Biochar from food waste: a sustainable amendment to reduce water stress and improve the growth of chickpea plants

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Received: 21 November 2021 / Revised: 23 February 2022 / Accepted: 10 March 2022 © The Author(s) 2022

Abstract

The application of biochar in agriculture is a developing means to improve soil water retention, fertility, and crop yield. The present work focuses on biochar preparation from mixed vegetable and fruit wastes, using cauliflower, cabbage, banana peels, corn leaves, and corn cobs. The biochar produced at 400 °C was applied to the soil as an amendment to observe the qualitative changes of soil quality, plant growth, and water retention capacity of the soil based on screening in a previous study. Pot experiments were conducted at a laboratory scale having 0%, 2%, and 6% biochar mixed with sand. Each pot was sown with seeds of chickpeas (Cicer arietinum L.) and monitored over 60 days. Two biochar application rates improved soil quality by increasing soil porosity from 49.3 to ≥ 53.4%, more than doubling cation exchange capacity to ≥ 21.1 cmolc.kg⁻¹, providing a small reduction in bulk density of approximately 10% and decreasing electrical conductivity of the extract by at least 40% in comparison to control condition. The biochar application also increased key soil nutrients K, Mn, S, and P by a factor of 2–9 times. Application of biochar at 2% and 6% improved water retention from 55 to 77 and 91 mL respectively over the study and, more importantly, more than doubled the biomass yield for the same water application. The lower biochar application rate of 2% led to more germinated seeds (p = 0.0001), leaves (p = 0.0001), flowers, and fruiting chickpeas than the control condition. The 6% biochar application rate slightly improved plant height (p = 0.01) and provided a small reduction in water loss compared with the 2% biochar. Both biochar loadings increased the root and shoot biomass (p = 0.005) and nutrient content of the shoot and root biomass, particularly K, P, and S (p = 0.0001). This study demonstrates that biochar application at 2–6% is an effective means to increase chickpea yield and reduce water stress. Given small differences in performance within this application range, 2% application is recommended. The study establishes valorization of cellulose rich food waste in the form of biochar as a potential method for positive soil management and increased agricultural productivity in arid environments.

Keywords Soil fertility · Nutrient content · Water use efficiency · Chickpea growth · Rain-fed agriculture · Water-food nexus

1 Introduction

Food security is an ever-pressing issue due to increasing population, deteriorated soil quality, and increasing water stress around the world. According to the Food and Agriculture Organization (FAO) of the United Nations, approximately 1.3 billion tonnes of food is wasted every year [1], in which fruit and vegetable losses in industrialized countries account for more than 32% before selling. Scialabba et al. [2] reported that out of 950 Mt of vegetable production, 500 Mt of waste is generated worldwide. While supply chain management and waste minimization are critical to the sustainable food supply, it is also important to find alternative ways to process rejected products and leftovers from food
processing plants [3]. Biochar is an emerging product to increase soil fertility and plant growth in different agricultural soil types [4]. It has advantages over compost in that it provides long-term carbon sequestration and soil remediation, does not produce odor during production, its production can simultaneously produce energy, and it is easier to store and transport. Biochar produced from a feedstock containing lignocellulosic compounds has an expected half-life of 100 to 1000 years, which is approximately 10–1000 times greater than the lifetime of soil organic matter [5]. Thus, biochar addition to soil could provide a potential sink for soil organic carbon.

Vegetable and fruit wastes have 7 to 44% cellulose, 4 to 34% hemicellulose, and 15 to 69% lignin [6], which are beneficial components for high quality biochar production. Vegetable and fruit wastes can be easily collected from farms and processing factories but are also commonly produced as mixed waste in restaurant and canteen kitchens and are therefore the focus of this study. Four vegetable/fruit wastes have been selected to create a mixed food waste, based on their different properties and common availability. These are cauliflower, cabbage, banana, and corn, which are commonly grown and consumed worldwide. Around 30–50% of waste is produced from cabbage and cauliflower stems and leaves from farm to plate [7]. These two wastes contain 11–15% cellulose, 2.6–3% hemicellulose, and 2.5–3.2% lignin by weight [8]. A total of 118 Mt of banana peel waste is generated annually from tropical and subtropical regions and contains around 41% cellulose, 10% hemicellulose, and 9% lignin [9, 10]. In the USA, it is estimated that 250 Mt of corn waste is produced from the processing of 345 Mt of corn, while global corn production stands at around 1207 Mt [11]. The corn wastes contain 29% of cellulose, 32% of hemicellulose, and 29% of lignin [12].

Chickpea (Cicer arietinum L.) is cultivated on large-scale in arid and semiarid environments and is widely consumed in Southwest Asia, the Middle East, North Africa, and the Mediterranean [13]. About 90% of the world’s chickpea is grown under rain-fed conditions where the crop grows and matures on a progressively depleting soil moisture profile and experiences terminal drought, causing reduction of the plant grain yield [14]. Average chickpea yields remain low in major producing countries due to the inadequate water supply and soil water retention. It has been commonly reported that application of biochar derived from lignin-rich biomass to marginal soils can improve soil water retention [4, 15], providing opportunity to enhance productivity in environments prone to drought and with limited irrigation capability.

