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CO_2 emissions and their changes with H_2O emissions, soil moisture, and temperature during the wetting–drying process of the soil mixed with different biochar materials

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ABSTRACT

Biochar is an organic regulator that improves crop yield by regulating soil properties. In addition, this organic regulator is also effective in reducing CO_2 emissions from soil. However, considering the management of CO_2 emissions together with many factors and the different properties of soil depending on the biochar content, CO_2 emissions can vary. Thus, the study investigated the soil moisture and temperature and H_2O emissions, which affect the emission, and CO_2 emission of biochars with different raw materials applied to the soil in the wetting–drying cycle of the soil. It was determined that biochar applications decreased CO_2 emissions, but the share of each biochar material in reduction differed, and CO_2 emissions were 82, 51, 20, and 13% lower in straw, hazelnut, apple, and sawdust biochar applications than in soil without biochar, respectively, and significant positive linear relationships of CO_2 emissions with soil moisture–temperature and H_2O emissions were determined. In addition, in biochar applications, H_2O and soil temperature decreased depending on the moisture retention in the soil. In the findings, it can be suggested that straw biochar application to soil is more effective in reducing the severity of increasing global warming, and that soil moisture and temperature should be managed to reduce CO_2 emissions.

Key words: biochar, CO_2 emission, soil moisture, soil temperature, wetting–drying

HIGHLIGHTS

- Biochar treatment decreased the CO_2 emissions from the soil.
- Straw biochar caused lower CO_2 emissions compared to hazelnut, apple, and sawdust biochar.
- Biochar treatment decreased H_2O emissions and soil temperature, while increased soil moisture.
- The relationships of CO_2 emissions with soil moisture, H_2O emissions, and soil temperature were positive linear.

INTRODUCTION

Agriculture is responsible for a quarter of global warming (Bennetzen *et al.* 2016). Soil can act as a reserve for organic carbon as well as a source of CO_2 emissions from the soil. Under faulty soil management conditions, the soil loses organic carbon and CO_2 is thus emitted into the atmosphere (Yerli *et al.* 2019). In this case, the increased CO_2 in the atmosphere absorbs the heat and causes global warming. Climate change, which is the effect of global warming, is regarded as the most worrying issue today (WMO 2019). In this context, studies investigating the effects of CO_2 emissions and thus global warming on agricultural activities are noteworthy.

Biochar can be defined as a charred organic improver as a result of the pyrolysis of biomass under oxygen-limited conditions at elevated temperatures. With its low bulk density, high porosity and surface area properties, biochar increases water retention in the soil and enables more profitable management of irrigation in today's conditions, in which effective management of water resources is very important (Tufenkci *et al.* 2022). Biochar both facilitates the crop's access to water and contributes to irrigation water savings by keeping soil moisture easier and preserving it for a long time, not only inside the pores but also between the particles due to its micropores (Cakmakci & Sahin 2022).

Biochar increases soil and crop productivity due to its low decomposition rate and long-term persistence in the soil (Tufenkci *et al.* 2022). The bulk density of biochar applied soil may decrease, and the soil porosity and soil hydraulic

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properties may improve (Ahmad Bhat *et al.* 2022). Thus, more effective irrigation management can be achieved. The biochar applied to the soil is effective in developing and improving the physical (Mukherjee & Lal 2013; Blanco-Canqui 2017; Zhang *et al.* 2020), chemical (Chintala *et al.* 2014; Rechberger *et al.* 2017; Jing *et al.* 2020), and biological (Luo *et al.* 2013; Dong *et al.* 2015; Somerville *et al.* 2020) properties of soil. In this context, it also provides positive reflections on the increase in the yield and quality of the crop (Zoghi *et al.* 2019). These contributions of biochar allow more economical and sustainable agricultural management by decreasing the need for synthetic fertilizers. Laghari *et al.* (2015) found that biochar increased phosphorus up to 70% and potassium up to 11% in the soil. Similarly, Apori *et al.* (2021) stated that nitrogen increased by 36% and phosphorus increased by 17% with biochar application. In addition, biochar plays an active role in biotic and abiotic stress conditions, increasing the resistance of the crop against stress conditions (Kul *et al.* 2021).

