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Determination of the effects of irrigation with recycled wastewater and biochar treatments on crop and soil properties in maize cultivation

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ABSTRACT

The study was conducted under two water qualities (fresh water (FW), recycled wastewater (RWW)) and two biochar treatments (no biochar (No-B) and biochar (B)). It was determined that B reduced the actual evapotranspiration by saving irrigation water and that biomass yield increased in RWW and B; thus, RWW and B provided higher $WP_{irrigation}$ and WP. RWW and B increased OM, TN, P_2O_5, K_2O, CEC, porosity, and aggregate stability, thus encouraging the development of the physical–physiological properties, ADF-NDF content, and biomass yields of the crop, but causing EC to increase. RWW and B resulted in higher macro–microelement contents and heavy metal (HM) contamination in the soil; thus, increases were observed in the macro–microelements and the HM content of the crop grown in RWW and B, but the absorption and buffering capacity of B limited the Na–Cd–Cr–Ni uptake of maize. However, the HM contents of the soil–crop did not exceed international standards in all treatments except the Cd content of maize. It was found that the use of B in irrigation with RWW can be recommended, considering the productivity-increasing contribution and the effectiveness of B in reducing the possible HM risks of RWW in maize cultivation, but monitoring the Cd content of maize and the EC of the soil.

Key words: biochar, irrigation, maize, recycled wastewater, soil properties, yield

HIGHLIGHTS

- Biochar saved irrigation water amounts by 3.7 and 4.1% in the experimental years, reducing actual evapotranspiration by up to 4.5%.
- Fresh biomass yield increased by 13.1 and 17.3% in irrigation with recycled wastewater and biochar treatment compared with irrigation with fresh water and no biochar conditions.

1. INTRODUCTION

Water scarcity is one of the biggest problems in the world. More than 25% of people on Earth experience severe water scarcity (Zhong *et al.* 2023). Forty percent of the world's land area consists of regions suffering from water scarcity, classified as arid, semi-arid, and dry semi-humid (Farhadkhani *et al.* 2018). Especially in recent years, the growing population against increasing global warming has made the severity of water scarcity even more felt. Therefore, it is inevitable that more people will face serious water scarcity in the coming years, and a greater majority of the world's land areas will experience water scarcity (Radini *et al.* 2023).

The agricultural sector is affected more by water scarcity, with 70% fresh water usage, compared with other sectors (Jaramillo & Restrepo 2017). Water scarcity in the agricultural sector disrupts the production balance, creates an uneconomic production table, and reduces the need for food production by limiting efficiency and quality. For this reason, searches for alternative water sources have emerged in the agricultural sector, and among these searches, the use of recycled wastewater in irrigation has been significantly adopted (Lahlou *et al.* 2021). Recycled wastewater not only serves as an alternative water source to fresh water but also provides increased yield and quality with its organic matter and nutrient content, and with this feature, it also enables more economical production by reducing the need for chemical fertilizers (Demir & Sahin 2017). In addition, the use of recycled wastewater improves soil properties (Cakmakci & Sahin 2021a) and reduces the risks that wastewater may pose to the environment by limiting the discharge of wastewater into the environment.

Despite these advantageous approaches to the use of recycled wastewater in irrigation, it also has some risks. The salt content of wastewater may cause the salinity level of the soil to increase, thus reducing crop productivity and quality and causing the soil to become barren in the future (Wen *et al.* 2018). The heavy metal content of wastewater is specifically evaluated because it poses serious risks to soils and crops (Natasha *et al.* 2020). Heavy metals can accumulate in the soil, make the soil infertile, pass into the crops, and cause toxic effects (Yerli & Sahin 2022). In addition, heavy metals, which can pose significant risks to the health of human and animal through soil or crops, can reduce crop productivity and directly cause the death of crops. Heavy metals that pass into the soil through recycled wastewater also cause negative effects on soil microorganisms, nitrification, ammonification, and enzyme activities (Mumivand *et al.* 2023). In addition to all these, wastewater changes some soil properties such as pH, cation exchange capacity (CEC), and organic matter, which may also cause an increased release of antagonist heavy metals (Nzediegwu *et al.* 2019).

Biochar, which is the high-carbon and black fine-grained output of biomass pyrolysis, can be defined as an environmentally friendly soil conditioner that emerges through thermochemical transformations under limited oxygen conditions. Biochar is a material that regulates soil salinity (Dahlawi *et al.* 2018) and reduces heavy metal pollution (Tang *et al.* 2020). By accelerating salt leaching from the soil, biochar can reduce the time required to reduce the salt concentration to a level suitable for crops (Yue *et al.* 2016). The biochar, which regulates heavy metal mobility in the soil, can limit the uptake of heavy metals by crops and enable crops to move away from the toxic effects of metals (Lashari *et al.* 2013). Thus, biochar can reduce the soil salinity and heavy metal risks of wastewater in irrigation with recycled wastewater (Nzediegwu *et al.* 2019).

Environmental benefits of biochar are not limited to this; biochar also improves the water retention capacity of the soil, causing less evaporation from the soil (Maroušek *et al.* 2019), regulating the air and water balance of the soil (Batista *et al.* 2018), accelerating germination and product development by increasing the soil temperature (Mumme *et al.* 2018), increasing the resistance and dynamism of soil biota and improving the crop's defense against diseases and pests and various abiotic and biotic stress conditions (Suliman *et al.* 2017). In addition, biochar increases many physical and chemical properties of the soil to a soil quality level that is desired as agricultural soil and more suitable for crop production (Omondi *et al.* 2016; Nzediegwu *et al.* 2019; Aon *et al.* 2023).

Biochar, which reduces pollutant transfers from soil to crops and regulates root zone soil salinity, is not always promising (Zhang *et al.* 2017). In fact, under some conditions, increased salinity and heavy metals may be encountered in the soil-applied biochar (Lucchini *et al.* 2014; Karimi *et al.* 2020; Yerli 2023). The interaction of biochar with soil is the result of an unclear complex relationship depending on the individual or combined variations in the biochar or soil (Qi *et al.* 2017). In addition, the raw material and pyrolysis process (temperature, method, oxygen) of biochar limit the clarity in explaining this unclear complex relationship (Yerli 2023). Zheng *et al.* (2010) explained the adsorption capacity of biochar with the surface charge of the biochar, hydrogen bonds, and electrostatic attraction forces, but Alburquerque *et al.* (2014) expressed the role of biochar in regulating the mobility of heavy metals depending on the raw material content of the biochar.

Previous studies have examined the effects of irrigation with recycled wastewater and/or biochar treatment on soil and/or crop productivity, but no study has focused on the effects of biochar on soil and crop fertility in the irrigation of silage maize fields with recycled wastewater. This two-year field study, which deals with liquid and solid waste management together by combining recycled wastewater and biochar, aimed to comprehensively examine the changes in soil and crop properties of silage maize irrigated with recycled wastewater under biochar treatment and to investigate the effect of biochar on water and irrigation efficiency by comparing it with freshwater irrigation. The hypotheses of the study were as follows: (i) Recycled wastewater would increase soil and crop productivity and this increase would increase further with biochar. (ii) Biochar would limit the crop's uptake of some heavy metals in irrigation with recycled wastewater. (iii) Biochar would improve irrigation and water productivity (WP) by reducing the irrigation water and water consumption of the crop.

2. MATERIALS AND METHODS

2.1. Location and climate of the experimental area

The experiment was carried out in 2022 and 2023 in the experimental area of Van Yuzuncu Yil University in Türkiye, located at 38°34′38″ north latitude and 43°17′26″ east longitude, at an altitude of ~1,670 m (Supplementary material 1). Although the experimental area is located in the continental climate zone, the partial marine effect of Lake Van causes the climate to be milder. The climate data of the vegetation period of silage maize measured by the climate station in the experimental area are given in Figure 1. Accordingly, the hottest months in both years of the experiment were July (25.4 °C for 2022 and 24.4 °C for

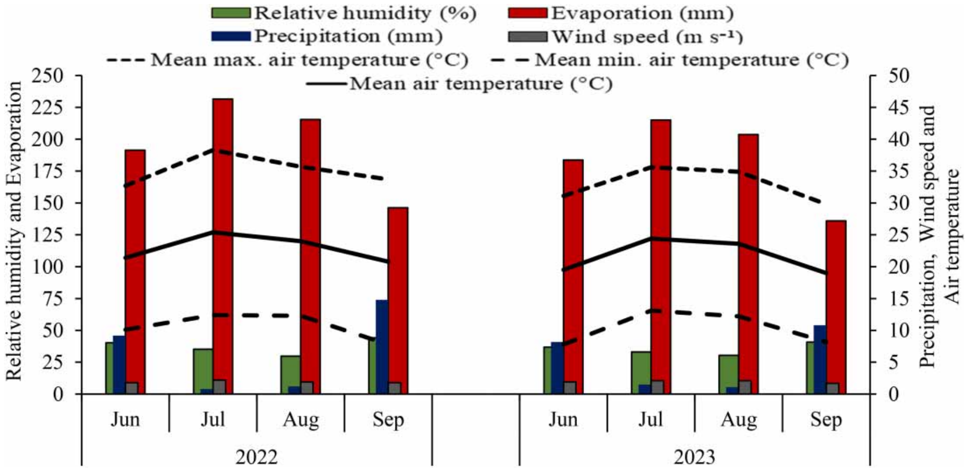

Figure 1 | Climatic data in the vegetation period of silage maize in 2022 (June 3–September 30) and 2023 (June 5–September 29).

2023), and 26.0 and 21.6 mm of precipitation occurred during the vegetation period of silage maize in these years, respectively. The total evaporation, mean relative humidity, and wind speed values for the same years were 784.8 mm, 37.4%, and 1.9 m s^{-1} and 738.4 mm, 35.3%, and 2.0 m s^{-1}, respectively.

2.2. Properties of experimental area soil and biochar

To determine the properties of the soil before the experiment, soil samples were taken from 0.3 m layers up to a depth of 0.9 m in profiles opened at three different points to represent the experimental area. The soil samples taken were subjected to analysis and the properties of the experimental area soil are given in Table 1. Accordingly, it was determined that the texture of the soil was sandy clay loam, it contained moderate amounts of lime, there were no drainage and salinity problems, its pH was moderately alkaline and its organic matter content was insufficient.

Oak biochar, which was brought to the experimental area, pyrolyzed at 400 °C, and subjected to sieving-homogenization processes, was commercially available. To determine the properties of the biochar before the experiment, the biochar material was subjected to analysis, and the properties of the biochar are given in Table 2. Accordingly, it was determined that the salinity of the biochar was high, its pH was significantly basic, and its organic matter content was rich.

2.3. Irrigation water resources and properties

While irrigation water line of the University was used as fresh water in the experiment, recycled wastewater was taken from the Van-Tusba-Iskele Wastewater Treatment Plant, which is ~5 km away from the experimental area. In this context, treated wastewater was transported to the experimental area by a tanker before each irrigation, transferred to the polyethylene tank, and used for irrigation.

In both years of the experiment, samples of fresh water and recycled wastewater were taken in the middle of each month representing the irrigation period, and these samples were subjected to analysis. EC and pH in water samples were measured using a conductometer and pH meter. Cations, microelements, and heavy metals were determined by inductively coupled plasma-optical emission spectrometer (ICP-OES) (Anonymous 2007). CO_3 and HCO_3 were obtained by the sulfuric acid titration method (Tuzuner 1990), and Cl and SO_4 were determined by the potassium chromate indicator approach (Tuzuner 1990) and HACH spectrophotometer with ready-made kits (HACH 2010). Total nitrogen (TN) and total phosphorus (TP) were determined by the Kjeldahl method (APHA AWWA WEF 1989) and using phosphorus reagent (Powder Pillow) in the HACH spectrophotometer (HACH 2010). Suspended solid matter (SSM) was determined according to the residue left by filtered water samples (APHA 1995). The spectrophotometer, adsorption incubator, thermoreactor, and cuvette test of the HACH brand were used to determine chemical oxygen demand (COD) and biological oxygen demand (BOD_5) (HACH 2005, 2010). While sodium adsorption rate (SAR), residual sodium carbonate (RSC), and percent sodium (Na%) values were calculated by taking into account ion concentrations (mEq l^{-1}) with standard

Table 1 | Properties of the experimental area soil

Property	0–0.3 m	0.3–0.6 m	0.6–0.9 m
Soil texture	Sandy clay loam	Sandy clay loam	Sandy clay loam
Sand (%)	46.5	45.1	45.9
Clay (%)	30.1	31.7	28.2
Silt (%)	23.4	23.2	25.9
Organic matter (%)	1.24	1.15	1.02
Total N (%)	0.091	0.085	0.074
P_2O_5 (Mg ha^{-1})	88.1	84.1	80.8
K_2O (Mg ha^{-1})	786	799	816
CEC (cmol kg^{-1})	24.6	23.4	25.1
EC (dS m^{-1})	0.418	0.445	0.479
pH	8.21	8.24	8.48
$CaCO_3$ (%)	10.5	12.1	14.9
Particle density	2.70	2.71	2.69
Bulk density (Mg m^{-3})	1.29	1.36	1.32
Porosity (%)	52.2	49.8	50.9
Aggregate stability (%)	44.1	45.1	44.9
Fe (Mg kg^{-1})	4.08	3.75	3.51
Cu (Mg kg^{-1})	2.11	1.99	1.84
Mn (Mg kg^{-1})	7.51	6.99	6.11
Zn (Mg kg^{-1})	45.9	40.3	32.9
Pb (Mg kg^{-1})	3.31	3.15	2.91
Cd (Mg kg^{-1})	0.022	0.021	0.020
Cr (Mg kg^{-1})	0.162	0.154	0.129
Ni (Mg kg^{-1})	0.099	0.081	0.069

CEC, cation exchange capacity.

equations (Kanber & Unlu 2010), the Langelier saturation index (LSI) was determined by calculation according to Ayers & Westcot (1994).