Our study aims to determine the potential impact of biochar on chickpea cultivation that has been derived from cellulose-rich mixed waste feedstock. For this purpose, we have used a mixed feedstock comprising cauliflower, cabbage, banana, and corn as a mock food plate waste. Specifically, we evaluate the effect of the biochar on soil water retention capacity, and chickpea plant growth and yield, given its importance in some of the most populated and water-stressed regions of the world.

2 Materials and method

2.1 Biochar application

Details of feedstock preparation, biochar production, and characterization have been previously reported by Pradhan et al. [16]. In brief, segregated vegetable/fruit wastes were collected from a university canteen in Qatar or purchased from a local market, chopped into pieces less than 3 cm in size, and washed with tap water. The four wastes were dried at 75 °C and mixed in equal quantities. The biochar was produced by pyrolyzing the feedstock at temperatures ranging from 300 to 600 °C in a muffle furnace (Lindberg Blue M-3504, Thermo Scientific). The biochars produced at different temperature conditions were ground and passed through a 75 μm size sieve. The fraction passing the sieve was used for characterization and testing. A detailed characterization of the different biochar was reported by Pradhan et al. [16]. Based on the outcome of that study, the mixed vegetable/fruit waste biochar produced at 400 °C was selected for pot tests in this study due to its high cation exchange capacity (CEC) of 53.2 cmolc.kg⁻¹, relatively neutral pH of 8.0, and low electrical conductivity of the extract (ECE) of 379.6 μS.cm⁻¹. High CEC, low ECE, and relatively neutral pH have been found most effective for plant growth [17].

Different functional groups and the surface morphology of biochar were analyzed by Fourier transform infrared (FT-IR) spectroscopy and scanning electron microscope (SEM), respectively, as described previously [16]. A Thermo Scientific Nicolet iS50 FT-IR spectrometer at a resolution of 4 cm⁻¹ was used for the FT-IR analysis of soil and biochar samples. The samples were crushed with KBr in a mortar with 1:100 ratios, and the pressed pellets were immediately analyzed in the region of 500–4000 cm⁻¹ at a scan rate of 64/sample [18]. A Quanta 650FEG (FEI Company) following gold sputter coating was used for the surface topography image under an acceleration voltage of 5 kV.

2.2 Biochar amended soil characteristics

Regional soil was collected from the university campus and characterized for the sand, silt, and clay content by following the standard procedure reported by Whiting et al. [19]. The
optimal biochar produced at 400 °C was mixed with soil at three different mass fractions of 0% (no biochar), 2%, and 6%. The two biochar application rates were chosen based on reports that application rates around 2% are most suitable in similar soil types and climatic conditions [20, 21], while 6% provides a higher rate for comparison. The grain size distribution was determined by oven drying and sieving according to ASTM standard D422-63 [22]. The granularity of the soil was analyzed based upon \( d_{10} \) (10% of particles are finer than this size), \( d_{30} \) (30% of particles are finer than this size), and \( d_{60} \) (60% of particles are finer than this size). The degree and uniformity of particle size grading were calculated by using Eqs. 1 and 2.

\[
C_u = \frac{d_{60}}{d_{10}} \quad (1)
\]

\[
C_c = \frac{d_{30}^2}{d_{60} \times d_{10}} \quad (2)
\]

\( C_u \)  Coefficient of uniformity

\( C_c \)  Coefficient of curvature

The porosity, moisture content, and bulk density of the soil at the three different biochar loadings were measured by following the procedure reported by Peterson [23]. The Brunauer–Emmett–Teller (BET) surface area of the soil mixture at the three biochar application rates was determined by \( \text{N}_2 \) gas sorption analysis at 77 K between a relative pressure of 0.05–0.35 using an ASAP 2020 plus surface area analyzer (Micrometrics). Samples weighing from 0.1 to 0.3 g were degassed for 6 to 8 h at a holding temperature of 105 to 110 °C before the analysis. SEM and FTIR were conducted following the same method as described for biochar alone.

Various chemical properties of the soil under the three biochar application rates were determined following different standard procedures reported by Pradhan et al. [16]. The pH and electrical conductivity were measured by using a calibrated pH meter (Orion Star A121, Thermo Scientific) and conductivity meter (Orion Star A329, Thermo Scientific), respectively. Soil samples and water were mixed at a ratio of 1:5 in a shaker for 1 h at 150 rpm before measuring pH and ECE (Dai et al. 2013). The CEC of biochar was determined by using the ammonium exchange (\( \text{NH}_4^+ \)) method followed by ASTM D7503-10 [24]. The concentration of ammonia was measured by segmented flow analyzer (Sans+, Skalar).