In addition to these positive reflections, considering biochar can increase the carbon storage capacity of the soil and stabilize the soil's organic carbon pools (Wang *et al.* 2014). As the effect of global warming is increasing day by day, biochar can also decrease the CO_2 emissions from agricultural soils (Deng *et al.* 2017). Thus, it can contribute to the increase in soil and crop yield by providing organic carbon increases and sequestration in the soil, and agricultural and environmental sustainability can be achieved by decreasing the emission values. However, considering that CO_2 emissions from soils can vary with soil moisture and soil temperature (Mancinelli *et al.* 2015; Yerli & Sahin 2021) and that the physical, chemical, and biological properties of soils can directly affect CO_2 emissions (Haddaway *et al.* 2017), it is possible to manage CO_2 emissions from soils effectively only with a good understanding of the CO_2 emissions relationships (Yerli *et al.* 2022a). Increasing moisture and temperature in the soil can trigger microorganism activities and increase CO_2 emissions by oxidizing organic carbon. After organic carbon encounters O_2, it turns into CO_2 and spreads from the soil to the atmosphere (Yerli *et al.* 2019). Zhao *et al.* (2020) reported a positive correlation between CO_2 emissions and soil temperature, and Buragiene *et al.* (2019) reported a positive correlation between CO_2 emissions and soil moisture. However, this is not always the case. Because situations such as water ingress into the soil increase the soil moisture and decrease the soil temperature by creating a cooling effect on the soil (Mancinelli *et al.* 2015), microorganism activities and thus oxidation can be effective between certain soil moisture and temperature values, and the increase in soil temperature due to a chemical reaction that occurs as a result of the oxidation of organic carbon additives mixed into the soil (Yerli & Sahin 2021) makes it difficult to understand and manage the CO_2 emissions from the soil. Yerli *et al.* (2022b) determined that CO_2 emissions from the soil showed positive correlations with H_2O emissions and soil moisture at 5-, 10-, and 20-cm soil depths, but the correlation with soil temperature was negative at the same soil depths.

Many studies have shown that biochar decreases CO_2 emissions from the soil (Liu *et al.* 2011; Wang *et al.* 2014; Zhang *et al.* 2017; Wu *et al.* 2018; Azeem *et al.* 2019; Akinyemi & Adesina 2020; Lehmann *et al.* 2021). Lehmann (2007) reported that biochar absorbs organic carbon and stabilizes soil carbon stocks due to its high surface area and porosity, thus decreasing CO_2 emissions. However, CO_2 emissions may also increase depending on the raw material content of biochar and preparation processes, such as stability, pyrolysis, and temperature, as well as the characteristics of the soil in which the biochar is mixed and its interaction with the soil (Zimmerman *et al.* 2011; Singh *et al.* 2012). In a study examining the effects of pine wood and grass-derived biochar applications in loamy soil on CO_2 emissions, it was determined that pine wood biochar did not affect CO_2 emissions, while grass-derived biochar increased CO_2 emissions (Hilscher *et al.* 2009). Karhu *et al.* (2011) reported that birch biochar mixed with soil has a negative effect on decreasing CO_2 emissions. Mohamed *et al.* (2015) evaluated the effects of woody waste mixed with sandy soil and its biochar on CO_2 emissions, and they found that both applications increased CO_2 emissions, but this increase was 3 times higher than biochar in the woody waste application and 6 times more than the control.

The insight shows that the mechanism of CO_2 emissions from the soil has a complex structure and that the effect of biochar on decreasing emissions varies. The studies have gained momentum to evaluate the effects of biochar applications on decreasing CO_2 emissions. However, there are no studies in the literature that compare the effects of different biochar sources on CO_2 emissions during the wetting–drying process of the soil and evaluate the soil moisture, H_2O emissions, and soil temperature that affect CO_2 emissions. Therefore, the objectives of this study were (i) to determine whether biochar applications would decrease the CO_2 emissions from the soil in the wetting–drying process, (ii) to evaluate the changes in CO_2 emissions depending on the raw material contents of the biochar, and (iii) to discuss the relationships of CO_2 emissions with the soil moisture, H_2O emissions, and soil temperature measured during the wetting–drying process. To achieve these objectives, this study investigated CO_2 emissions during the wetting–drying process of soil including biochars with different raw materials, and evaluated the relationships of CO_2 emissions with soil moisture and temperature and H_2O emissions.

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MATERIALS AND METHODS

Study area and experimental design

The experiment was carried out in the laboratory of Van Yuzuncu Yıl University, Faculty of Agriculture, Department of Biosystem Engineering. During the experiment, the mean air temperature was 24 ± 2 °C and the air humidity was 38 ± 5%. The experiment was conducted with three replications using a completely randomized factorial design with hazelnut, straw, apple, and sawdust biochar materials and as a control in the soil in which biochar was not applied. Each wetting–drying cycle was completed in 1 week and repeated three times in total for 3 weeks.