The properties of irrigation waters are given in Table 3. Thus, as a result of the evaluation of fresh water and recycled wastewater according to international criteria (Ayers & Westcot 1994; WHO 2001; EPA 2004; Kanber & Unlu 2010; Cakmakci & Sahin 2019a; Yerli & Sahin 2022), it was concluded that there is no harm in using it for irrigation.

2.4. Irrigation system and experimental design

Irrigation was done by a drip irrigation system using lateral pipes with in-line drippers (2.3 l h^{-1}) at 33 cm intervals, according to the infiltration value of the experimental area (~15 mm h^{-1}). While the operating pressure (1 atm) required to operate the irrigation system was provided by a centrifugal pump, a screen filter, pressure regulator manometer was included in the control unit for the operation of the irrigation system. In addition, a water meter was placed at the entrance of each parcel to control the irrigation water amount. In the system, the diameters of the main, manifold, and lateral pipes were 50, 32, and 16 mm, respectively, and the lateral pipes were placed in each crop row with an interval of 0.7 m.

The experiment was conducted in a total of 12 parcels with 3 replications under 2 different water qualities (fresh water (control) and recycled wastewater) and 2 different biochar treatments (no biochar: 0 t ha^{-1} (control) and biochar: 10 t ha^{-1}), according to the completely randomized block factorial experimental design (Supplementary material 2). The experimental plots were planned as five rows, with 0.7 m × 0.15 m row spacing and crop spacing, each plot being 3.5 m × 7.2 m in size (25.2 m^2), and a 3 m interval was left between plots and blocks to prevent side effects (Supplementary material 2).

Table 2 | Properties of biochar

Property	Biochar
Organic matter (%)	56.1
CEC (cmol kg^{-1})	30.0
EC (dS m^{-1})	4.26
pH	9.65
N (%)	1.80
P (g kg^{-1})	0.18
K (g kg^{-1})	3.57
Fe (Mg kg^{-1})	51.1
Cu (Mg kg^{-1})	8.61
Mn (Mg kg^{-1})	25.3
Zn (Mg kg^{-1})	15.8
Pb (Mg kg^{-1})	0.551
Cd (Mg kg^{-1})	–
Cr (Mg kg^{-1})	–
Ni (Mg kg^{-1})	–

CEC, cation exchange capacity; –, not detected.

2.5. Cultural practices and biochar treatments

The experimental field was first tillaged with a moldboard plow from a soil depth of 20–25 cm. Subsequently, the clods were broken up using a cultivator rotary harrow, and the field surface was leveled. Biochar was spread homogeneously on the soil surface of the biochar plots with a calculation of 10 t ha^{-1}, taking into account the fertilization depth of 15 cm. A hoeing machine was used to mix the biochar into the soil. Finally, silage maize seeds (cv. DKC-6777) were sown with a pneumatic seeder. To see the cumulative effect of biochar, biochar was applied only in the first year of the experiment, and in the second year of the experiment, soil tillage was provided only with a hoeing machine, without mixing biochar into the soil.

For weed control, the first hoeing was carried out when the crop height was 15–20 cm, and the second hoeing was carried out in the form of throat filling when the crop height was 40–50 cm. During sowing, 100 kg ha^{-1} urea and 150 kg ha^{-1} triple superphosphate were manually applied to all plots, and when the crop reached a height of 40–50 cm (4–6 leaf stages), the second urea fertilization was applied by fertigation equal to the first dose during the throat filling period.

2.6. Irrigation treatments

During the period until the crop reached 30–39 stages according to the BBCH scale, irrigation was carried out with fresh water at a 30% wetting percentage, taking into account biochar treatments in the form of completing the current moisture determined at a depth of 0.3 m in the fresh water parcels to field capacity, separately for each biochar treatment (Yerli *et al.* 2023). After the crop reached 30–39 stages according to the BBCH scale, irrigation treatments were started with recycled wastewater, and during this period, irrigation was carried out with fresh water and recycled wastewater at a 65% wetting percentage, taking into account biochar treatments in the form of completing the current moisture determined at a depth of 0.9 m in the fresh water parcels to field capacity, separately for each biochar treatment (Cakmakci & Sahin 2021a). In determining the irrigation time, it was taken into account that the sum of the difference between crop water consumption (ET_c) and precipitation (P) [$\Sigma(ET_c - P)$] reached a value corresponding to 40% of the available water capacity at a depth of 0.3 for the first period and at a depth of 0.9 for the second period (Allen *et al.* 1998).

While the moisture retained at the field capacity and wilting point required for irrigation were obtained by a pressurized membrane device before the experiment (Klute 1986), the available water capacity was calculated from the field capacity, wilting point, and the bulk density values (Kanber & Unlu 2010). In addition, the ET_c value required for irrigation was obtained by multiplying the reference crop water consumption (ET_o) by the crop coefficient (k_c) of silage maize ($ET_c = ET_o \times k_c$). When the ET_o value was calculated with the Penman–Monteith equation (FAO) in the CROPWAT program,

Table 3 | Properties of irrigation waters

Property	Fresh water	Recycled wastewater
EC (dS m^{-1})	0.335 ± 0.021	1.051 ± 0.065
pH	8.13 ± 0.09	7.75 ± 0.10
Ca (mEq l^{-1})	0.85 ± 0.05	2.12 ± 0.15
Mg (mEq l^{-1})	1.44 ± 0.11	2.98 ± 0.25
Na (mEq l^{-1})	0.99 ± 0.05	4.39 ± 0.12
K (mEq l^{-1})	0.17 ± 0.02	1.12 ± 0.09
CO_3 (mEq l^{-1})	–	–
HCO_3 (mEq l^{-1})	2.19 ± 0.18	5.21 ± 0.15
Cl (mEq l^{-1})	0.37 ± 0.04	2.38 ± 0.18
SO_4 (mEq l^{-1})	0.85 ± 0.09	1.58 ± 0.18
Fe (Mg l^{-1})	0.048 ± 0.005	0.438 ± 0.014
Cu (Mg l^{-1})	–	0.009 ± 0.003
Mn (Mg l^{-1})	–	0.081 ± 0.006
Zn (Mg l^{-1})	–	0.010 ± 0.003
Pb (Mg l^{-1})	–	0.002 ± 0.001
Cd (Mg l^{-1})	–	0.001 ± 0.001
Cr (Mg l^{-1})	–	0.001 ± 0.001
Ni (Mg l^{-1})	–	0.025 ± 0.002
TN (Mg l^{-1})	–	9.65 ± 0.91
TP (Mg l^{-1})	–	1.31 ± 0.17
SSM (Mg l^{-1})	–	28.9 ± 1.9
COD (Mg l^{-1})	–	37.3 ± 3.1
BOD_5 (Mg l^{-1})	–	25.5 ± 2.5
SAR	0.92 ± 0.04	2.75 ± 0.08
RSC (mEq l^{-1})	−0.10 ± 0.06	0.11 ± 0.05
Na%	28.7 ± 0.7	41.4 ± 0.8
LSI	0.34 ± 0.05	0.60 ± 0.027

TN, total nitrogen; TP, total phosphorus; SSM, suspended solid matter; COD, chemical oxygen demand; BOD_5, biological oxygen demand; SAR, sodium adsorption rate; RSC, residual sodium carbonate; Na%, percent sodium; LSI, Langelier saturation index; ±, standard error of the mean; –, not detected.

the climate data required in the calculations were obtained from the climate station in the experimental area, while the k_c value was taken directly from a guide valid for Türkiye (CWCG 2017).

Soil moisture measurements were done in the middle replication of the experimental plots, taking into account biochar treatments, using gravimetric sampling from 0.3 m layers to a depth of 0.9 m, before each irrigation and during the sowing and harvest periods. The moisture measurements were made at a distance of approximately 15–20 cm from the dripper, corresponding to between two crops, and moisture was also monitored by gravimetric sampling in the 0.9–1.2 m soil layer to determine deep percolation. The amount and volumes of irrigation water applied during the experimental period were calculated with Equations (1) and (2) and were also confirmed by water meter readings and time calculation approaches:

$$I = (\mathrm{FC}-\mathrm{CM}) \times \gamma_s \times D \times P \tag{1}$$

$$V = I \times A \tag{2}$$

where I is the irrigation water amount (mm), FC is the field capacity ($\%\mathrm{P}_{\mathrm{weight}}$), CM is the current moisture ($\%\mathrm{P}_{\mathrm{weight}}$), γ_s is the bulk density of the soil (Mg m^{-3}), D is the soil depth (0.3 and 0.9 m), P is the wetting ratio (30 and 65%), V is the irrigation water volume (l), and A is the plot area (25.2 m^2).

2.7. Actual evapotranspiration, $WP_{irrigation}$, and WP

While actual evapotranspiration was calculated with Equation (3), irrigation water productivity ($WP_{irrigation}$) and WP were calculated with Equations (4) and (5):

$$ET_a = I + P \pm \Delta S \tag{3}$$

$$WP_{irrigation} = FBY \times 100/I \tag{4}$$

$$WP = FBY \times 100/ET_a \tag{5}$$

where ET_a is the actual evapotranspiration (mm), I is the irrigation water amount (mm), P is the precipitation amount (mm), ΔS is the change in soil moisture content (mm), $WP_{irrigation}$ and WP are the irrigation water productivity and water productivity (kg m^{-3}), respectively, and FBY is the fresh biomass yield (t ha^{-1}).

Considering that there is no groundwater problem in the experimental area and no water loss occurs through surface runoff since a dripper flow rate suitable for soil infiltration was selected and no deep percolation was encountered in the moisture measurements at a depth of 0.9–1.2 m in the soil, capillary rise, surface runoff, and deep percolation are not included in the water budget equation (Equation (3)) used to calculate actual evapotranspiration.

2.8. Analyses and measurements of soil

After the harvest of both experiment years, soil samples were taken from 0.3 m layers up to a depth of 0.9 m in profiles opened to represent the parcel from all parcels. While organic matter and total N in soil samples were determined according to the Walkey-Black (Nelson & Sommers 1982) and Kjeldahl methods (Bremner & Mulvaney 1982), respectively, P_2O_5 and K_2O were obtained by an atomic absorption spectrophotometer (Olsen *et al.* 1982) and flame photometer readings (Knudsen *et al.* 1982), respectively. The ammonium acetate method was used to determine the CEC according to Kacar (1995). EC and pH were measured in the saturation extract by a conductometer and pH meter. The Scheibler Calcimeter was used to determine $CaCO_3$ (Nelson 1982). Aggregate stability was obtained according to the wet-sieving (Kemper & Rosenau 1986). Microelements and heavy metals in soil samples were obtained by ICP-OES (Anonymous 2007). While particle and bulk densities were determined by pycnometer (Blake & Hartge 1986a) and soil-roller (Blake & Hartge 1986b), respectively, the porosity was calculated from these two values with Equation (6) (Danielson & Sutherland 1986):

$$n = [1–(\gamma_s/G_s \times \gamma_w)] \times 100 \tag{6}$$

where n is the porosity (%), γ_s is the bulk density of the soil (Mg m^{-3}), G_s is the particle density of the soil, and γ_w is the bulk density of pure water at +4 °C (1 Mg m^{-3}).

2.9. Analyses and measurements of silage maize

At the end of both experiment years, some analyses and measurements were made during and after the harvest of silage maize in all parcels, representing the parcel. In the harvested crop samples, the Kjeldahl method used for N and P was obtained colorimetrically in the solution in the combustion (Kacar 2014). ICP-OES was used to determine the macro- and microelements and heavy metal contents of the crop samples (Anonymous 2007). While crop height was determined by measuring the part of the crop from the soil surface to the top tassel, the stem diameter was obtained by measuring the thickness of the crop between the second and third nodes with a digital caliper. Fresh biomass yield was calculated by adapting the weights of the harvested crops to t ha^{-1}, and dry biomass yield was adapted to t ha^{-1} after drying the same samples at 78 °C for 48 h (Kacar 2014). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) contents of crop samples were determined on the ANKOM 200 Fiber Analyser by adding solutions according to the Fiber Bag System, Gerhardt (Van Soest 1963). A chlorophyll meter (SPAD-502, Konica Minolta Sensing, Inc., Osaka, Japan) was used for chlorophyll measurement. The leaf area was measured with a leaf area meter (LiCor-300C, LiCor, Lincoln, Nebraska), and the leaf area index was obtained by proportioning it to the unit area of a crop (0.7 m × 0.15 m). Electrolyte leakage was obtained by keeping a 1-cm diameter disk sample taken from crop leaves in pure water for 24 h and measuring its EC1 and by keeping the same sample in a water bath at 95 °C for 20 min and measuring its EC2, dividing the first EC value by the second EC value. Leaf relative water content (LRWC) was calculated with Equation (6):

$$\mathrm{LRWC} = (\mathrm{FW} - \mathrm{DW})/(\mathrm{TW} - \mathrm{DW}) \times 100 \quad (7)$$

where LRWC is the leaf relative water content (%), FW is the fresh weight of the leaf (g), DW is the dry weight of the leaf kept in an oven at 65 °C for 24 h (g), and TW is the turgor weight of the leaf kept in pure water for 4 h (g).