The micronutrient (K, Mn, Zn, Ni) content of biochar amended soil was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) using an Agilent 5100 ICP-OES following microwave acid digestion. A total of 100 mg of sample was digested with 8 mL concentrated nitric acid (\( \text{HNO}_3 \)) and 2 mL of hydrogen peroxide (\( \text{H}_2\text{O}_2 \)) using a microwave digester (Ethos UP, Milestone). The temperature was set at 200 °C with a ramp rate of 13 °C min\(^{-1}\) under a pressure of 90 bar and a residence time of 45 min. After digestion, the samples were removed and kept outside to cool down. Then 10 mL of concentrated hydrochloric acid (\( \text{HCl} \)) was added and left overnight for complete digestion of any residue. After digestion, the samples were diluted with deionized water and filtered through a 0.45-μm filter paper. The concentration of orthophosphate (\( \text{PO}_4^{3-} \)) was measured by a segmented flow analyzer (Sans+, Skalar) and sulfate (\( \text{SO}_4^{2-} \)) was measured by ion chromatography (940 Professional IC Vario, Metrohm) to give the P and S contents following the microwave digestion.

### 2.3 Pot test with chickpea

Soil with a particle size less than 1 mm diameter was used for the pot tests. Pot tests were conducted using both planted and unplanted pots and to test biochar interaction with soil with and without plant. In each 9 cm diameter pot, 400 g of soil was packed to a depth of 5.5 cm. For the planted pots, 20 chickpea seeds (\( \text{Cicer arietinum L.} \)) were sown in each. All pot conditions were run in triplicate. The application of biochar to the soil with particle sizes < 1 mm was used to as finer soil is intensive for agriculture practice by increasing soil water retention and reducing the volume of water irrigation [20]. Pot tests were conducted outdoors at the Hamad Bin Khalifa University campus, Qatar located at 25.3157° N and 51.4341° E under a green mesh shade cloth to prevent exposure from the intense sun in Qatar. Temperatures during the test averaged 35 ± 5 °C during the daytime and approximately 25 ± 5 °C in the night. The temperature was measured from a weather station situated just outside the green shade area.

A water balance was conducted for unplanted and planted pots by measuring the quantity of water drained, retained, and evapotranspired daily. Water evapotranspiration has been estimated by taking the weight difference of the pots after drainage of the irrigated water and just before the subsequent irrigation 24 h later. The total water mass balance in unplanted and planted pots was determined according to Eqs. 3, 4, 5 and 6.

\[
TWL = WLE + WD \quad (3)
\]

\[
WR = TWS - WD - WLE \quad (4)
\]

\[
WD_i = m_{i,pre} + m_{i,WS} - m_{i,post} \quad (5)
\]
Biomass Conversion and Biorefinery (2022) 12:4549–4562

Seeds germination, germination period, plant height, number of leaves, and number of flowers were measured daily for a period of 60 days. A period of 50 to 60 days is required for chickpea plant growth, flowering, and fruiting in a short-season temperature environment [25]. Chickpea at the end of the experiment on day 61 was harvested from each pot. The roots and shoots were separated and dried by a mechanical oven (Heratherm, Thermo Scientific) at 70 °C for 48 h. After drying, the weights were measured to determine root and shoot biomass mass [21].

2.4 Nutrient test for plant biomass

The oven-dried shoot and root biomass were crushed separately by a mortar and pestle to a finer size for microwave digestion. A total of 500 mg of shoot and root biomass was used for the digestion. The digested samples were prepared for the nutrient test by following the procedure reported in section 2.3. The leached nutrients from the pot were calculated according to Eq. 7.

\[
\text{LN} = (N)_T - [(N)_{\text{BMS}} + (NR)_{\text{soil}}]
\]

\[
\text{LN} \quad \text{leached nutrient}
\]

\[
(N)_T \quad \text{total nutrient in soil biochar mixture prior to the pot test}
\]

\[
(N)_{\text{BMS}} \quad \text{nutrients in plant biomass}
\]

\[
(NR)_{\text{soil}} \quad \text{nutrients retained in soil after harvesting.}
\]

2.5 Statistical analysis

The statistical significance of changes in plant growth and water retention capacity at different biochar application rates was determined using analysis of variance (ANOVA) with a Fishers lowest significant difference test (LSD) at \( p = 0.05 \) for posthoc comparisons. The significance of variation for the three different conditions over the incubation period was analyzed using a one-way, linear model in the Statistical Package for the Social Sciences (SPSS).

3 Results and discussion

3.1 Sand and biochar characteristics

The mixed vegetable waste biochar produced at 400 °C was used as an amendment for the pot tests in this study due to its high CEC of 53.2 cmolc.kg\(^{-1}\), relatively low pH of 8.0, and low ECE of the extract of 379.6 \( \mu \text{S.cm}\(^{-1}\)\). Similar properties of biochar from previous studies (high CEC, low ECE, slightly alkali pH) have been found most effective for plant growth [17]. The improved soil CEC that results from application of biochar with a high CEC reflects a higher nutrient retention capability and reduced nutrient loss by leaching, which is beneficial for soil microbial activity, especially for microbes living in soils with low organic matter content [26].