Properties of soil and biochar materials

Prior to the experiment, the particle size distribution (texture), pH, EC, total N, organic matter and organic carbon contents of the experimental soil were analyzed (Table 1). The particle size distribution was determined by the Bouyoucos hydrometer method (Gee & Bauder 1986), and the soil texture was sandy loam (sand: 66.3%, silt: 15.6%, clay: 18.1%) according to the USDA classification. According to the pH and EC determined by pH-meter and EC-meter in 1:2.5 saturation extract, the experimental soil was very slightly alkaline and nonsaline. The total N determined by the Kjeldahl method (Bremner & Mulvaney 1982) was insufficient, and the organic matter content determined by the Walkley-Black method (Nelson & Sommers 1982) and the organic carbon calculated from the organic matter content (Avramidis *et al.* 2015) were low.

All biochar materials were prepared using the same procedures. First, the materials were dried, sieved, and homogenized, and finally, subjected to pyrolysis at 400 °C. Prior to the experiment, analyses and calculations were made to determine the pH, EC, total N, organic matter, and organic carbon contents of the biochar materials in the same way as the analysis and calculations of the soil (Table 1).

Applications and irrigation practices

Air-dried soil, sieved through a 2-mm sieve, was mixed with 1% biochar on a weight basis and tapped into pots with volumes of 1.5 l (diameter: 13 cm, height: 11 cm) by preserving the soil bulk density (1.31 Mg m^{-3}). All pots were incubated for two weeks at moisture level at field capacity. In the planning of irrigation events, the dry weights of control application pots with the soil were determined. To determine the water retained at field capacity (pot capacity), the pots without biochar (control) were first saturated with water and then surface covered to prevent evaporation. When the drainage completely stopped, the pots were weighed, and this moisture after conversion by bulk density, wet and dry weights was expressed as field capacity as the volume (0.320 m^3 m^{-3}). The irrigations were applied with the same water amounts in all applications to complete missing moisture to the field capacity considering the weights in control pots when each wetting–drying process was completed.

CO_2 emission measurement process

The CO_2 emission from the soil was measured daily during three wetting–drying periods with the EGM-5 infrared gas analyzer device (CFX-2, PPSystems, Stotfold, UK) by taking three readings from each pot. Soil moisture, H_2O emissions, and soil temperature were also measured simultaneously with CO_2 emissions. Soil moisture was determined by weighing the pots, while a CO_2 measuring device was used for H_2O emission and soil temperature measurements. The H_2O emission was automatically recorded by a CO_2 measuring device during CO_2 measurement. The STP-1 temperature probe connected to the CO_2 emission device was used to measure soil temperature at a 5-cm soil depth (Yerli & Sahin 2021; Yerli *et al.* 2022a, 2022b).

Table 1 | The properties of soil and biochar materials used in the experiment

Properties	Soil	Hazelnut biochar	Straw biochar	Apple biochar	Sawdust biochar
pH	7.17	8.11	8.56	7.88	8.88
EC (dS m^{-1})	0.62	1.16	1.85	0.82	0.80
Total N (%)	0.04	0.19	0.22	0.17	0.20
Organic matter (%)	0.81	56.1	58.2	42.3	45.2
Organic carbon (%)	0.47	32.5	33.8	24.5	26.2

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Statistical analysis

Data analyses were performed using the General Linear Model in the SPSS program (Ver. 23). Duncan multiple comparison test at the 5% level of probability was used to compare significant means. Pearson correlation analysis was used to determine the relationships of CO_2 emissions with soil moisture, H_2O emissions, and soil temperature.

RESULTS AND DISCUSSION

Soil moisture increased in biochar applications in the experimental period compared to the control, and the highest soil moisture was determined in the straw biochar application (Figure 1). Mean soil moisture was found to be 7.6, 9.8, 2.2, and 4.0% higher in hazelnut, straw, apple, and sawdust biochar applications than in the control, respectively. The lowest H_2O emission was determined in the straw biochar application, and the highest soil moisture was obtained (Figure 2). Mean H_2O emissions were 6.1, 8.0, 2.2, and 3.4% lower in hazelnut, straw, apple, and sawdust biochar applications than in the control, respectively. These results showed that increased soil moisture decreased H_2O emissions considering a significant ($p < 0.01$) negative linear correlation ($r = -0.654$) between soil moisture and H_2O emissions. Similarly, Yerli & Sahin (2021) indicated that H_2O emissions decrease with increased moisture retention in the soil.