2.10. Analyses of data

Analyses were done in the SPSS package program. As a result of the ANOVA conducted to determine differences between the experiment years (2022 and 2023) and between the soil layers (0–0.3 m, 0.3–0.6 m, and 0.6–0.9 m), it was observed that all parameters examined in the experiment showed a general similarity between experiment years and between soil layers. In addition, considering that the surface soil layer is more critical and meaningful than deeper soil layers in agricultural production and the concept of effective root depth (Demir & Sahin 2017), statistical analyses were carried out in the 0–0.3 m soil layer and the mean of the experimental years (Cakmakci & Sahin 2021a). Thus, irrigation water quality and biochar treatment variables were evaluated as fixed factors, and the data were analyzed through the general linear model. The significant means were separated at a 5% probability level using the Duncan multiple comparison test. Furthermore, the Pearson correlation test was used to determine the correlation relationships between the data.

3. RESULTS AND DISCUSSION

3.1. Irrigation water amount and actual evapotranspiration

Data on irrigation water amounts are presented in Figure 2. Equal amounts of irrigation water were used in the irrigation of biochar treatments with fresh water and recycled wastewater. In the period until the crop reached a height of 40–50 cm (4–6 leaf stages), in 2022–2023, in conditions without biochar and with biochar, 35.6–33.9 mm and 34.5–33.6 mm of irrigation water, respectively, was provided with fresh water only. After this period, irrigation was carried out with 328.2–315.8 mm

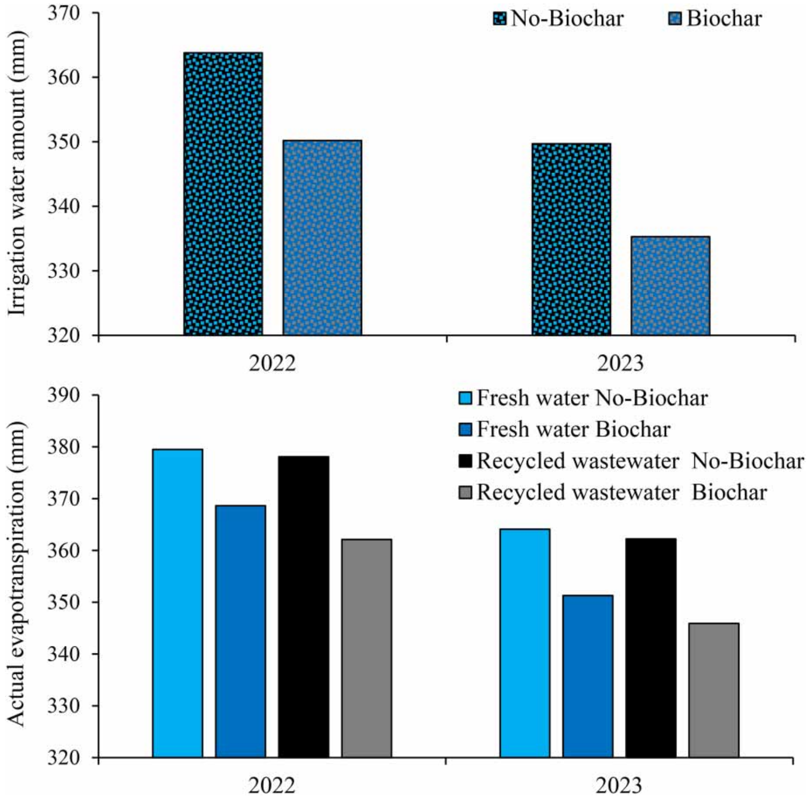

Figure 2 | Irrigation water amount and actual evapotranspiration in irrigation and biochar treatments in 2022 and 2023.

and 315.7–301.7 mm of fresh water and recycled wastewater in biochar treatments, respectively, for the same years. Thus, in the mean of the experiment years, a total of 356.8 and 342.8 mm of irrigation water was applied in conditions without biochar and with biochar, respectively.

In total, of 13 irrigations were carried out in both years of the experiment; the first 4 of these irrigations were done only with fresh water, and the remaining 8 were carried out in the form of planned irrigation with fresh water and recycled wastewater. In the experiment in which the mean irrigation interval was 8 days, the most frequent irrigation interval was in July and August, when air temperatures were higher (Figure 1). In the first year of the experiment, 4.0 and 4.4% more irrigation water was applied under conditions without biochar and with biochar, respectively, compared with the second year due to higher air temperatures and therefore evaporation in the first year of the experiment compared with the second year (Figure 1).

Biochar saved 3.7 and 4.1% of the irrigation water amount in the experimental years, respectively. This can be explained by the spongy and porous structure of the biochar. The spongy and porous structure of the biochar preserves soil moisture (Abel *et al.* 2013; Omondi *et al.* 2016), and the structural features of the biochar reduce the amount of irrigation water by limiting evaporation in the soil (Ahmed *et al.* 2019). Biochar retains soil water not only within the pores but also between micropores. For this reason, it takes a longer time for soil with biochar to lose moisture (Cakmakci & Sahin 2023). Additionally, biochar enriches the soil with organic matter (Table 4), which may support moisture retention in the soil, resulting in less irrigation water. Organic matter has a regulating and protective effect on soil moisture (Yerli *et al.* 2023). Soil organic matter causes more water retention by improving the pore size distribution of the soil (Minasny & McBratney 2018). A 1% increase in organic matter content for standard soil represents an increase of approximately 3 liters of soil water storage for every 0.0283 m^3 of soil (Gould 2015).

Data on actual evapotranspiration are presented in Figure 2. Irrigation water was the most important structure of actual evapotranspiration due to the low amount of precipitation in the vegetation period (Figure 1). Thus, in 2022–2023, in the biochar treatments of irrigation with fresh water and recycled wastewater, the actual evapotranspiration values were 2.9 and 4.2% to 3.5 and 4.5% lower, respectively, compared with the conditions without biochar, which can be explained by the lower amount of irrigation water (Figure 2). The actual evapotranspiration values in the irrigation of biochar treatments with fresh water and recycled wastewater resulted in actual evapotranspiration values close to each other as a result of the equal amount of irrigation water in these treatments (Figure 2). In addition, the higher amount of irrigation water in the first year of the experiment compared with the second year (Figure 2) caused more actual evapotranspiration in the first year. Ghanem *et al.* (2022) and El-Sayed *et al.* (2023) also reported that biochar treatment caused less actual evapotranspiration by reducing the amount of irrigation water.

3.2. WP$_{\text{irrigation}}$ and WP

The effects of irrigation and biochar treatments on WP$_{\text{irrigation}}$ and WP values were found to be statistically significant (Figure 3 and Supplementary material 3). WP$_{\text{irrigation}}$ and WP were 13.2 and 14.3% higher in irrigation with recycled wastewater than in irrigation with fresh water. This can be explained by the increased fresh biomass yield of silage maize in irrigation with recycled wastewater compared with irrigation with fresh water (Table 5). Because equal amounts of irrigation water were applied in irrigation treatments with recycled wastewater and fresh water, the actual evapotranspiration values

Table 4 | Chemical properties of the soil in irrigation and biochar treatments

Treatments		Organic matter (%)	Total N (%)	P$_2$O$_5$ (Mg ha^{-1})	K$_2$O (Mg ha^{-1})	CEC (cmol kg^{-1})	EC (dS m^{-1})	pH	CaCO$_3$ (%)
FW	No-B	1.18 ± 0.02$^{\text{N.S}}$	0.088 ± 0.002$^{\text{N.S}}$	87.0 ± 0.9$^{\text{N.S}}$	740 ± 10$^{\text{N.S}}$	26.6 ± 0.6$^{\text{N.S}}$	0.436 ± 0.006$^{\text{N.S}}$	8.15 ± 0.03$^{\text{N.S}}$	10.2 ± 0.3$^{\text{N.S}}$
	B	1.31 ± 0.02	0.107 ± 0.005	99.7 ± 0.8	811 ± 24	28.0 ± 0.1	0.672 ± 0.063	8.02 ± 0.05	9.5 ± 0.2
	Mean	1.25 ± 0.03 B**	0.098 ± 0.005 B**	93.3 ± 2.9 B**	776 ± 20 B**	27.3 ± 0.4 B**	0.554 ± 0.060 B**	8.09 ± 0.04 A**	9.9 ± 0.2 A**
RWW	No-B	1.52 ± 0.04	0.133 ± 0.007	118.3 ± 4.7	930 ± 15	28.9 ± 0.6	0.820 ± 0.043	7.92 ± 0.02	8.8 ± 0.4
	B	1.75 ± 0.02	0.157 ± 0.007	129.4 ± 4.0	997 ± 10	30.5 ± 0.2	0.918 ± 0.014	7.79 ± 0.04	7.9 ± 0.4
	Mean	1.63 ± 0.05 A	0.145 ± 0.007 A	123.9 ± 3.7 A	963 ± 17 A	29.7 ± 0.5 A	0.869 ± 0.030 A	7.85 ± 0.04 B	8.4 ± 0.3 B
Mean	No-B	1.35 ± 0.08 B**	0.110 ± 0.011 B**	102.6 ± 7.3 B**	835 ± 43 B**	27.8 ± 0.6 B**	0.628 ± 0.08 B**	8.04 ± 0.06 A**	9.5 ± 0.4 A*
	B	1.53 ± 0.11 A	0.132 ± 0.012 A	114.6 ± 6.9 A	904 ± 44 A	29.3 ± 0.7 A	0.795 ± 0.062 A	7.90 ± 0.06 B	8.7 ± 0.4 B

FW, fresh water; RWW, recycled wastewater; No-B, no biochar; B, biochar; CEC, cation exchange capacity; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

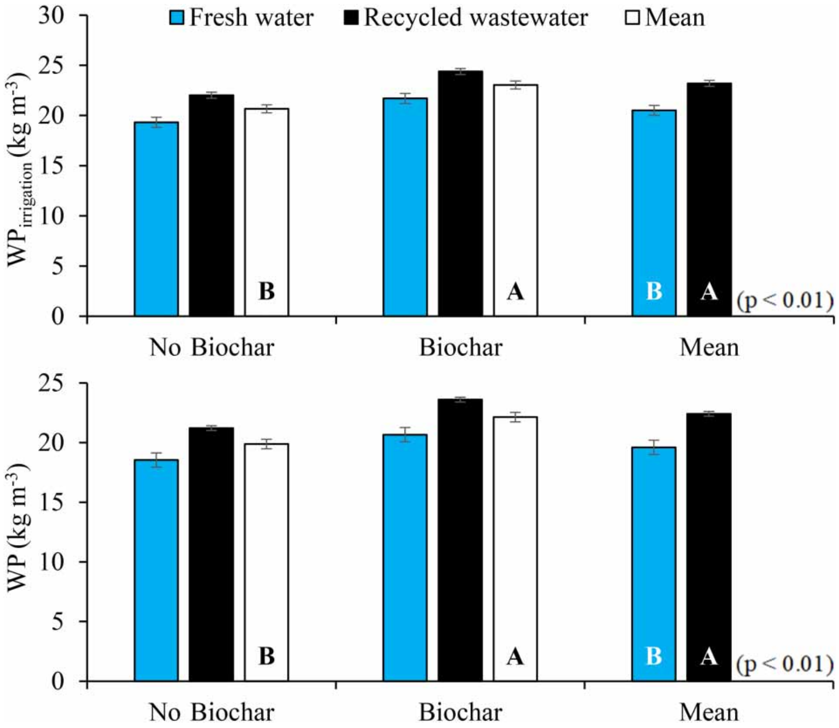

Figure 3 | Irrigation water productivity ($WP_{irrigation}$) and water productivity (WP) in irrigation and biochar treatments.

Table 5 | Physical properties, biomass yields, ADF, and NDF contents of the silage maize in irrigation and biochar treatments

Treatments		Crop height (cm)	Stem diameter (mm)	FBY (t ha^{-1})	DBY (t ha^{-1})	ADF (%)	NDF (%)
FW	No-B	229.8 ± 3.0$^{N.S}$	22.3 ± 0.5$^{N.S}$	68.9 ± 0.8$^{N.S}$	20.3 ± 0.4$^{N.S}$	28.1 ± 0.2$^{N.S}$	48.5 ± 0.4$^{N.S}$
	B	237.0 ± 4.4	23.0 ± 0.3	74.4 ± 0.3	22.5 ± 0.3	26.7 ± 1.9	47.3 ± 0.4
	Mean	233.4 ± 2.9 B**	22.7 ± 0.4 B**	71.7 ± 0.7 B**	21.4 ± 0.6 B**	27.4 ± 0.9 A**	47.9 ± 0.4 A**
RWW	No-B	246.4 ± 2.6	24.4 ± 0.2	78.6 ± 0.8	24.0 ± 0.4	23.3 ± 1.2	40.8 ± 1.1
	B	256.0 ± 2.8	25.0 ± 0.3	83.6 ± 0.7	26.1 ± 0.2	21.3 ± 0.4	38.6 ± 0.6
	Mean	251.2 ± 2.8 A	24.7 ± 0.5 A	81.1 ± 0.9 A	25.1 ± 0.4 A	22.3 ± 0.7 B	39.7 ± 0.7 B
Mean	No-B	238.1 ± 4.1 B*	23.3 ± 0.6$^{N.S}$	73.7 ± 0.9 B**	22.2 ± 0.9 B**	25.7 ± 1.2$^{N.S}$	44.6 ± 1.8 A*
	B	246.5 ± 4.8 A	24.0 ± 0.5	79.0 ± 0.8 A	24.3 ± 0.7 A	24.0 ± 1.5	43.0 ± 2.0 B

FW, fresh water; RWW, recycled wastewater; No-B, no biochar; B, biochar; FBY, fresh biomass yield; DBY, dry biomass yield; ADF, acid detergent fiber; NDF, neutral detergent fiber; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

were similar between the two treatments (Figure 2). Demir & Sahin (2017) reported that the increased yield due to the nutritious effect of recycled wastewater on the crop resulted in an increase in $WP_{irrigation}$ and WP. In the biochar treatment, $WP_{irrigation}$ and WP were 11.1 and 11.0% higher than in the conditions without biochar. This can be explained by both the increased fresh biomass yield (Table 5) and the decreased amount of irrigation water and actual evapotranspiration (Figure 2) in the biochar treatment compared with the conditions without biochar. Based on the formulaic calculation component of $WP_{irrigation}$ and WP (Equations (4) and (5)), the decreasing amount of irrigation water and actual evapotranspiration values against the increasing yield potential results in an increase in $WP_{irrigation}$ and WP. Cakmakci & Sahin (2021b) also stated that $WP_{irrigation}$ and WP values increased due to the increase in fresh biomass yield under irrigation conditions with recycled wastewater, while Baiamonte *et al.* (2020) also reported that $WP_{irrigation}$ and WP values increased due to increased yield and decreased amount of irrigation water and actual evapotranspiration in biochar treatment.