The FT-IR spectra of the sand sample (Fig. 1a) showed characteristic peaks of silica sand (SiO\(_2\)) including asymmetric Si-O stretching vibrations at 460 cm\(^{-1}\), and symmetric Si-O stretching vibrations at 695 cm\(^{-1}\), 777 cm\(^{-1}\), and 797 cm\(^{-1}\) and E symmetric bands at 1080 and 1072 cm\(^{-1}\) [18]. The sandy loam soil also contained a reasonable amount of calcite (CaCO\(_3\)), giving rise to the peaks at 714 cm\(^{-1}\), 875 cm\(^{-1}\), 1085 cm\(^{-1}\) and 1425 cm\(^{-1}\), 1800 cm\(^{-1}\), and 2510 cm\(^{-1}\) [27]. This is consistent with Qatar geology where typical rock is either calcite or gypsum. A small portion of organic material, given by the C-H bending indicated by the band at 2871 cm\(^{-1}\), was also present. The broad band at 3430 cm\(^{-1}\) is associated with O-H stretching vibrations and could indicate adsorbed water.

The biochar used had the highest CEC and a relatively low pH of the biochars produced at differing temperatures. The high CEC of biochar at 400 °C is due to the presence of various charged functional groups which are shown in the FTIR spectra (Fig. 1a). In the biochar FTIR spectra, characteristic bands of carbon-rich aromatic compounds with C=C stretching were present at 621 cm\(^{-1}\) and a broad peak through 700 to 840 cm\(^{-1}\). A small peak at 1100 cm\(^{-1}\) could represent C-O stretching of functional groups such as ketones and aldehydes or aliphatic amines (C-NH\(_2\)) [28]. The more notable peak at 1375 cm\(^{-1}\) is indicative of phenolic groups (O–H bending), while the large peak at 1581 cm\(^{-1}\) is associated with amine groups (N-H bending). The small change at 1700 cm\(^{-1}\) may indicate conjugated aldehydes (C=O stretching) while the large overtone up to 1800 cm\(^{-1}\) is indicative of aromatic C-H bending vibrations [28]. The small peaks around 2920 and 2960 cm\(^{-1}\) are characteristic of
alkane groups (C-H bend) while the broad peak from 2600 cm\(^{-1}\) through to 3700 cm\(^{-1}\) indicates the presence of carboxyl (-COOH stretching), amine (N-H stretching), and hydroxyl (-OH stretching) groups [28]. In particular, the peak present at 3410 cm\(^{-1}\) indicates hydroxyl groups associated with the presence of phenols and alcohols [29]. Gámiz et al. [26] reported biochar produced at low temperatures generally has a variety of surface functional groups compared to high-temperature biochars, the latter, which more closely resemble aromatic graphitic carbon. The biochar had a C content of 66.83 ± 3.23%, N content of 2.76 ± 0.52%, H content of 2.09 ± 0.13%, and O content of 11.8 ± 6.12% [16], supporting the FTIR observations and presence of various functional groups on the biochar. The C and N contents were much higher than that of the loamy sand, which were 1.32 ± 0.04% and 0.42 ± 0.02%, respectively. Blending of biochar with soil will alter the ratios of these elements at a proportional rate. SEM imaging showed small macropores present in the surface of the biochar produced at 400 °C (Fig. 1b). These pores could reduce water flux past the biochar particles and retain more water in sand-biochar mixtures [30], as well as provide sites for microbial colonization.

Fig. 1 a The FT-IR spectrum of sand and biochar and b surface morphology of biochar produced at 400 °C analyzed by SEM
3.2 Biochar impacts on soil mixture characteristics

Before conducting the pot test, different fractions of the soil and soil-biochar mixtures were characterized and are reported in Table 1. The soil is loamy sand type that contains 73.6% sand, 15.7% silt, and 16.2% clay. The soil particle size distribution indicates 10% of particles less than 0.07 mm, 30% less than 0.15 mm, and 60% less than 0.34 mm. The soil has a Cc value of 1.1 and Cu of 5.15 and is therefore classified as a well-graded soil [22]. The application of 2% biochar reduced the bulk density by 4% from the control bulk density of 1.54 ± 0.02 g.cm⁻³ (p = 0.01). Only a slight, not statistically significant, difference in bulk density was observed between the 2 and 6% biochar application rate (p = 0.60). Compared to the control condition, an increase of 4% soil porosity was noticed by applying 2% biochar (p = 0.01). Again, minor differences existed between the two biochar application rates (p = 0.43). Biochar application also resulted in an increase of the soil BET surface area of 2.44–2.55 times. The sand (0% biochar) had a high ECE and low CEC. A beneficial reduction in soil ECE was noticed in biochar-amended soil compared to the control (p = 0.0001). Lower ECE values are associated with lower salinity, a condition that could lead to an increase in water uptake by plant roots and subsequently nutrients [31]. The application of 2% and 6% biochar increased the CEC of sand from 10.2 to 21.1 cmol_离子.kg⁻¹ and 27.3 cmol_离子.kg⁻¹, respectively (p = 0.0001). The improved soil CEC that results from application of biochar with a high CEC reflects a higher nutrient retention capability and reduced nutrient loss by leaching, which is beneficial for soil microbial activity, especially for microbes living in soils with low organic matter content [26]. Ghorbani et al. [32] reported in their study that 1% and 3% of rice husk biochar application increased CEC in loam sandy soil by 20% and 30% respectively, which also increased the soil nutrients [33, 34]. In comparison to the control condition, a significant increase in soil pH was noticed by applying 6% biochar (p = 0.01), while a mild pH increase was observed using 2% biochar (p = 0.17). However, the pH in all the three biochar conditions remained in a suitable range (7.24 to 7.47). The pH of the actual biochar is quite alkaline and could cause localized immobilization of nutrients on its surface while overall maintaining conditions in the soil that are conducive for nutrient uptake [35]. The increased nutrient retention ability of the soil by mixing with biochar could be due to increased carboxylic group presence and CEC [36]. There was a large increase in various nutrients (PO₄³⁻ and SO₄²⁻) and micronutrients (K, Ni, Mn, Zn), ranging from 2 to 9 times (p = 0.0001). The highest values were generally associated with 6% biochar application rate, though for phosphate, 2% application rate was greatest. Small variations were noticed between 2 and 6% biochar for K, Mn, Zn, and