The decrease in H_2O emissions in parallel with the increase in moisture retention in biochar applications can be explained by the porous structure of biochar. Biochar retains moisture not only inside the pores but also between the particles and micropores, so it takes a longer time for the biochar applied soil to lose water and dry out (Cakmakci & Sahin 2022). Ahmad Bhat *et al.* (2022) stated that the improved hydraulic properties of the soil with biochar increased moisture retention in the soil. Ahmed *et al.* (2019) stated that biochar application improved the soil water holding capacity, thus preserving soil moisture and decreasing H_2O emissions, and reported that this contribution was due to the spongy structure of the biochar. Chen *et al.* (2010) also indicated that biochar application increases water storage in pores by improving soil aggregation and soil pore size distribution. The high soil moisture of the straw biochar among biochar applications can be related to its higher organic matter content than other biochar materials (Table 1). Lal (2020) reported that soil organic matter is very important in soil water-holding ability and H_2O emissions from soil. Charles Gould (2015) stated that by increasing the soil organic matter from 1 to 2%, the soil water storage can be increased by approximately 3 l for each 0.0283 m^3 of soil. Organic

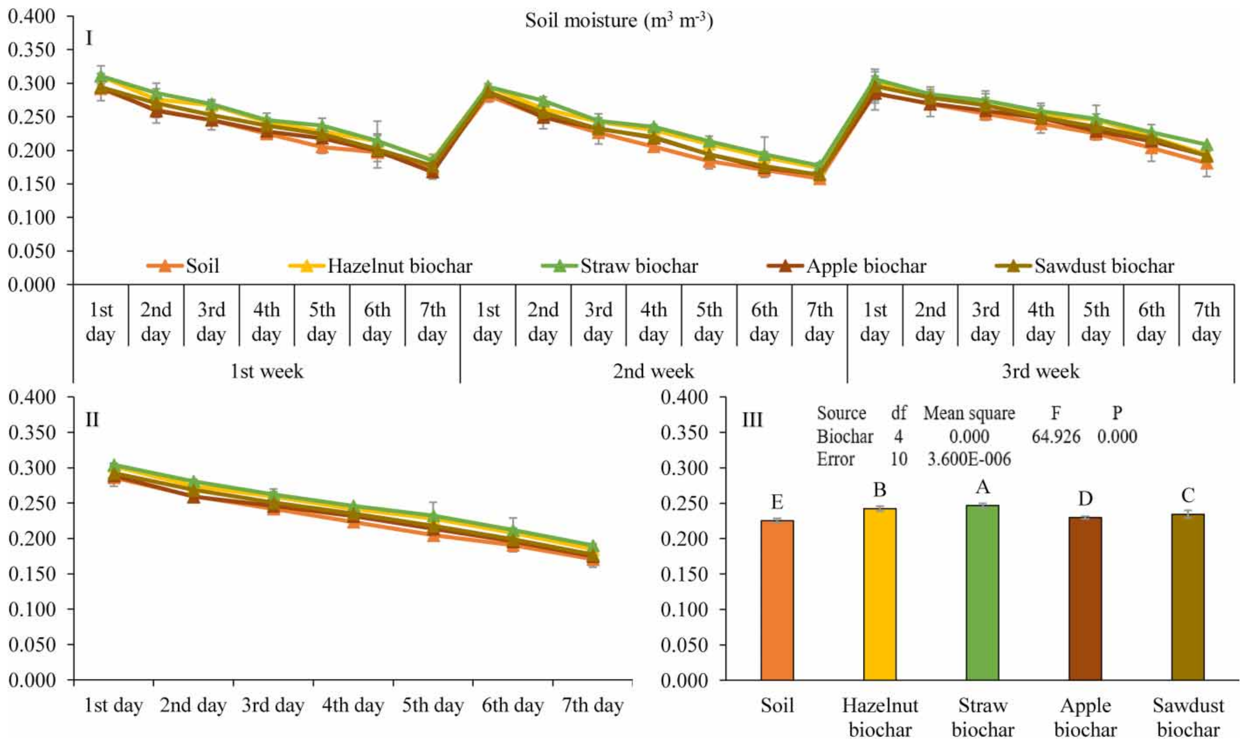

Figure 1 | Soil moisture contents in (I) biochar treatments daily, (II) daily in the mean of all weeks, and (III) mean of all measurements.

