors contributed equally to the present study. All the authors read and approved the final manuscript. They verify that the text, figures and tables are original and have not been published before.

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