| Table 1 Variation in soil properties by the application of different loadings of biochar |
| Different properties | 0% (control) | 2% | 6% |
|----------------------|-------------|----|----|
| Structure            | Sandy loam  | -  | -  |
| Sand (%)             | 73.6        | -  | -  |
| Silt (%)             | 15.7        | -  | -  |
| Clay (%)             | 16.2        | -  | -  |
| d₁₀:d₃₀:d₆₀ (mm)     | 0.07:0.15:0.34 | - | - |
| Cᵥ: Cᵥ              | 5.15:1.1    | -  | -  |
| Bulk density (g.cm⁻³) | 1.54 ± 0.02蹉 | 1.48 ± 0.03蹉 | 1.47 ± 0.01蹉 |
| Porosity (%)         | 49.3 ± 1.0蹉 | 53.36 ± 1.43蹉 | 54.26 ± 1.45蹉 |
| pH                   | 7.24 ± 0.12蹉 | 7.35 ± 0.02蹉 | 7.47 ± 0.05蹉 |
| ECE (μS.cm⁻¹)        | 3583 ± 144蹉 | 2161 ± 93蹉 | 1849 ± 86蹉 |
| BET surface area (m².g⁻¹) | 0.72      | 1.76 | 1.84 |
| CEC (cmol_离子.kg⁻¹) | 10.20 ± 0.62蹉 | 21.07 ± 1.80蹉 | 27.26 ± 2.64蹉 |
| K (mg.kg⁻¹)          | 27.03 ± 0.75蹉 | 84.82 ± 8.14蹉 | 92.40 ± 6.56蹉 |
| Mn (mg.kg⁻¹)         | 0.42 ± 0.04蹉 | 3.55 ± 0.26蹉 | 4.10 ± 0.22蹉 |
| Ni (mg.kg⁻¹)         | 5.23 ± 0.06蹉 | 15.51 ± 0.04蹉 | 5.31 ± 0.08蹉 |
| Zn (mg.kg⁻¹)         | 14.53 ± 0.50蹉 | 25.72 ± 1.64蹉 | 25.87 ± 1.40蹉 |
| PO₄³⁻ (mg.kg⁻¹)      | 138.70 ± 5.45蹉 | 675.33 ± 4.47蹉 | 618.87 ± 5.83蹉 |
| SO₄²⁻ (mg.kg⁻¹)      | 196.70 ± 6.03蹉 | 389.00 ± 5.53蹉 | 421.50 ± 4.44蹉 |

Same letter superscripts denote no significant differences (p > 0.05); table entries in the same row with the same letter denote no significant difference between the values and different letter superscripts denote a significant difference at p < 0.05

ECE electrical conductivity; CEC cation exchange capacity; K potassium; Mn manganese; Ni nickel; Zn zinc; Cᵥ coefficient of uniformity; Cᵥ coefficient of curvature
Ni ($p > 0.14$). Overall, the bulk soil properties were significantly enhanced by the addition of biochar [17].

### 3.3 Biochar impact on chickpea growth

The growth of chickpeas in biochar amended soil was faster than the control and even early on showed a slightly greater number of germinated plants (Fig. 2a). Both control and 6% biochar showed a statistical difference to the intermediate 2% biochar plant height ($p = 0.007$ and $p = 0.03$, respectively) after 10 days. From day 11 to day 31, seed germination was relatively similar in the control, 2% biochar, and 6% biochar ($p > 0.15$) pots and reached a maximum of 60, 70, and 61% of total seeds after 30 days, respectively. Due to the limited watering conditions applied to all test conditions and the high rate of evapotranspiration, the control plants showed deterioration in health from day 30 and started to die after 40 days due to water stress. The differences in seed germination between the control and 2% and 6% biochar were statistically significant ($p = 0.02$) after 40 days. During the same period, the treatments with biochar showed the loss of a few plants, but not to the same degree as the control. The loss was slightly more in the 6% biochar than the 2% biochar ($p = 0.22$). However, the two biochar conditions both had approximately 50% of germinated plants surviving at the end of the test (day 60).