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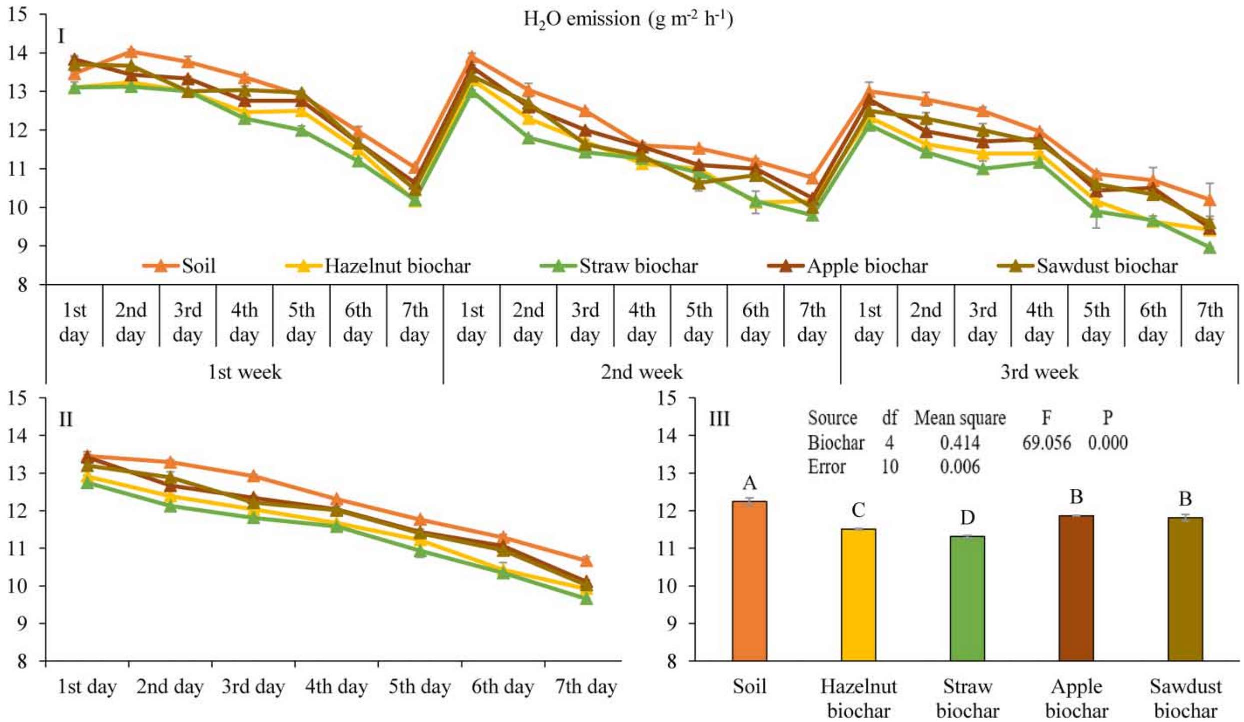

Figure 2 | H_2O emission from soil in (I) biochar treatments daily, (II) daily in the mean of all weeks, and (III) mean of all measurements.

matter additives decrease H_2O emissions from the soil by increasing the pore number and size and distribution of the soil and also the specific surface area of the soil and provide moisture to the soil (Devi *et al.* 2019; Yerli & Sahin 2021).

Soil temperature decreased in biochar applications in the experimental period compared to the control, and the lowest soil temperature was determined in straw and hazelnut biochar applications (Figure 3). The mean soil temperature was found to be 3.9, 4.4, 1.4, and 1.6% lower in hazelnut, straw, apple, and sawdust biochar applications than in the control, respectively. This can be explained by increasing soil moisture, which reduced soil temperature in biochar applications based on a significant ($p < 0.01$) negative linear correlation ($r = -0.625$) between soil moisture and temperature.

Longer preservation of soil moisture can significantly affect the heat capacity and thermal conductivity of the soil, resulting in a decrease in soil temperature. Licht & Kaisi (2005) reported that increased soil moisture causes lower soil temperatures. Soil temperature tends to decrease depending on the cooling of the surface soil and the increase in moisture values in the soil by supplying water to the soil, thus changing its thermal conductivity (Yerli *et al.* 2022a). Similarly, Mancinelli *et al.* (2015) also stated that water ingress into the soil can create a cooling effect on the soil by increasing soil moisture.