3.3. Chemical properties of soil

The effects of irrigation and biochar treatments on organic matter, total N, P_2O_5, K_2O, CEC, electrical conductivity (EC), pH, and $CaCO_3$ values were found to be statistically significant (Table 4 and Supplementary material 3).

The organic matter, total N, P_2O_5, and K_2O contents of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the rich content of recycled wastewater and biochar (Tables 2 and 3). While the chemical (COD) and biological oxygen demands (BOD_5) of recycled wastewater improve the organic matter content of the soil, the N, P, and K contents of the recycled wastewater support an increase in the total N, P_2O_5, and K_2O contents of the soil (Cakmakci & Sahin 2021a). Similarly, the nutrient-rich content of biochar offers soil development that can eliminate the soil's need for fertilizer (Tang *et al.* 2020). Both the effect of biochar on providing organic matter, N, P, and K to the soil and its ability to preserve them for a longer period of time without mineralization (Zhang *et al.* 2017) more clearly explain the increased organic matter, total N, P_2O_5, and K_2O content of the soil in the biochar treatment in this study. In addition, as a result of the better development of the crop grown in the soil irrigated with recycled wastewater and applied biochar (Table 5), the fact that the crop residues contribute more organic matter to the soil can be considered a different explanation for the increased organic matter content in irrigation with recycled wastewater and biochar treatments.

The CEC content of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can also be explained by the organic matter content that irrigation with recycled wastewater and biochar provides to the soil (Table 4), as well as the cation content of recycled wastewater and biochar (Tables 2 and 3). Organic matter not only provides larger cation exchange volume due to its charged surfaces but also reduces the loss of exchangeable cations from the soil. Lu *et al.* (2015) also explained the increase in CEC by organic matter providing a wide cation exchange area. In this study, the positive correlation relationship of CEC with organic matter also supports this situation (Supplementary material 4). Additionally, similar to the findings of this study, Angin *et al.* (2005) stated that there was a two-fold increase in CEC in irrigation with recycled wastewater compared with irrigation with fresh water, and this increase was due to the effect of recycled wastewater on increasing the organic matter content of the soil, while Banik *et al.* (2018) reported that biochar mixed into the soil increased the CEC content of the soil and that this increase was a result of *O*-containing functional groups on the surface of the biochar.

The EC content of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the salt content of the recycled wastewater and biochar (Tables 2 and 3). Since wastewater contains salt even after the treatment process, the EC of the soil must be monitored, especially in long-term irrigation with recycled wastewater. Similar to the findings of this study, a different study also mentioned a two-fold increase in EC in irrigation with recycled wastewater compared with irrigation with fresh water (Cakmakci & Sahin 2021a). The various organic materials and fertilizers applied to the soil can increase soil salinity directly depending on their salt concentration (Atkinson *et al.* 2010) explaining the increase in soil EC in the biochar treatment in this study. Additionally, similar to the findings of this study, Karimi *et al.* (2020) reported that the EC of soil applied with biochar increased between 17 and 49%. In contrast, Hossain *et al.* (2020) found that biochar could regulate salinity rather than increase soil salinity, and this situation was explained by the characterization relationships of the biochar depending on the raw material and pyrolysis processes.

The pH content of the soil decreased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the organic matter and total N that recycled wastewater and biochar provide to the soil (Table 4), depending on their nutrient-rich content (Tables 2 and 3). During the mineralization phase of organic matter, hydrogen ions become free and acidify the soil (Adeleke *et al.* 2017). Similarly, free hydrogen ions resulting from the mineralization of ammonium reduce soil pH as a result of higher rates of nitrification (Singh & Agrawal 2012). In addition, decreases in soil pH may occur due to the breakdown of carboxyl-containing acids of different organic structures depending on organic matter (Zhi-An *et al.* 2008). In this study, the negative correlation relationships of pH with organic matter and total N also support this situation (Supplementary material 4). Additionally, similar to the findings of this study, Demir & Sahin (2017) and Yerli (2023) also reported that soil pH decreased in irrigation with recycled wastewater and biochar treatment, respectively.

The $CaCO_3$ content of the soil decreased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the pH-reducing effect of irrigation with recycled wastewater and biochar treatment (Table 4). Decreasing pH increases the dissolution of $CaCO_3$ (Mazen *et al.* 2010). In addition, organic acids produced in the mineralization of organic matter in the soil can cause further pH decreases and thus more $CaCO_3$ dissolution in the soil (Leogrande & Vitti 2019). In this study, the positive correlation relationship of $CaCO_3$ with pH also supports this situation (Supplementary material 4). Additionally, similar to the findings of this study, Cakmakci & Sahin (2021a) reported that $CaCO_3$ content decreased due to the decreasing pH content of the soil in irrigation with recycled wastewater, while Chintala *et al.* (2014) pointed out that biochar applied to acidic soils reduced $CaCO_3$.

3.4. Physical properties of the soil

While the effects of irrigation and biochar treatments on particle density values were not found to be statistically significant, the effects of irrigation and biochar treatments on bulk density, porosity, and aggregate stability values were found to be statistically significant (Table 6 and Supplementary material 3).

The bulk density content of the soil decreased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the organic matter that recycled wastewater and biochar provide to the soil (Table 4), depending on their nutrient-rich content (Tables 2 and 3). The lower bulk density of organic matter results in increased organic matter in the soil decreasing the bulk density of the soil. In addition, organic matter improves soil aggregation, reduces soil compaction, and reduces bulk density (Demir & Sahin 2019). Six *et al.* (2000) explained the lower bulk density with the formation of more stable aggregation in the soil associated with the presence of organic matter. In this study, the negative correlation relationships of bulk density with organic matter and aggregate stability also support this situation (Supplementary material 4). Additionally, similar to the findings of this study, Demir & Sahin (2019) and Verheijen *et al.* (2019) also reported that the bulk density of the soil decreased in irrigation with recycled wastewater and biochar treatment, respectively.

The porosity content of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the fact that irrigation with recycled wastewater and biochar treatment reduces the bulk density (Table 6). Since there was no significant change in particle density depending on the irrigation and biochar treatments, the change in porosity depended on the bulk density (Table 6). Based on the formulaic calculation component of porosity (Equation (6)), decreasing bulk density increases porosity under conditions where particle density is constant. In this study, the negative correlation relationship of porosity with bulk density also supports this situation (Supplementary material 4). In addition, increasing organic matter in the soil reduces soil compaction and provides more space in the soil, which also increases porosity (Chaudhari *et al.* 2013). Thus, it can be stated that increasing the organic matter content of the soil enables porosity development. In this study, the positive correlation relationship of porosity with organic matter also supports this situation (Supplementary material 4). Similar to the findings of this study, Cakmakci & Sahin (2021a) also reported that porosity increased in irrigation with recycled wastewater. Moreover, while all of these can be considered as the indirect effect of biochar increasing porosity, the porous structure of biochar can be evaluated as the direct effect of biochar increasing porosity. Omondi *et al.* (2016) pointed out that biochar mixed into the soil supports the development of soil porosity due to the porous structure of the biochar.

Table 6 | Physical properties of the soil in irrigation and biochar treatments

Treatments		**Particle density**	**Bulk density ($Mg\ m^{-3}$)**	**Porosity (%)**	**Aggregate stability (%)**
FW	No-B	2.70 ± 0.003$^{N.S}$	1.29 ± 0.003$^{N.S}$	52.2 ± 0.2$^{N.S}$	46.8 ± 0.7$^{N.S}$
	B	2.71 ± 0.007	1.28 ± 0.003	52.6 ± 0.2	50.4 ± 1.0
	Mean	2.71 ± 0.003$^{N.S}$	1.29 ± 0.003 A**	52.4 ± 0.2 B**	48.6 ± 1.0 B**
RWW	No-B	2.71 ± 0.003	1.27 ± 0.003	53.0 ± 0.1	52.2 ± 0.6
	B	2.71 ± 0.006	1.26 ± 0.003	53.4 ± 0.2	55.2 ± 0.6
	Mean	2.71 ± 0.003	1.27 ± 0.03 B	53.2 ± 0.1 A	53.7 ± 0.8 A
Mean	No-B	2.71 ± 0.002$^{N.S}$	1.28 ± 0.005 A*	52.6 ± 0.2 B*	49.5 ± 1.3 B**
	B	2.71 ± 0.004	1.27 ± 0.005 B	53.0 ± 0.2 A	52.8 ± 1.2 A

FW, fresh water; RWW, recycled wastewater; No B, no biochar; B, biochar; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

The aggregate stability content of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the organic matter that recycled wastewater and biochar provide to the soil (Table 4). In this study, the positive correlation relationship of aggregate stability with organic matter also supports this situation (Supplementary material 4). Organic matter improves aggregation by ensuring closer contact with soil colloidal particles (Aslam *et al.* 2014). The effect of organic matter on increasing aggregate stability arises from supporting the development of clay-humic complexes and water-repellent coatings (Heikkinen *et al.* 2019). In addition, the improving effect of organic matter on other physical properties of the soil also supports the development of aggregate stability. In particular, the improvement in soil porosity promotes an increase in aggregate stability (Demir & Sahin 2019). In this study, the positive correlation relationship of aggregate stability with porosity also supports this situation (Supplementary material 4). Similar to the findings of this study, Cakmakci & Sahin (2021a) also stated that increased organic matter and porosity of the soil in irrigation with recycled wastewater improved aggregate stability. In addition, Hossain *et al.* (2020) explained the aggregate stability-enhancing effect of biochar in relation to the pore structure of biochar, and Hua *et al.* (2014) reported that biochar improved soil biology and increased aggregate stability as a result of the secretion of polysaccharides by microorganisms.

3.5. Microelement and heavy metal contents of the soil

While the effects of irrigation treatments on microelement and heavy metal (Fe, Cu, Mn, Zn, Pb, Cd, Cr, and Ni) values of the soil were found to be statistically significant, the effects of biochar treatments on microelement and heavy metal (Fe, Cu, Mn, Zn, and Pb) values of the soil, except Cd, Cr, and Ni, were found to be statistically significant (Table 7 and Supplementary material 3).

The microelement and heavy metal contents of the soil increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar (except Cd, Cr, and Ni). This can be explained depending on the microelement and heavy metal contents of the recycled wastewater and biochar (Tables 2 and 3). Similarly, Singh & Agrawal (2012) also stated that irrigation with recycled wastewater increased the microelement and heavy metal content of the soil compared with irrigation with fresh water, while Lucchini *et al.* (2014) also reported that biochar treatment caused minor changes in the microelement content of the soil and the fractionation of some heavy metals. Demir & Sahin (2020) pointed out that the heavy metal content of recycled wastewater tends to accumulate in the soil and that heavy metals should be monitored, especially in long-term irrigation with recycled wastewater. In contrast to this study, Zhang *et al.* (2017) stated that biochar treatment did not have a significant effect on the heavy metal content of the soil, and researchers emphasized the effect of biochar's raw materials and pyrolysis processes on increasing or decreasing the heavy metal content of the soil. While the raw material characterization of the biochar determines the microelement and heavy metal content of the biochar, pyrolysis processes (temperature, method, and oxygen) are also an important criterion that determines the scale of this content (Yerli 2023).