![Figure 2](image-url)
In the control condition, plant height was increased from day 11 to day 41 and achieved a maximum plant height of 15 ± 1.1 cm (Fig. 2a). At the same time, applying 2% and 6% biochar to the soil, the plant height significantly increased ($p_{\text{max}} = 0.04$) and achieved a plant height of 22 ± 2.1 cm and 25 ± 0.8 cm, respectively, after 40 days. From day 31 to 61, the growth of plant height in 6% biochar was relatively stable (approximately 2 cm) in comparison to the 2% biochar application rate ($p > 0.18$). At the end of the test, 2% and 6% biochar application achieved a maximum plant height of 23 ± 0.7 and 25 ± 1.0 cm, respectively. Yadav et al. [37] reported in their study that neutral soil amended with a lower fraction of biochar (0.25%) prepared using Napier grass (*Pennisetum purpureum*) achieved 19% germination of chickpeas and a 50% increase in plant height in comparison to their control after a 20-day period. In the present study, 2% application of vegetable waste biochar increased seed germination by 60% and plant height by 43% in comparison to the control after 40 days, which suggests that biochar derived from vegetable waste is an excellent soil amendment material for chickpea cultivation.

A large difference was noticed in the average number of leaves produced per plant among all three conditions (Fig. 2b). In the control condition, the average number of leaves per plant reached a maximum of 75 ± 9.5 after 30 days. For soil having 2% biochar, the average leaves per plant at the same time of the experiment were 273 ± 8.1, which was significantly more than the control ($p = 0.001$), while the 6% biochar treatment was similar to the 2% condition ($p = 0.79$). However, the maximum number of leaves for 2% biochar (284 ± 10) was achieved after 40 days while for 6% biochar, it was achieved at 50 days (280 ± 5.7). After 60 days, the 2% biochar condition showed an 11% reduction in leaves from its maximum value, while the 6% biochar condition was relatively stable.

With respect to flowers and chickpeas, the control showed no production of either during the entire experimental period, while soil having 6% biochar developed 3 ± 0.6 flowers by the 50th day and 3 ± 1.5 chickpeas at the 60th day (Fig. 2c). The 2% biochar condition had the maximum flower and chickpea production, reaching 6 ± 2.1 flowers after day 40 and 6 ± 1.5 chickpeas after day 60. At the end of the pot test, flowering was noticed in 2% biochar, while no flowering was observed in 6% biochar. These results suggest that a relatively lower application of biochar (2%) in soil is efficient for chickpea cultivation and plant health.

The 2 and 6% biochar application in soil showed differences in the growth performance of the shoot and root biomass compared with the control (Fig. 2d). The maximum root biomass of 8.2 ± 0.5 g and the maximum shoot biomass of 8.8 ± 0.2 g were both observed for the 6% biochar application. The 2% biochar application showed a competitive root and shoot biomass reaching 7.7 ± 0.6 g and 8.5 ± 0.4 g of root and shoot biomass, respectively. The 2% biochar application increased the root biomass by 139% and shoot biomass by 112% in comparison to the control ($p = 0.0001$). For the 6% biochar condition, the increase was 155% for root biomass and 120% for shoot biomass in comparison to control ($p = 0.0001$). No significant difference was noticed for biomass quantity between the 2 and 6% biochar conditions ($p = 0.28$). Sg et al. [38] applied 2% poultry litter biochar in Pinedene and Griffin soils and found similar improvements in chickpea shoot and root biomass with an increase of 80% compared to the control. An increasing rate of root to shoot biomass ratio in 2% and 6% biochar compared to control could reduce transpiration and increase nutrient uptake [39, 40]. Root to shoot ratio of harvested biomass is an indication of plant response to growing conditions, where root development is promoted with nutrient and water availability [41].

### 3.4 Biochar impact on water retention capacity

Drought stress negatively affects the plant growth and yield. However, it was found that biochar application significantly mitigates the detrimental effects of water stress (Fig. 3) and improves plant growth. The water loss via drainage and evapotranspiration was monitored for the unplanted and planted pots for all three soil conditions over the experiment and is shown in Fig. 3. The 2% biochar condition significantly reduced the total water loss of soil compared to the control ($p = 0.01$) in the unplanted pot condition (Fig. 3a) after 60 days. A further small reduction in total water occurred for the 6% biochar condition but was not statistically significant compared to the 2% biochar condition ($p = 0.08$). This indicates that a higher fraction of biochar addition to the loamy sand can improve the soil structure to hold more water but that 2% is sufficient to realize most of the potential improvement. In total, by the end of the experiment, the control retained 55 ± 7 mL of water out of a total of 3115 mL of water supplied. The addition of 2% biochar to the soil increased soil water retention to 77 ± 7 mL ($p = 0.03$). A small increase of 14 mL of water retention was observed in 6% biochar in comparison to 2% biochar ($p = 0.18$). The improvements in water retention are most likely due to increased soil-tension caused by changes in soil porosity and uniformity [42], but may also be due to changes in surface charges of the soil.