CO_2 emissions decreased in biochar applications in the experimental period compared to the control, and the lowest CO_2 emission was determined in straw biochar application (Figure 4). Mean CO_2 emissions were 51.0, 82.2, 20.3, and 13.2% lower in hazelnut, straw, apple, and sawdust biochar applications than in the control, respectively.

Biochar is a very effective material to decrease the emission of greenhouse gases from the soil, especially CO_2 (He *et al.* 2017). Organic carbons in the soil applied biochar become labile, thereby stabilizing the organic carbon in the soil (Wang *et al.* 2014), and the emission from soils decreases (Deng *et al.* 2017). Biochar can stabilize the carbon stocks of the soil for hundreds of years with its recalcitrant organic carbon (Schmidt *et al.* 2002). Due to the porosity of the biochar integrated with the soil, it absorbs organic carbon in the environment and decreases CO_2 emissions from the soil (Lehmann 2007). Case *et al.* (2014) stated that biochar traps the CO_2 emissions from the soil in its structure. Ge *et al.* (2020) indicated that biochar applied to soil limits CO_2 emissions from the soil by being effective on the labile carbon fraction, soil aggregates and soil respiration components. In addition, as a result of many studies, it was found that different biochar materials applied to the soil have a positive effect on decreasing CO_2 emissions from the soil (Liu *et al.* 2011; Wang *et al.* 2014; Zhang *et al.* 2017; Wu *et al.* 2018; Azeem *et al.* 2019; Akinyemi & Adesina 2020; Lehmann *et al.* 2021).

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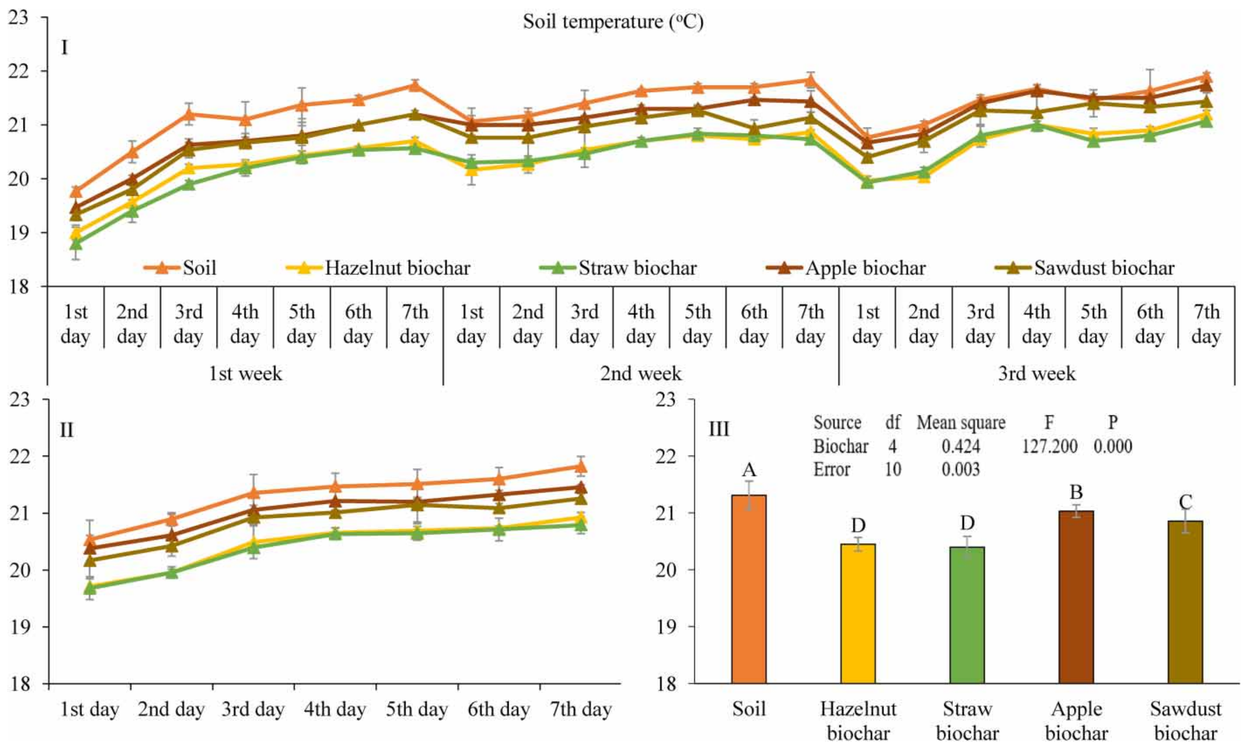

Figure 3 | Soil temperature contents in (I) biochar treatments daily, (II) daily in the mean of all weeks, and (III) mean of all measurements.