The movement of heavy metals in the soil, their transition to crops, or their binding forms are governed by many external and internal factors. While climatic factors can be listed at the top of external factors, internal factors can be evaluated depending on soil characteristics. In this study, the positive correlation relationships of soil heavy metal content (Fe, Cu, Mn, Zn, Pb, Cd, Cr, and Ni) with organic matter, total N, P_2O_5, K_2O, CEC, and EC and the negative correlation relationships with $CaCO_3$ and pH were determined (Supplementary material 4). Low molecular weight organic acids in the structure of

Table 7 | The microelement and heavy metal contents of the soil in irrigation and biochar treatments

Treatments		Fe (Mg kg^{-1})	Cu (Mg kg^{-1})	Mn (Mg kg^{-1})	Zn (Mg kg^{-1})	Pb (Mg kg^{-1})	Cd (Mg kg^{-1})	Cr (Mg kg^{-1})	Ni (Mg kg^{-1})
FW	No-B	3.45 ± 0.08$^{N.S}$	2.03 ± 0.24 a*	6.50 ± 0.17$^{N.S}$	40.9 ± 1.1$^{N.S}$	3.09 ± 0.17$^{N.S}$	0.018 ± 0.002$^{N.S}$	0.158 ± 0.004$^{N.S}$	0.087 ± 0.006$^{N.S}$
	B	5.92 ± 0.49	3.15 ± 0.09 b	10.64 ± 0.53	50.8 ± 2.7	3.66 ± 0.21	0.019 ± 0.001	0.160 ± 0.003	0.093 ± 0.003
	Mean	4.69 ± 0.60 B**	2.59 ± 0.28 B**	8.57 ± 0.96 B**	45.9 ± 2.6 B**	3.38 ± 0.17 B**	0.019 ± 0.001 B**	0.159 ± 0.002 B**	0.090 ± 0.003 B**
RWW	No-B	7.81 ± 0.11	4.07 ± 0.20 c	15.70 ± 1.22	78.7 ± 3.9	4.13 ± 0.06	0.085 ± 0.002	0.212 ± 0.028	0.383 ± 0.017
	B	9.96 ± 0.03	4.30 ± 0.03 c	20.53 ± 0.55	90.8 ± 1.1	4.87 ± 0.05	0.089 ± 0.001	0.214 ± 0.004	0.391 ± 0.017
	Mean	8.88 ± 0.10 A	4.19 ± 0.48 A	18.12 ± 1.24 A	84.8 ± 3.3 A	4.50 ± 0.17 A	0.087 ± 0.001 A	0.213 ± 0.013 A	0.387 ± 0.011 A
Mean	No-B	5.63 ± 0.48 B**	3.05 ± 0.98 B**	11.10 ± 2.13 B**	59.8 ± 8.7 B**	3.61 ± 0.24 B**	0.052 ± 0.015$^{N.S}$	0.185 ± 0.017$^{N.S}$	0.235 ± 0.067$^{N.S}$
	B	7.94 ± 0.26 A	3.72 ± 0.93 A	15.59 ± 2.24 A	70.8 ± 9.1 A	4.27 ± 0.29 A	0.054 ± 0.016	0.187 ± 0.012	0.242 ± 0.067

FW, fresh water; RWW, recycled wastewater; No-B, no biochar; B, biochar; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

organic matter increase the accumulation of heavy metals in the soil and control their distribution (Park *et al.* 2016). These organic acids act as chelators, limiting the uptake of heavy metals by crops and increasing the mobilization of heavy metals away from the rhizosphere region (Cakmakci & Sahin 2021a). It is an indirect effect that total N increases the mobility of heavy metals. The decrease in pH in the mineralization of ammonium with increasing N in the soil supports the accumulation of heavy metals in the soil (Singh & Agrawal 2012). The increase in heavy metals with the increase in P_2O_5 and K_2O is due to the antagonist effect of P and K. P and K compounds reduce the bioavailability of heavy metals, causing heavy metal contamination in the soil (Bolan *et al.* 2014). The increase in heavy metal accumulation in the soil with the increase in CEC depends on organic matter. The increase in organic matter supports the increase in CEC, causing heavy metal accumulation in the soil (Kizilkaya *et al.* 2004). In addition, the competition of cations with metals is also effective in heavy metal movement in soil (Acosta *et al.* 2011). Soil salinity can limit metal uptake by creating osmotic stress and increasing the accumulation of heavy metals in the soil. Bartkowiak *et al.* (2020) reported that heavy metal behavior changes in saline soils and metal accumulation in the soil increase with the decrease in the uptake of heavy metals by crops. Similarly, Acosta *et al.* (2011) also stated that increasing soil EC increased the mobilization of heavy metals. The relationship between $CaCO_3$ and heavy metals can be evaluated depending on pH. Decreasing pH increases the solubility of $CaCO_3$ (Mazen *et al.* 2010) and thus supports the accumulation of heavy metals in the soil (Cakmakci & Sahin 2021a). Soil pH is the most important factor affecting the mobility of heavy metals in soil solution. Low pH increases the mobility of heavy metals as a result of the higher ionic attraction of hydrogen to the metal (Singh *et al.* 2009). Decreasing pH creates competition between dissolved heavy metals and hydrogen ions, resulting in heavy metal contamination (Singh & Agrawal 2012). In general, soil pH values below 6.5–7.0 support an increase in the mobility of heavy metals in the soil (McBride *et al.* 1997). However, the lowest pH value in this study was found to be 7.79 (Table 4), indicating that the mobility of heavy metals did not increase in all treatments. In addition, as a result of this study, the heavy metal content of the soil in all treatments did not exceed the limit values determined by WHO (140, 300, 300, 3, and 75 Mg kg^{-1} for Cu, Zn, Pb, Cd, and Ni, respectively).

3.6. Macro- and microelements and heavy metal contents of silage maize

While the effects of irrigation treatments on micro- and macroelements and heavy metal (N, P, K, Ca, Mg, Na, Fe, Cu, Mn, Zn, Pb, Cd, Cr, and Ni) values of the silage maize were found to be statistically significant, the effects of biochar treatments on the micro- and macroelements and heavy metal (N, P, K, Ca, Mg, Na, Fe, Cu, Mn, Cd, Cr, and Ni) values of the silage maize, except Zn and Pb, were found to be statistically significant (Table 8 and Supplementary material 3).

The macro- and microelements and heavy metal contents of silage maize increased under irrigation with recycled wastewater compared with irrigation with fresh water. This can be explained by the effect of recycled wastewater on providing macro- and microelements and heavy metals to the soil (Tables 4 and 7), depending on its content (Table 3). With increased

Table 8 | The macro- and microelements and heavy metal contents of the silage maize in irrigation and biochar treatments

Treatments		**N (%)**	**P (Mg kg^{-1})**	**K (Mg kg^{-1})**	**Ca (Mg kg^{-1})**	**Mg (Mg kg^{-1})**	**Na (Mg kg^{-1})**	**Fe (Mg kg^{-1})**
FW	No-B	$1.86 \pm 0.13^{\mathrm{N.S}}$	$0.41 \pm 0.03^{\mathrm{N.S}}$	$1.09 \pm 0.05^{\mathrm{N.S}}$	$0.56 \pm 0.03^{\mathrm{N.S}}$	$0.49 \pm 0.04^{\mathrm{N.S}}$	$0.069 \pm 0.003^{\mathrm{N.S}}$	$119.5 \pm 4.3^{\mathrm{N.S}}$
	B	2.29 ± 0.16	0.54 ± 0.01	1.21 ± 0.04	0.67 ± 0.04	0.69 ± 0.03	0.026 ± 0.005	140.5 ± 2.9
	Mean	2.08 ± 0.13 B**	0.47 ± 0.03 B**	1.15 ± 0.04 B**	0.61 ± 0.03 B**	0.59 ± 0.05 B**	0.048 ± 0.010 B**	130.0 ± 5.3 B**
RWW	No-B	2.61 ± 0.19	0.91 ± 0.04	1.44 ± 0.07	0.81 ± 0.02	0.80 ± 0.03	0.206 ± 0.006	167.6 ± 3.7
	B	3.01 ± 0.08	1.10 ± 0.06	1.60 ± 0.03	0.96 ± 0.02	1.03 ± 0.05	0.153 ± 0.016	191.3 ± 4.3
	Mean	2.81 ± 0.13 A	1.01 ± 0.05 A	1.52 ± 0.05 A	0.89 ± 0.04 A	0.92 ± 0.06 A	0.180 ± 0.014 A	179.5 ± 5.9 A
Mean	No-B	2.24 ± 0.20 B*	0.66 ± 0.12 B**	1.26 ± 0.09 B*	0.68 ± 0.06 B**	0.64 ± 0.07 B**	0.138 ± 0.031 A**	143.5 ± 11.1 B**
	B	2.65 ± 0.18 A	0.82 ± 0.13 A	1.40 ± 0.09 A	0.82 ± 0.07 A	0.86 ± 0.08 A	0.090 ± 0.029 B	165.9 ± 11.6 A
Treatments		**Cu (Mg kg^{-1})**	**Mn (Mg kg^{-1})**	**Zn (Mg kg^{-1})**	**Pb (Mg kg^{-1})**	**Cd (Mg kg^{-1})**	**Cr (Mg kg^{-1})**	**Ni (Mg kg^{-1})**
FW	No-B	$2.81 \pm 0.17^{\mathrm{N.S}}$	$33.2 \pm 1.6^{\mathrm{N.S}}$	$17.4 \pm 1.4^{\mathrm{N.S}}$	$0.067 \pm 0.004^{\mathrm{N.S}}$	$0.076 \pm 0.001^{\mathrm{N.S}}$	$0.36 \pm 0.06^{\mathrm{N.S}}$	$0.045 \pm 0.004^{\mathrm{N.S}}$
	B	3.83 ± 0.51	39.9 ± 1.8	18.9 ± 0.8	0.089 ± 0.039	0.036 ± 0.005	0.10 ± 0.03	0.025 ± 0.006
	Mean	3.32 ± 0.33 B**	36.5 ± 1.8 B**	18.2 ± 0.9 B**	0.078 ± 0.018 B**	0.056 ± 0.009 B**	0.23 ± 0.07 B**	0.035 ± 0.005 B**
RWW	No-B	6.50 ± 0.20	72.2 ± 1.1	36.4 ± 2.0	0.421 ± 0.016	0.145 ± 0.008	0.86 ± 0.07	0.184 ± 0.007
	B	7.94 ± 0.13	80.5 ± 1.1	37.6 ± 0.9	0.448 ± 0.007	0.098 ± 0.008	0.57 ± 0.03	0.158 ± 0.008
	Mean	7.22 ± 0.34 A	76.4 ± 2.0 A	37.0 ± 1.1 A	0.435 ± 0.010 A	0.122 ± 0.011 A	0.72 ± 0.07 A	0.171 ± 0.008 A
Mean	No-B	4.66 ± 0.83 B**	52.7 ± 8.8 B**	$26.9 \pm 4.4^{\mathrm{N.S}}$	$0.244 \pm 0.080^{\mathrm{N.S}}$	0.110 ± 0.016 A**	0.61 ± 0.12 A**	0.115 ± 0.031 A**
	B	5.88 ± 0.95 A	60.2 ± 9.1 A	28.3 ± 4.2	0.268 ± 0.082	0.067 ± 0.015 B	0.33 ± 0.11 B	0.092 ± 0.030 B

FW, fresh water; RWW, recycled wastewater; No-B, no biochar; B, biochar; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

transpiration, the crop absorbs water from the soil with together macro- and microelements and heavy metals present in the soil. Thus, the presence of more macro- and microelements and heavy metals in the soil enables the crop to absorb more elements and metals from the soil. In addition, the fact that maize is an accumulator crop may have caused it to take in more heavy metals from the soil and accumulate them in its body. Similar to the findings of this study, Cakmakci & Sahin (2019b) also stated that the macro- and microelements and heavy metal contents of silage maize irrigated with recycled wastewater increased. Demir & Sahin (2017) also confirmed a similar statement and evaluated this increase as being related to the transition of recycled wastewater to the soil and therefore to the crop, depending on its chemical content.

The N, P, K, Ca, Mg, Fe, Cu, and Mn contents of silage maize increased in the biochar treatment compared with conditions without biochar but the Na, Cd, Cr, and Ni contents decreased, while the Zn and Pb contents were similar between the biochar and no biochar treatments. The increase in macro- and microelements and heavy metal contents of silage maize in the biochar treatment can be evaluated by the accumulation of biochar in the soil (Table 7) parallel to the crop, depending on its content (Table 2), similar to irrigation with recycled wastewater. Despite the accumulation of Na, Cd, Cr, and Ni in the soil in the biochar treatment (Table 7), it is thought that the decrease in Na, Cd, Cr, and Ni contents of silage maize compared with conditions without biochar is due to the exclusionary effect of biochar. Atkinson *et al.* (2010) reported that the elemental and metallic concentrations of various soil conditioners applied to the soil, depending on their contents, can be directly absorbed by crops. However, Fellet *et al.* (2014) pointed out that the surface capacity of biochar limits the uptake of some elements and heavy metals from the soil by crops. Park *et al.* (2016) explained this limiting effect of biochar with the absorption capacity of biochar. The limiting absorption capacity effect of biochar, which has a high buffering capacity, on the use of some heavy metals by crops was also emphasized by a different study (Nzediegwu *et al.* 2019). In addition, differences in the crop's uptake of elements and metals from the soil can be mentioned as a result of the competition of some elements and metals and their interactions with organic matter, clay, Fe, and Al_2O_3. There is strong competition between Na and K. Increasing K in the soil reduces the possibility of Na accumulation in crop organs (Grattan & Grieve 1998). This situation is also valid for Cd, Cr, and Ni. Increased Fe in the soil limits the crop's uptake of Cd and Cr (Kobaissi *et al.* 2014). In addition to its high chelation properties, Ni replaces heavy metals found in enzymes and physiologically active centers in crops (Daghan *et al.* 2013). In addition, as a result of this study, the heavy metal content of silage maize in all treatments, except Cd (0.05 Mg kg^{-1}), did not exceed the limit values determined by FAO/WHO (425.5, 40, 500, 60, 0.1, 2.3, and 67.9 Mg kg^{-1} for Fe, Cu, Mn, Zn, Pb, Cr, and Ni, respectively).

3.7. Physical properties and acid–neutral detergent fiber contents of silage maize

While the effects of irrigation treatments on crop height, stem diameter, fresh biomass yield, dry biomass yield, ADF, and NDF values were found to be statistically significant, the effects of biochar treatments on crop height, fresh biomass yield, dry biomass yield, and ADF values, except stem diameter and NDF, were found to be statistically significant (Table 5 and Supplementary material 3).

The crop height and stem diameter contents increased in irrigation with recycled wastewater compared with irrigation with fresh water. This can be explained by the nutritional effect of recycled wastewater on the soil (Tables 4 and 7) and therefore on the crop due to its nutrient-rich content (Table 3). Similarly, the crop height content increased in the biochar treatment compared with the conditions without biochar can be evaluated as related to biochar supporting the development of the crop depending on the nutrient content (Table 2). In particular, increasing N in the soil is an important nutrient element that supports the increase in crop height and stem diameter of silage maize (Yerli *et al.* 2023). In this study, the positive correlation relationships of crop height and stem diameter with total N also support this situation (Supplementary material 4). Similar correlation relationships were found by Kale *et al.* (2018), and the researchers emphasized that the physical development of maize increased with increasing N in soil. Cakmakci & Sahin (2021b) and Khan *et al.* (2022) also reported an increase in the crop height and/or stem diameter of silage maize under irrigation with recycled wastewater and biochar treatment, respectively, depending on their nutrient-enhancing effects on the soil.