Considering an earlier period of 30 days, since this is just prior to the loss of plants in the control, 22 ± 3 mL of water was retained in control conditions with good plant growth, while 34 ± 7 mL and 45 ± 12 mL of water was retained in soil containing 2% biochar ($p = 0.14$) and 6% biochar ($p = 0.01$), respectively. In the control, 238 ± 4 mL and 1493 ± 12 mL of water were lost to drainage and evapotranspiration, respectively, while in 2% biochar, 224 ± 9 mL and 1476 ± 17 mL of water were lost by drainage and evapotranspiration out of a total water supply of 1810 mL. Water loss in...
the 6% biochar treatment comprised drainage of $211 \pm 8$ mL and evapotranspiration of $1453 \pm 6$ mL. By the end of the test, evapotranspiration losses differed by only a small amount among the test conditions with no significant difference ($p = 0.09$). However, higher plant growth was observed in the biochar treatments resulting in a lower evapotranspiration per mass of plant productivity and per plant produced (Fig. 3c), indicating a higher water use efficiency. The number of plants per liter of water supplied increased from 12 for the control to 15 for the 6% biochar case. Even more marked improvements were realized for biomass productivity, where both biochar amended conditions more than doubled the biomass output per liter of water in comparison to the control ($p = 0.0001$). However, it is important to note that these numbers are inflated by the loss of plants in the control condition due to water stress between day 30 and 60, which was more severe than the biochar conditions. At the same time, this highlights the criticality of improved water retention and reduced drainage losses in arid rain-irrigated agricultural areas where chickpea cultivation is common to realize successful plant survival and biomass yields.

### 3.5 Nutrients content by plant shoots and roots

A significant enhancement in chickpeas shoot and root nutrient contents was noticed in 2% and 6% biochar pot compared...
to the control condition ($p = 0.03$). Figure 4 shows the nutrient contents within root and shoot biomass. In 2% and 6% biochar application, potassium (K) accumulation in the shoot biomass was higher than in the root biomass, whereas manganese (Mn) and nickel (Ni) were more concentrated in the root biomass and zinc (Zn) was similar (Fig. 4a). In the biochar treatments, K was much higher in both the shoot and root biomass than the control, while for Zn, the shoots in biochar treatments were also much higher than the control. For Mn, the biochar treatments had much higher concentrations in the roots than the control. K and Zn are good sources for plants to increase metabolic processes like photosynthesis and chlorophyll biosynthesis and explain or correlate well with the improved growth in the biochar treatments [43]. The only measure where the control had higher concentrations than both biochar treatments was for Ni in the shoot. Higher Ni concentrations are known to retard branch and leaves development, as well as result in abnormal flower shape [44].

Addition of 2% and 6% biochar to the soil increases PO$_4^{3-}$ and SO$_4^{2-}$ content in shoot biomass by more than 85% compared to the control ($p = 0.0001$). For the root biomass, biochar addition increased PO$_4^{3-}$ and SO$_4^{2-}$ by more than 70% compared with the control ($p = 0.0001$) (Fig. 4b). The extremely high uptake of nutrients relative to the control may be related to the high mobility of these ions in wet soil, since biochar-amended soil had greater water retention. It is also expected biochar-loaded soil will reduce the leaching of these elements to lower soil levels or groundwater. The 2% biochar application showed a slightly higher PO$_4^{3-}$ concentration in shoot and root biomass than 6% biochar. Phosphorus content in plants increases the number of leaves, leaf surface area, flower formation, and improvement of crop production [45, 46], which was consistent with observations in 2% biochar planted pots (Fig. 2c). Soil water content and P availability interactions have been shown to have a significant effect on the shoot and root biomass. Lower water availability limits the diffusion of P, making P limitations more severe than under conditions with available water [41], such as with biochar addition. Higher root-to-shoot ratio increased the accumulation of P in all plant parts, but predominantly in shoots, whereas further increasing the concentration increased the accumulation primarily in roots and flowers [46]. Higher levels of P in the shoot than root is a common trait among plants, as the petiole is the plant organ with the greatest accumulation of P. S is an essential element to form proteins, enzymes, vitamins, and chlorophyll in plants. It is crucial in root nodule development and efficient nitrogen fixation in legumes [47]. The assimilation of S and N is strongly interrelated, therefore the S deficiency in plants could reduce nitrogen (N) content of plant tissue. The higher S in root and shoot biomass represents higher rate of photosynthesis as high S is required for legumes (alfalfa, clover, soybean etc.) and also without S the N utilization in plant also reduced [47].