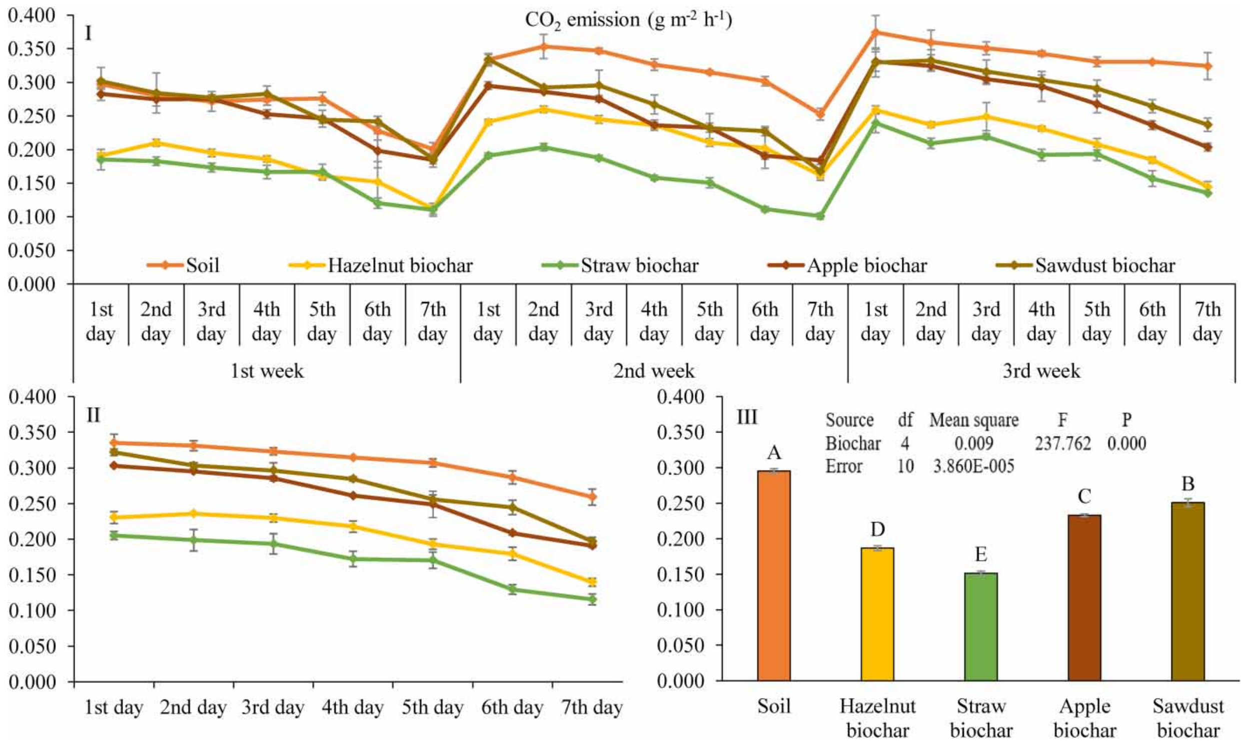

Figure 4 | CO_2 emission from soil in (I) biochar treatments daily, (II) daily in the mean of all weeks, and (III) mean of all measurements.

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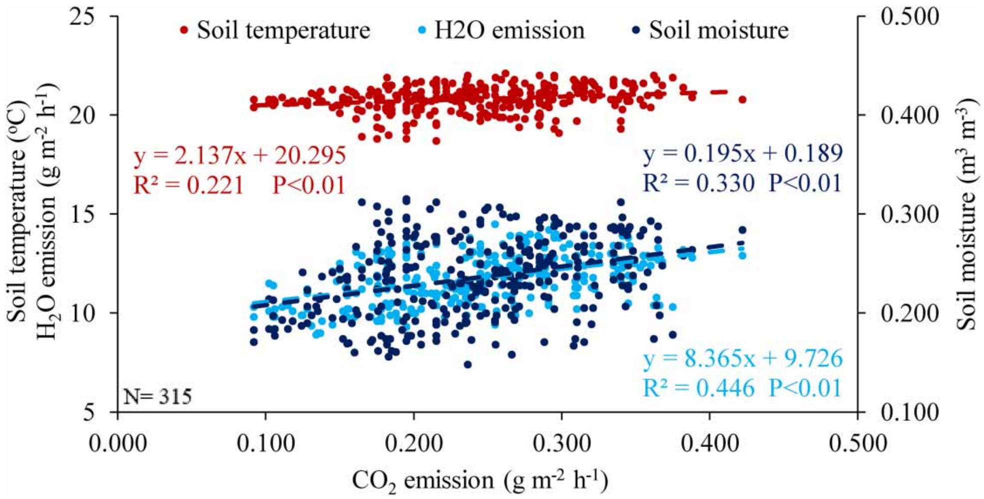