The fresh–dry biomass yields increased by 13.1 and 7.2% to 17.3 and 9.5%, respectively, in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. The increase in dry biomass yield was parallel to the fresh biomass yield and a positive correlation relationship was determined between dry biomass yield and fresh biomass yield (Supplementary material 4). Cakmakci & Sahin (2021b) drew attention to a similar relationship and stated that the changes in dry biomass yield of silage maize were directly related to fresh biomass yield. The yield increases can be explained by the fertilization effect of recycled wastewater and biochar due to the high nutrient content (Tables 2 and 3). Increasing the macro- and micronutrient contents of the soil under irrigation with recycled wastewater and biochar treatment (Tables 4 and 7) provides better crop growth. In particular, N is an important element that improves the yield characteristics of crops. N is involved in physical, chemical, and physiological regulations for the crop to provide higher productivity (Daghan *et al.* 2013). In this study, the positive correlation relationships of fresh and dry biomass yields with the total N and the N content of the crop also support this situation (Supplementary material 4). In addition, increased crop height and/or stem diameter in irrigation with recycled wastewater and biochar treatment (Table 5) are important factors that support the increase in fresh and dry biomass yields. In this study, the positive correlation relationships of fresh and dry biomass yields with crop height and stem diameter also support this situation (Supplementary material 4). In addition, chlorophyll is a good indicator of crop productivity and development. Increasing chlorophyll increases crop growth and biomass by increasing photosynthetically active radiation and radiation use efficiency (Gomaa *et al.* 2021). Physiological properties such as the area and relative water content of the leaf and electrolyte leakage are also helpful parameters in interpreting the biomass yield of the crop (Yerli *et al.* 2023). Changes in these parameters directly affect the biomass yield of the crop. In this study, the positive correlation relationships of fresh and dry biomass yields with chlorophyll, leaf area index, and LRWC also support this situation (Supplementary material 4). Similar correlation relationships were determined by Camoglu *et al.* (2011), and the researchers pointed out the relationship between the yield and physiological characteristics of maize. Additionally, similar to the findings of this study, many studies also stated that yield increases occur in irrigation with recycled wastewater (Demir & Sahin 2017; Nzediegwu *et al.* 2019; Cakmakci & Sahin 2021b; Mumivand *et al.* 2023) and biochar treatment (Lashari *et al.* 2013; Alburquerque *et al.* 2014; Aon *et al.* 2023; Cakmakci & Sahin 2023). In addition to all these, the spongy and porous structure of biochar preserves soil moisture for a longer period of time, thus protecting it from stress, and the increase in the availability of nutrients by crops by preserving moisture in the soil can be considered a different explanation for the increased fresh and dry biomass yields of the silage maize under biochar treatment. Yildirim *et al.* (2021) stated that crops growing in soil-applied biochar showed an increase in productivity as a result of their being able to access soil moisture more easily. Cakmakci & Sahin (2023) also stated a similar situation and pointed out that the soil moisture protective effect of biochar increases crop yield.

The ADF and NDF contents decreased in irrigation with recycled wastewater compared with irrigation with fresh water. This can be explained by the N content of silage maize (Table 8). Similarly, the NDF content decreased in the biochar treatment compared with the conditions without biochar, which can be evaluated in relation to the N content of silage maize (Table 8). The increase in the N content of the crop reduces ADF and NDF values. Similarly, Kale *et al.* (2018) also reported that increasing N decreased the ADF and NDF contents in silage maize. In this study, the negative correlation relationships of ADF and NDF with the N content of the crop also support this situation (Supplementary material 4). Increasing N reduces the ADF and NDF values of the crop, which has a longer maturation period, allowing the crop to remain physiologically active for a longer period of time (Safdarian *et al.* 2014). Thus, the relationship of the change in physical properties of the crop related to yield with ADF and NDF depending on the maturation period can be mentioned and it can be said that the increased development of silage maize (Table 5) reduces the ADF and NDF values. In this study, the negative correlation relationships of ADF and NDF with crop height and stem diameter also support this situation (Supplementary material 4). Similarly, Mut & Kose (2018) also mentioned the negative correlation relationships of ADF and NDF with the physical properties of the triticale crop. In addition, ADF and NDF, which represent cellulose, hemicellulose, lignin, fibrous carbohydrates, protein, and silicon in feed quality, provide an idea about the energy intake and digestibility of feed. Therefore, high values of ADF and NDF cause a decrease in the quality and digestibility of feed and insufficient energy intake (Khatiwada *et al.* 2021). As a result of this study, the ADF and NDF contents of silage maize irrigated with recycled wastewater and biochar treatment complied with the limit values (<25 and <46% for ADF and NDF) determined by the National Research Council of the National Academies, while the ADF and NDF contents in the control treatments were above these limit values.

3.8. Physiological properties of silage maize

While the effects of irrigation treatments on chlorophyll, leaf area index, and electrolyte leakage values, except LRWC, were found to be statistically significant, the effects of biochar treatments on chlorophyll, leaf area index, LRWC, and electrolyte leakage values were found to be statistically significant (Table 9 and Supplementary material 3).

The chlorophyll content increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained with N and Fe contents of the recycled wastewater and biochar (Tables 2 and 3). Total N and Fe provided by recycled wastewater and biochar to the soil (Tables 4

Table 9 | Physiological properties of the silage maize in irrigation and biochar treatments

Treatments		Chlorophyll (SPAD)	Leaf area index	LRWC (%)	Electrolyte leakage
FW	No-B	$48.1 \pm 0.3^{N.S}$	$5.14 \pm 0.05^{N.S}$	$86.0 \pm 0.5^{N.S}$	$14.6 \pm 0.3^{N.S}$
	B	50.1 ± 0.6	5.28 ± 0.04	88.4 ± 0.3	13.7 ± 0.2
	Mean	49.1 ± 0.5 B**	5.21 ± 0.04 B**	$87.2 \pm 0.6^{N.S}$	14.2 ± 0.3 B**
RWW	No-B	51.0 ± 0.3	5.35 ± 0.06	86.2 ± 0.7	16.3 ± 0.4
	B	52.9 ± 0.7	5.56 ± 0.03	88.3 ± 0.9	15.5 ± 0.4
	Mean	51.9 ± 0.5 A	5.45 ± 0.05 A	87.3 ± 0.7	15.9 ± 0.3 A
Mean	No-B	49.6 ± 0.7 B**	5.24 ± 0.06 B**	86.1 ± 0.4 B**	14.6 ± 0.4 B*
	B	51.5 ± 0.7 A	5.42 ± 0.07 A	88.4 ± 0.4 A	15.5 ± 0.4 A

FW, fresh water; RWW, recycled wastewater; No-B, no biochar; B, biochar; LRWC, leaf relative water content; ±, standard error of the mean. ** $p < 0.01$, * $p < 0.05$, N.S, not significant.

and 7) provide better chloroplast development. N and Fe, as the building blocks of chlorophyll, take part in chloroplast and protein formation processes. In particular, N is very effective in the chlorophyll development process of maize, which is a C4 crop. Maize metabolizes N in the soil and uses it during the chlorophyll development stage (Yerli *et al.* 2023). In this study, the positive correlation relationships of chlorophyll with the total N and the Fe content of soil also support this situation (Supplementary material 4). In addition, the chlorophyll content of the crops growing in soil containing sufficient levels of macro- and micronutrients increases (Bolat & Kara 2017).

Thus, the chlorophyll-enhancing effect of the macro- and micronutrients provided by recycled wastewater and biochar to the soil (Tables 4 and 7) can be mentioned. Additionally, similar to the findings of this study, Khalilzadeh *et al.* (2020) also explained that the increase in chlorophyll in irrigation with recycled wastewater since recycled wastewater increases the biosynthesis rate of chlorophyll, while Cakmakci & Sahin (2023) also pointed out that the nutrient and water retaining effect of biochar in the soil provides better chloroplast development.

The leaf area index content increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the total N that recycled wastewater and biochar provide to the soil (Table 4), depending on their N content (Tables 2 and 3). The increased N in the leaves by the uptake of N from the soil increases the leaf area of the crop (Amanullah *et al.* 2007). In this study, the positive correlation relationships of the leaf area index with the total N and the N content of the crop also support this situation (Supplementary material 4). Additionally, similar to the findings of this study, Yerli *et al.* (2023) and Yildirim *et al.* (2021) also reported that the N-providing effect of irrigation with recycled wastewater and biochar treatment to the soil and crop increased the leaf area index.

The similarity of LRWC in irrigation treatments can be explained by equal irrigation water amounts and similar real evapotranspiration values (Figure 2), while the increase in LRWC in biochar treatment compared with conditions without biochar can be evaluated by the effect of biochar on providing organic matter to the soil, in addition to preserving soil moisture with the specific surface area of biochar. Increased moisture retention in the soil causes an increase in LRWC and provides crops with easier access to both nutrients and soil moisture (Cakmakci & Sahin 2021a). Organic matter contribution also helps preserve moisture for a longer period of time and thus helps crops access soil moisture more easily (Yerli *et al.* 2023). Yildirim *et al.* (2021) also reported that LRWC increased in biochar treatment as a result of the protective effect of biochar on soil moisture.

The electrolyte leakage content increased in irrigation with recycled wastewater compared with irrigation with fresh water and in biochar treatment compared with conditions without biochar. This can be explained by the fact that recycled wastewater and biochar increase soil salinity (Table 4) depending on their EC content (Tables 2 and 3). Increased EC in the soil causes damage to the membrane systems as a result of damage to the mesophyll cells in the leaves, thus increasing electrolyte leakage (Marcinska *et al.* 2013). In this study, the positive correlation relationship of electrolyte leakage with EC also supports this situation (Supplementary material 4). In addition, increasing EC restricts the water intake and the water content of the crop, which cannot provide sufficient water, decreases and its stomata close (Yildirim *et al.* 2021). The stress experienced by the crop due to increased leaf temperature when the stomata are closed results in an increase in electrolyte conductivity as a result of damage to the cellular membrane systems (Ozturk 2015). Cakmakci & Sahin (2021a) also reported that irrigation with recycled wastewater increased the electrolyte leakage of silage maize, while Mehmood *et al.* (2020) also stated that electrolyte leakage may increase with increasing soil EC depending on the salt concentration of biochar.

4. CONCLUSIONS

The study showed that biochar reduced the actual evapotranspiration by saving irrigation water and that the increase in the yield of silage maize with the contribution of recycled wastewater and biochar caused higher $WP_{irrigation}$ and WP in irrigation with recycled wastewater and biochar treatment. While irrigation with recycled wastewater and biochar treatment supported the improvement of the physical and chemical properties of the silage maize field soil, it caused a decrease in bulk density, pH, and $CaCO_3$ and an increase in soil salinity. Improved soil properties increased the physical and physiological properties and biomass yield of silage maize and improved the ADF and NDF contents of silage maize, but irrigation with recycled wastewater and biochar treatment caused higher macro- and microelement contents and heavy metal contamination in the soil compared with irrigation with fresh water and conditions without biochar. Thus, increases were observed in the macro- and microelements and heavy metal contents of the crop grown in the soil irrigated with recycled wastewater and applied biochar, but the absorption and buffering capacity of the biochar limited the Na, Cd, Cr, and Ni uptake of silage maize. However, as a result, the heavy metal contents of the soil and crop did not exceed international standards in all treatments except the Cd content of silage maize.

The findings obtained within the scope of this study showed that the use of biochar in irrigation with recycled wastewater can be recommended, taking into account the productivity-increasing contribution and the effectiveness of biochar in reducing the possible heavy metal risks of wastewater in silage maize cultivation irrigated with recycled wastewater. However, considering that the Cd content of silage maize exceeds international standards and the increase in soil salinity in irrigation with recycled wastewater and biochar treatment, monitoring the Cd contamination in the crop and the salt content in the soil, as well as examining the effects of biochars with different raw material contents under irrigation conditions with recycled wastewater are among recommendable results of this study.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The author declares there is no conflict.

REFERENCES

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M. & Wessolek, G. 2013 Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* **202**, 183–191. https://doi.org/10.1016/j.geoderma.2013.03.003.

Acosta, J. A., Jansen, B., Kalbitz, K., Faz, A. & Martínez-Martínez, S. 2011 Salinity increases mobility of heavy metals in soils. *Chemosphere* **85** (8), 1318–1324. https://doi.org/10.1016/j.chemosphere.2011.07.046.

Adeleke, R., Nwangburuka, C. & Oboirien, B. 2017 Origins, roles and fate of organic acids in soils: A review. *South African Journal of Botany* **108**, 393–406. https://doi.org/10.1016/j.sajb.2016.09.002.

Ahmed, R., Li, Y., Mao, L., Xu, C., Lin, W., Ahmed, S. & Ahmed, W. 2019 Biochar effects on mineral nitrogen leaching, moisture content, and evapotranspiration after 15N urea fertilization for vegetable crop. *Agronomy* **9** (6), 331. https://doi.org/10.3390/agronomy9060331.

Alburquerque, J. A., Calero, J. M., Barrón, V., Torrent, J., del Campillo, M. C., Gallardo, A. & Villar, R. 2014 Effects of biochars produced from different feedstocks on soil properties and sunflower growth. *Journal of Plant Nutrition and Soil Science* **177** (1), 16–25. https://doi.org/10.1002/jpln.201200652.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper No: 56.

Amanullah, M. J. H., Nawab, K. & Ali, A. 2007 Response of specific leaf area (SLA), leaf area index (LAI) and leaf area ratio (LAR) of maize (*Zea mays* L.) to plant density, rate and timing of nitrogen application. *World Applied Sciences Journal* **2** (3), 235–243.

Angin, I., Yaganoglu, A. V. & Turan, M. 2005 Effects of long-term wastewater irrigation on soil properties. *Journal of Sustainable Agriculture* **26** (3), 31–42. https://doi.org/10.1300/J064v26n03_05.

Anonymous 2007 *Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils*. Available from: https:/www.epa.gov/sites/production/files2015-12/documents/3051a.pdf (accessed 5 May 2018).

Aon, M., Aslam, Z., Hussain, S., Bashir, M. A., Shaaban, M., Masood, S., lqbal, S., Khalid, M., Rehim, A., Mosa, W. F. A., Sas-Paszt, L., Marey, S. A. & Hatamleh, A. A. 2023 Wheat straw biochar produced at a low temperature enhanced maize growth and yield by influencing soil properties of typic calciargid. *Sustainability* **15** (12), 9488. https://doi.org/10.3390/su15129488.

APHA 1995 *Standard Methods for Examination of Water and Wastewater*. Available from: https://www.mwa.co.th/download/file_upload/SMWW_1000-3000.pdf (accessed 17 October 2018).

APHA-AWWA-WPCF 1989 *Standart Methods for Examination of Water and Wastewater*. Available from: https://www.techstreet.com/standards/standard-methods-for-the-examination-of-water-and-wastewater-23rdedition?gclid=EAIaIQobChMI8cO8p8K24AIVFojVCh3qvwxIEAAYASAAEgLc_vD_BwE&sid=goog&product_id=1974889 (accessed 19 September 2018).

Aslam, Z., Khalid, M. & Aon, M. 2014 Impact of biochar on soil physical properties. *Journal of Agricultural Science* **4** (5), 280–284.

Atkinson, C. J., Fitzgerald, J. D. & Hipps, N. A. 2010 Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant and Soil* **337**, 1–18. https://doi.org/10.1007/s11104-010-0464-5.

Ayers, R. S. & Westcot, D. W. 1994 *Water Quality for Agriculture. Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper No: 29.

Baiamonte, G., Minacapilli, M. & Crescimanno, G. 2020 Effects of biochar on irrigation management and water use efficiency for three different crops in a desert sandy soil. *Sustainability* **12** (18), 7678. https://doi.org/10.3390/su12187678.

Banik, C., Lawrinenko, M., Bakshi, S. & Laird, D. A. 2018 Impact of pyrolysis temperature and feedstock on surface charge and functional group chemistry of biochars. *Journal of Environmental Quality* **47** (3), 452–461. https://doi.org/10.2134/jeq2017.11.0432.

Bartkowiak, A., Dabkowska-Naskret, H., Jaworska, H. & Rydlewska, M. 2020 Effect of salinity on the mobility of trace metals in soils near a soda chemical factory. *Journal of Elementology* **25**, 2. https://doi.org/10.5601/jelem.2019.24.2.1875.

Batista, E. M., Shultz, J., Matos, T. T., Fornari, M. R., Ferreira, T. M., Szpoganicz, B., de Freitas, R. A. & Mangrich, A. S. 2018 Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. *Scientific Reports* **8** (1), 10677. https://doi.org/10.1038/s41598-018-28794-z.

Blake, G. R., Hartge, K. H., 1986a Methods of soil analysis. In: *Bulk Density* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 363–375.

Blake, G. R., Hartge, K. H., 1986b Methods of soil analysis. In: *Particle Density* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 377–382.

Bolan, N., Kunhikrishnan, A., Thangarajan, R., Kumpiene, J., Park, J., Makino, T., Kirkham, M. B. & Scheckel, K. 2014 Remediation of heavy metal(loid)s contaminated soils to mobilize or to immobilize? *Journal of Hazardous Materials* **266**, 141–166. https://doi.org/10.1016/j.jhazmat.2013.12.018.

Bolat, I. & Kara, O. 2017 Plant nutrients: Sources, functions, deficiencies and redundancy. *Journal of Bartin Faculty of Forestry* **19** (1), 218–228. https://doi.org/10.24011/barofd.251313.

Bremner, J. M., Mulvaney, C. S., 1982 Methods of soil analysis. In: *Nitrogen Total* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 595–624.

Cakmakci, T. & Sahin, U. 2019a Evaluation of treated wastewater quality in terms of irrigation water within the framework of related legislation: The case of Van province. *Mustafa Kemal University Journal of Agricultural Sciences* **24** (Special issue), 249–256.

Cakmakci, T. & Sahin, U. 2019b The effect of using treated wastewater with different irrigation methods on silage maize macro-micro element and heavy metal accumulation. *Journal of Tekirdag Agricultural Faculty* **17** (1), 12–23. https://doi.org/10.33462/jotaf.589446.

Cakmakci, T. & Sahin, U. 2021a Productivity and heavy metal pollution management in a silage maize field with reduced recycled wastewater applications with different irrigation methods. *Journal of Environmental Management* **291**, 112602. https://doi.org/10.1016/j.jenvman.2021.112602.

Cakmakci, T. & Sahin, U. 2021b Improving silage maize productivity using recycled wastewater under different irrigation methods. *Agricultural Water Management* **255**, 107051. https://doi.org/10.1016/j.agwat.2021.107051.

Cakmakci, T. & Sahin, U. 2023 Yield, physiological responses and irrigation water productivity of capia pepper at deficit irrigation and different biochar levels. *Gesunde Pflanzen* **75** (2), 317–327. https://doi.org/10.1007/s10343-022-00703-5.

Camoglu, G., Genc, L. & Asik, S. 2011 The effects of water stress on physiological and morphological parameters of sweet corn. *Journal of Agriculture Faculty of Ege University* **48** (2), 141–149.

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M. & Maity, S. 2013 Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. *International Journal of Scientific and Research Publications* **3** (2), 1–8.

Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D. & Julson, J. L. 2014 Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science* **60** (3), 393–404. https://doi.org/10.1080/03650340.2013.789870.

CWCG 2017 *Crop Water Consumption Guide for Irrigated Crops in Türkiye*. Available from: https://www.tarimorman.gov.tr/TAGEM/Belgeler/yayin/Tu%CC%88-rkiyede%20Sulanan%20Bitkilerin%20Bitki%20Su%20Tu%CC% 88ketimleri.pdf (accessed 1 June 2020).

Daghan, H., Uygur, V., Koleli, N., Arslan, M. & Eren, A. 2013 The effect of heavy metal treatments on uptake of nitrogen, phosphorus and potassium in transgenic and non-transgenic tobacco plants. *Journal of Agricultural Sciences* **19** (2), 129–139. https://doi.org/10.1501/Tarimbil_0000001237.

Dahlawi, S., Naeem, A., Rengel, Z. & Naidu, R. 2018 Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Science of the Total Environment* **625**, 320–335. https://doi.org/10.1016/j.scitotenv.2017.12.257.

Danielson, R. E., Sutherland, P. L., 1986 Methods of soil analysis. In: *Porosity* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 443–461.

Demir, A. D. & Sahin, U. 2017 Effects of different irrigation practices using treated wastewater on tomato yields, quality, water productivity, and soil and fruit mineral contents. *Environmental Science and Pollution Research* **24**, 24856–24879. https://doi.org/10.1007/s11356-017-0139-3.

Demir, A. D. & Sahin, U. 2019 Changes in physical and hydraulic properties of a clay soil due to the irrigation of tomatoes with recycled wastewater. *Eurasian Journal of Forest Science* **7** (3), 252–268. https://doi.org/10.31195/ejejfs.585595.

Demir, A. D. & Sahin, U. 2020 Effects of recycled wastewater applications with different irrigation practices on the chemical properties of a vertisol. *Environmental Engineering Science* **37** (2), 132–141. https://doi.org/10.1089/ees.2019.0156.

El-Sayed, M. M., Mahdy, A. Y., Gebreel, M. & Abdeen, S. A. 2023 Effectiveness of biochar, organic matter and mycorrhiza to improve soil hydrophysical properties and water relations of soybean under arid soil conditions. *Eurasian Soil Science* **56**, 1055–1066. https://doi.org/10.1134/S1064229323600276.

EPA 2004 *Guidelines for Water Reuse*. United States Environmental Protection Agency, Washington, USA.

Farhadkhani, M., Nikaeen, M., Yadegarfar, G., Hatamzadeh, M., Pourmohammadbagher, H., Sahbaei, Z. & Rahmani, H. R. 2018 Effects of irrigation with secondary treated wastewater on physicochemical and microbial properties of soil and produce safety. *Water Research* **144**, 356–364. https://doi.org/10.1016/j.watres.2018.07.047.

Fellet, G., Marmiroli, M. & Marchiol, L. 2014 Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. *Science of the Total Environment* **468**, 598–608. https://doi.org/10.1016/j.scitotenv.2013.08.072.

Ghanem, K. Z., Hasham, M. M., El-Sheshtawy, A. N. A., El-Serafy, R. S. & Sheta, M. H. 2022 Biochar stimulated actual evapotranspiration and wheat productivity under water deficit conditions in sandy soil based on non-weighing lysimeter. *Plants* **11** (23), 3346. https://doi.org/10.3390/plants11233346.

Gomaa, M. A., Kandil, E. E., El-Dein, A. A. M. Z., Abou-Donia, M. E. M., Ali, H. M. & Abdelsalam, N. R. 2021 Increase maize productivity and water use efficiency through application of potassium silicate under water stress. *Science Reports* **11**, 224. https://doi.org/10.1038/s41598-020-80656-9.

Gould, C. M. 2015 *Compost Increases Water Holding Capacity of Droughty Soils*. Available from: https://www.manuremanager.com/compost-increases-water-holding-capacity-of-droughty-soils-18241/ (accessed 26 October 2023).

Grattan, S. R. & Grieve, C. M. 1998 Salinity-mineral nutrient relations in horticultural crops. *Scientia Horticulturae* **78** (1–4), 127–157. https://doi.org/10.1016/S0304-4238(98)00192-7.

HACH 2005 *DR 5000 Spectrometer Procedures Manual*. Searchdownloadsearch.jsa?keywords = kullanC4B1 (accessed 17 October 2018).

HACH 2010 *Hach Bodtrak II*. Available from: http://tr.hach.com/bod-trak-ii-aksesuarlar-ile-birlikte-respirometrikboi-aparat/productdownloadsd (accessed 17 October 2018).

Heikkinen, J., Keskinen, R., Soinne, H., Hyväluoma, J., Nikama, J., Wikberg, H., Källi, V., Siipola, V., Melkior, T., Dupont, C., Campargue, M., Larsson, S. H., Hannula, M. & Rasa, K. 2019 Possibilities to improve soil aggregate stability using biochars derived from various biomasses through slow pyrolysis, hydrothermal carbonization, or torrefaction. *Geoderma* **344**, 40–49. https://doi.org/10.1016/j.geoderma.2019.02.028.

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S. & Bolan, N. 2020 Biochar and its importance on nutrient dynamics in soil and plant. *Biochar* **2**, 379–420. https://doi.org/10.1007/s42773-020-00065-z.

Hua, L., Lu, Z., Ma, H. & Jin, S. 2014 Effect of biochar on carbon dioxide release, organic carbon accumulation, and aggregation of soil. *Environmental Progress & Sustainable Energy* **33** (3), 941–946. https://doi.org/10.1002/ep.11867.

Jaramillo, M. F. & Restrepo, I. 2017 Wastewater reuse in agriculture: A review about its limitations and benefits. *Sustainability* **9** (10), 1734. https://doi.org/10.3390/su9101734.

Kacar, B. 1995 *Chemical Analysis of Crop and Soil*. Ankara University Faculty of Agriculture Publications, Ankara, Türkiye.

Kacar, B. 2014 *Plant, Soil and Fertilizer Analysis-2*. Nobel Publications, Ankara, Türkiye.

Kale, H., Kaplan, M., Ulger, I., Unlukara, A. & Akar, T. 2018 Feed value of maize (*Zea mays* var. *indentata* (Sturtev. L. H. Bailey) grain under different irrigation levels and nitrogen doses. *Turkish Journal of Field Crops* **23** (1), 56–61. https://doi.org/10.17557/tjfc.421974.

Kanber, R. & Unlu, M. 2010 *Water and Soil Salinity in Agriculture*. Cukurova University Faculty of Agriculture Publications, Adana, Türkiye.

Karimi, A., Moezzi, A., Chorom, M. & Enayatizamir, N. 2020 Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *Journal of Soil Science and Plant Nutrition* **20**, 450–459. https://doi.org/10.1007/s42729-019-00129-5.

Kemper, W. D., Rosenau, R. C., 1986 Methods of soil analysis. In: *Aggregate Stability and Size Distribution* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 425–442.

Khalilzadeh, R., Pirzad, A., Sepehr, E., Khan, S. & Anwar, S. 2020 Long-term effect of heavy metal–polluted wastewater irrigation on physiological and ecological parameters of *Salicornia europaea* L. *Journal of Soil Science and Plant Nutrition* **20**, 1574–1587. https://doi.org/10.1007/s42729-020-00299-7.

Khan, I., Iqbal, B., Khan, A. A., Inamullah, R., Fayyaz, A., Shakoor, A., Farooq, A., & Wang, T. H. & X, L. 2022 The interactive impact of straw mulch and biochar application positively enhanced the growth indexes of maize (*Zea mays* L. crop). *Agronomy* **12** (10), 2584. https://doi.org/10.3390/agronomy12102584.