Figure 5 | The relationships of CO_2 emissions with soil moisture, H_2O emissions, and soil temperature.

Mukherjee & Lal (2013) reported that the CO_2 emissions from the soil decreased with the application of different biochar materials to the soil, but the emission rates can differ because biochars change the soil properties in different ways depending on their different characteristics. He *et al.* (2017) indicated that the effect of biochar on decreasing CO_2 emissions from the soil may vary depending on the properties of the soil to which the biochar is mixed and its interaction with the soil. Therefore, the lower CO_2 emissions in straw biochar among biochar applications can be explained by its higher EC value (Table 1). Yerli & Sahin (2021) reported that CO_2 emissions vary depending on the EC value of organic residues mixed into the soil. Increasing EC negatively affects soil microorganism activity and weakens oxidation processes (Zhai *et al.* 2011). Sakin & Yanardag (2019) stated that CO_2 emissions decreased with increasing EC values in the soil. In addition, due to the higher organic matter content of the straw biochar (Table 1), changing soil environmental conditions based on changed soil properties with a decrease in mineralization may have decreased CO_2 emissions. Chaudhari *et al.* (2013) reported that bacteria, fungi, and actinomycetes in the soil decreased by 40% with the addition of organic matter to the soil, decreasing the bulk density of the soil and thus, oxidation processes in the soil were adversely affected.

The strong ($p < 0.01$) positive linear relationships of CO_2 emissions with soil moisture, H_2O emissions, and soil temperature (Figure 5) show that emissions can be managed with soil moisture, H_2O emissions, and soil temperature. The relationship of CO_2 emissions with soil moisture and temperature can be explained by the increase in organic carbon mineralization due to increased soil moisture and temperature, while the relationship of CO_2 emissions with H_2O emissions can be evaluated indirectly by inducing H_2O emissions from increased soil moisture. The moisture balance of the soil greatly affects the oxidation of organic carbon in the soil (Shi & Marschner 2014). It is known that re-wetting dried soil triggers microbial activities and increases the emissions (Lamparter *et al.* 2009). Li *et al.* (2010) reported that the amount of irrigation changed the organic matter dynamics in the soil. Entry *et al.* (2008) stated that the continuous supply of water to the soil increases emissions by increasing organic carbon decomposition. Yerli *et al.* (2022a) stated in their study that examined the CO_2 emissions at different irrigation water levels that the soil microorganism activity slowed down with the decreasing amount of irrigation water, and thus the CO_2 emissions also decreased. In addition, as a result of many studies, positive linear relationships were determined between CO_2 emissions and soil temperature, similar to this study (Chen *et al.* 2018; Du *et al.* 2019; Zhao *et al.* 2020). Fan *et al.* (2021) reported that soil temperature has a direct effect on the population and number of microorganisms. Gonzalez-Mendez *et al.* (2015) determined that CO_2 emissions increased as a result of the acceleration of microorganism activities that carry out mineralization processes depending on the increasing soil temperature. Similarly, Jabro *et al.* (2008) stated that soil temperature increased CO_2 emissions by 59%.

CONCLUSION

As a result of this study, it was determined that (i) all biochar applications decreased CO_2 emissions, but the biochar material that decreased the emissions the most was straw biochar; (ii) with the biochar applications, the moisture retention in the soil

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increased, and accordingly, the H_2O emissions and soil temperature decreased, and the straw biochar was more effective; and (iii) CO_2 emissions have strong positive linear relationships with soil moisture, H_2O emissions, and soil temperature. It has been concluded that the content and properties of the biochar applied to the soil are very important to decrease the CO_2 emissions from the soil and that the CO_2 emissions can be managed with soil moisture, H_2O emissions, and soil temperature. Therefore, it can be suggested to apply biochar to the soil by evaluating these strategies and to monitor the soil moisture and temperature to decrease emissions for more effective agricultural and environmental management, and it can be recommended to develop studies in this context.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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