Khatiwada, B., Acharya, S. N., Larney, F. J., Lupwayi, N. Z., Smith, E. G., Islam, M. A., Thomas, J. E. & Poudel, H. P. 2021 Pasture rejuvenation using sainfoin and cicer milkvetch. *Agronomy Journal* **113** (1), 26–41. https://doi.org/10.1002/agj2.20466.

Kizilkaya, R., Askin, T., Bayraklı, B. & Saglam, M. 2004 Microbiological characteristics of soils contaminated with heavy metals. *European Journal of Soil Biology* **40** (2), 95–102. https://doi.org/10.1016/j.ejsobi.2004.10.002.

Klute, A., 1986 Methods of soil analysis. In: *Water Retention* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 225–246.

Knudsen, D., Peterson, G. A., Pratt, P. F., 1982 Methods of soil analysis. In: *Lithium, Sodium, and Potassium* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 225–246.

Kobaissi, A. N., Kanso, A. A. & Kanbar, H. J. 2014 Translocatıon of heavy metals in *Zea mays* L. treated with wastewater and consequences on morphophysiological aspects. *Revista Internacional de Contaminación Ambiental* **30** (2), 297–305.

Lahlou, F. Z., Mackey, H. R. & Al-Ansari, T. 2021 Wastewater reuse for livestock feed irrigation as a sustainable practice: A socio-environmental-economic review. *Journal of Cleaner Production* **294**, 126331. https://doi.org/10.1016/j.jclepro.2021.126331.

Lashari, M. S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., Zheng, J., Zheng, J., Zhang, X. & Yu, X. 2013 Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. *Field Crops Research* **144**, 113–118. https://doi.org/10.1016/j.fcr.2012.11.015.

Leogrande, R. & Vitti, C. 2019 Use of organic amendments to reclaim saline and sodic soils: A review. *Arid Land Research and Management* **33** (1), 1–21. https://doi.org/10.1080/15324982.2018.1498038.

Lu, X., Mao, Q., Mo, J., Gilliam, F. S., Zhou, G., Luo, Y., Zhang, W. & Huang, J. 2015 Divergent responses of soil buffering capacity to long-term N deposition in three typical tropical forests with different land-use history. *Environmental Science & Technology* **49** (7), 4072–4080. https://doi.org/10.1021/es5047233.

Lucchini, P., Quilliam, R. S., DeLuca, T. H., Vamerali, T. & Jones, D. L. 2014 Does biochar application alter heavy metal dynamics in agricultural soil? *Agriculture, Ecosystems & Environment* **184**, 149–157. https://doi.org/10.1016/j.agee.2013.11.018.

Marcinska, I., Czyczylo-Mysza, I., Skrzypek, E., Filek, M., Grzesiak, S., Grzesiak, M. T., Janowiak, F., Hura, T., Dziurka, M., Dziurka, K., Nowakowska, A. & Quarrie, S. A. 2013 Impact of osmotic stress on physiological and biochemical characteristics in drought-susceptible and drought-resistant wheat genotypes. *Acta Physiologiae Plantarum* **35**, 451–461. https://doi.org/10.1007/s11738-012-1088-6.

Maroušek, J., Stehel, V., Vochozka, M., Kolář, L., Maroušková, A., Strunecký, O., Peterka, J., Kopecký, M. & Shreedhar, S. 2019 Ferrous sludge from water clarification: Changes in waste management practices advisable. *Journal of Cleaner Production* **218**, 459–464. https://doi.org/10.1016/j.jclepro.2019.02.037.

Mazen, A., Faheed, F. A. & Ahmed, A. F. 2010 Study of potential impacts of using sewage sludge in the amendment of desert reclaimed soil on wheat and jews mallow plants. *Brazilian Archives of Biology and Technology* **53**, 917–930. https://doi.org/10.1590/S1516-89132010000400022.

McBride, M. B., Richards, B. K., Steenhuis, T., Russo, J. J. & Sauvé, S. 1997 Mobility and solubility of toxic metals and nutrients in soil fifteen years after sludge application. *Soil Science* **162** (7), 487–500.

Mehmood, S., Ahmed, W., Ikram, M., Imtiaz, M., Mahmood, S., Tu, S. & Chen, D. 2020 Chitosan modified biochar increases soybean (*Glycine max* L.) *resistance to salt-stress by augmenting root morphology, antioxidant defense mechanisms and the expression of stress-responsive genes*. *Plants* **9** (9), 1173. https://doi.org/10.3390/plants9091173.

Minasny, B. & McBratney, A. B. 2018 Limited effect of organic matter on soil available water capacity. *Eurasian Journal of Soil Science* **69** (1), 39–47. https://doi.org/10.1111/ejss.12475.

Mumivand, H., Izadi, Z., Amirizadeh, F., Maggi, F. & Morshedloo, M. R. 2023 Biochar amendment improves growth and the essential oil quality and quantity of peppermint (*Mentha* × *piperita* L.) grown under waste water and reduces environmental contamination from waste water disposal. *Journal of Hazardous Materials* **446**, 130674. https://doi.org/10.1016/j.jhazmat.2022.130674.

Mumme, J., Getz, J., Prasad, M., Lüder, U., Kern, J., Mašek, O. & Buss, W. 2018 Toxicity screening of biochar-mineral composites using germination tests. *Chemosphere* **207**, 91–100. https://doi.org/10.1016/j.chemosphere.2018.05.042.

Mut, Z. & Kose, O. D. E. 2018 Grain yield and some quality properties of triticale genotypes. *Anadolu Journal of Agricultural Sciences* **33** (1), 47–57. https://doi.org/10.7161/omuanajas.336108.

Natasha, N., Shahid, M., Khalid, S., Murtaza, B., Anwar, H., Shah, A. H., Sardar, A., Shabbir, Z. & Niazi, N. K. 2020 A critical analysis of wastewater use in agriculture and associated health risks in Pakistan. *Environmental Geochemistry and Health* **45**, 5599–5618. https://doi.org/10.1007/s10653-020-00702-3.

Nelson, R. E., 1982 Methods of soil analysis. In: *Carbonate and Gypsum* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 181–197.

Nelson, D. W., Sommers, L. E., 1982 Methods of soil analysis. In: *Total Carbon, Organic Carbon, and Organic Matter* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 961–1010.

Nzediegwu, C., Prasher, S., Elsayed, E., Dhiman, J., Mawof, A. & Patel, R. 2019 Effect of biochar on the yield of potatoes cultivated under wastewater irrigation. *Journal of Soil Science and Plant Nutrition* **19**, 865–877. https://doi.org/10.1007/s42729-019-00085-0.

Olsen, S. R., Sommers, L. E., Page, A. L., 1982 Phosphorus. In: *Carbonate and Gypsum* (Page, A. L., Miller, M. H. & Keeney, D. R., eds.). American Society of Agronomy and Soil Science Society, Madison, WI, pp. 159–165.

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K. & Pan, G. 2016 Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* **274**, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029.

Ozturk, N. Z. 2015 Literature review and new approaches on plant drought stress response. *Turkish Journal Agriculture Food Science and Technology* **3** (5), 307–315.

Park, J. H., Lee, S. J., Lee, M. E. & Chung, J. W. 2016 Comparison of heavy metal immobilization in contaminated soils amended with peat moss and peat moss-derived biochar. *Environmental Science: Processes & Impacts* **18** (4), 514–520. https://doi.org/10.1039/C6EM00098C.

Qi, F., Dong, Z., Lamb, D., Naidu, R., Bolan, N. S., Ok, Y. S., Liu, C., Khan, N., Johir, M. A. H. & Semple, K. T. 2017 Effects of acidic and neutral biochars on properties and cadmium retention of soils. *Chemosphere* **180**, 564–573. https://doi.org/10.1016/j.chemosphere.2017.04.014.

Radini, S., González-Camejo, J., Andreola, C., Eusebi, A. L. & Fatone, F. 2023 Risk management and digitalisation to overcome barriers for safe reuse of urban wastewater for irrigation – A review based on European practice. *Journal of Water Process Engineering* **53**, 103690. https://doi.org/10.1016/j.jwpe.2023.103690.

Safdarian, M., Razmjoo, J. & Dehnavi, M. M. 2014 Effect of nitrogen sources and rates on yield and quality of silage corn. *Journal of Plant Nutrition* **37** (4), 611–617. https://doi.org/10.1080/01904167.2013.867986.

Singh, A. & Agrawal, M. 2012 Effects of waste water irrigation on physical and biochemical characteristics of soil and metal partitioning in *Beta vulgaris* L. *Agricultural Research* **1**, 379–391. https://doi.org/10.1007/s40003-012-0044-4.

Singh, A., Sharma, R. K., Agrawal, M. & Marshall, F. 2009 Effects of wastewater irrigation on physicochemical properties of soil and availability of heavy metals in soil and vegetables. *Communications in Soil Science and Plant Analysis* **40** (21–22), 3469–3490. https://doi.org/10.1080/00103620903327543.

Six, J., Paustian, K., Elliott, E. T. & Combrink, C. 2000 Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Science Society of America Journal* **64** (2), 681–689. https://doi.org/10.2136/sssaj2000.642681x.

Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A. M., Dallmeyer, I. & Garcia-Pérez, M. 2017 The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. *Science of the Total Environment* **574**, 139–147. https://doi.org/10.1016/j.scitotenv.2016.09.025.

Tang, J., Zhang, L., Zhang, J., Ren, L., Zhou, Y., Zheng, Y., Luo, L., Yang, Y., Huang, H. & Chen, A. 2020 Physicochemical features, metal availability and enzyme activity in heavy metal-polluted soil remediated by biochar and compost. *Science of the Total Environment* **701**, 134751. https://doi.org/10.1016/j.scitotenv.2019.134751.

Tuzuner, A. 1990 *Soil and water analysis laboratories handbook*. T. R. Ministry of Agriculture, Forestry and Rural Affairs. General Directorate of Rural Services, Ankara, Türkiye.

Van Soest, P. J. 1963 Use of detergents in the analysis of fibrous feeds 2. A rapid method for the determination of fiber and lignin. *Journal of the Association of Official Agricultural Chemists* **46**, 829–835. https://doi.org/10.1093/jaoac/46.5.829.

Verheijen, F. G., Zhuravel, A., Silva, F. C., Amaro, A., Ben-Hur, M. & Keizer, J. J. 2019 The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma* **347**, 194–202. https://doi.org/10.1016/j.geoderma.2019.03.044.

Wen, J., Dong, H. & Zeng, G. 2018 Application of zeolite in removing salinity/sodicity from wastewater: A review of mechanisms, challenges and opportunities. *Journal of Cleaner Production* **197**, 1435–1446. https://doi.org/10.1016/j.jclepro.2018.06.270.

WHO 2001 *Water Quality Guidelines, Standards and Health: Assessment of Risk and Risk Management for Water-Related Infectious Disease*. IWA Publishing, London, UK.

Yerli, C. 2023 The effects of biochar pyrolyzed at varying temperatures and different water types on the properties of lettuce and soil. *Water, Air, & Soil Pollution* **234** (8), 1–26. https://doi.org/10.1007/s11270-023-06582-4.

Yerli, C. & Sahin, U. 2022 Quality proficiency to crop, soil and irrigation system of recycled wastewater from the Van/Edremit wastewater treatment plant. *YYU Journal of Agricultural Sciences* **32** (3), 497–506. https://doi.org/10.29133/yyutbd.1139773.

Yerli, C., Sahin, U., Ors, S. & Kiziloglu, F. M. 2023 Improvement of water and crop productivity of silage maize by irrigation with different levels of recycled wastewater under conventional and zero tillage conditions. *Agricultural Water Management* **277**, 108100. https://doi.org/10.1016/j.agwat.2022.108100.

Yildirim, E., Ekinci, M. & Turan, M. 2021 Impact of biochar in mitigating the negative effect of drought stress on cabbage seedlings. *Journal of Soil Science and Plant Nutrition* **21** (3), 2297–2309. https://doi.org/10.1007/s42729-021-00522-z.

Yue, Y., Guo, W. N., Lin, Q. M., Li, G. T. & Zhao, X. R. 2016 Improving salt leaching in a simulated saline soil column by three biochars derived from rice straw (*Oryza sativa* L.), sunflower straw (*Helianthus annuus*), and cow manure. *Journal of Soil and Water Conservation* **71** (6), 467–475. https://doi.org/10.2489/jswc.71.6.467.

Zhang, R. H., Li, Z. G., Liu, X. D., Wang, B. C., Zhou, G. L., Huang, X. X., Lin, C. F., Wang, A. H. & Brooks, M. 2017 Immobilization and bioavailability of heavy metals in greenhouse soils amended with rice straw-derived biochar. *Ecological Engineering* **98**, 183–188. https://doi.org/10.1016/j.ecoleng.2016.10.057.

Zheng, W., Guo, M., Chow, T., Bennett, D. N. & Rajagopalan, N. 2010 Sorption properties of greenwaste biochar for two triazine pesticides. *Journal of Hazardous Materials* **181** (1–3), 121–126. https://doi.org/10.1016/j.jhazmat.2010.04.103.

Zhi-An, L., Bi, Z., Han-Ping, X., Yong-Zhen, D., Wan-Neng, T. & Sheng-Lei, F. 2008 Role of low-molecule-weight organic acids and their salts in regulating soil pH. *Pedosphere* **18** (2), 137–148. https://doi.org/10.1016/S1002-0160(08)60001-6.

Zhong, R., Chen, A., Zhao, D., Mao, G., Zhao, X., Huang, H. & Liu, J. 2023 Impact of international trade on water scarcity: An assessment by improving the Falkenmark indicator. *Journal of Cleaner Production* **385**, 135740. https://doi.org/10.1016/j.jclepro.2022.135740.

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