### 3.6 Nutrients retained in soil after plant harvest

Figure 5 represents the nutrients retained in the soil mixture after harvesting the plants. The retention of K and Ni in the control was greater than the biochar conditions. This appears to be due to reduced uptake by plants due to less developed roots and the early loss of plants in the control by day 50 of the test (Fig. 1a and d). A slight increase of Mn and Zn retention was detected in 2% and 6% biochar than control. After the utilization of K, Mn, Ni, and Zn by the plant and considering that retained by the soil, a loss of $1.2 \pm 1.0, 0.2 \pm 0.1, 1.0 \pm 0.5$, and

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**Fig. 4** a Nutrient content b P and S content by dry shoot and root biomass. P: phosphorous; S: sulphur. Same letter superscripts denote no significant difference ($p > 0.05$); different letter superscripts denote a significant difference at $p < 0.05$.
0.3 ± 0.2 mg.kg⁻¹ of K, Mn, Ni, and Zn occurred in the control condition. For 2% biochar application, the loss of nutrients was reduced by approximately 80% for K, 30% for Mn, 85% for Zn, and 69% for Ni, while for 6% biochar the loss of nutrients reduction was 90% for K, 26% for Mn, 91% for Zn, and 86% for Ni compared to the control. This is most likely due to the reduction in drainage-related water losses under biochar application compared to the control, as well as improved adsorption ability of biochar due to its high surface area, porosity, and surface charge that together result in reduced nutrient leaching.

After considering both the consumption of PO₄³⁻ and SO₄²⁻ by the plants and that retained by the soil, a loss of 11 ± 6.0 and 20 ± 7.3 mg.kg⁻¹ of PO₄³⁻ as P and SO₄²⁻ as S occurred in the control condition by leaching (Fig. 5b). In comparison, 5.8 ± 1.0 and 6.0 ± 1.0 mg.kg⁻¹ of PO₄³⁻ (as P) and 4.0 ± 0.7 and 3.2 ± 0.8 mg.kg⁻¹ of SO₄²⁻ (as S) was lost in 2% and 6% biochar, respectively. P and S retention in 2% and 6% biochar varied slightly, with each retaining more of certain nutrients and could be associated with slight differences in soil pH and water retention. Overall, 6% biochar loading showed the lowest leaching losses for all nutrients. This performance is associated with both increased uptake by plants and improved adsorption within the soil. Kizito et al. [31] reported corn and wood biochar increased nutrients as TP (63%), Ca (83%), K (48%), and Mg (38%) uptake from the soil in comparison to the control condition and reduced the availability of nutrients in soil. Knoblauch et al. [48] reported plant available nutrient concentrations increased after biochar application and potentially reduced the availability in soil.

3.7 Validation with reported studies

Sg et al. [38] conducted a study where they applied poultry litter and acacia-derived biochar to two sandy loam soils for chickpea growth at application rates of 0.5, 1, and 2%. In their study, biochar application increased the pH of the acidic soils by around 1–2 pH units to a pH that was still slightly acidic. Poultry litter biochar, another more cellulose-rich (28%) feedstock, increased the CEC more than lignin-rich acacia biochar in all soil types. It also resulted in better chickpea growth in all three soils tested, particularly the two finer more acidic soils, as well as improving nutrient uptake by the plants. In general, similar observations were seen from our study. However, Sg et al. did note that their highest application rate of 2% led to a deterioration in the chickpea growth in the sandiest soil, which they associated with increased retention of PO₄³⁻ in the soil. In another study, Lusiba et al. [49] applied 0, 5, 10, and 20 t.ha⁻¹ biochar to two types of sandy loam soil along with phosphorus fertilizer at 90 kg.ha⁻¹. The lowest rate of biochar application (5 t.ha⁻¹) in two types of soil significantly increased chickpea plant biomass, grain yield, and water moisture content than higher rates of biochar application. Therefore, growth and yield of chickpea varied in biochar application produced from different feed stocks, soil type, and seasons. However, in the current study with sandy loam soil, only small differences were observed between the biochar loading rates used, which both were considerably better than the control. This indicates that for the growth stage of chickpea tested and climatic conditions in this study, 2% provided sufficient retention of nutrients and water to not significantly limit growth. From an economic perspective, it is beneficial if a lower biochar application rate can be used to get similar improvements in agricultural performance at lower cost.
4 Conclusion

The properties of biochar produced from pyrolysis of vegetable and fruit wastes showed that it is an efficient soil amendment agent for sandy loam soils to increase soil fertility, plant growth, and water retention capacity. The application of vegetable waste biochar as a soil amender for the chickpea growth showed a positive effect for plant growth in terms of plant height, foliage, flowers, chickpeas, and biomass generation. The application of biochar also enhanced nutrient retention in the soil and uptake of nutrients by the plant root. Importantly, for arid agriculture and natural rain-fed chickpea cultivation, the application of biochar improved the water holding ability of the soil and reduced water losses, resulting in more than double the yield of biomass per unit of water applied. Overall, only small differences existed between the two biochar loadings; for instance, 2% gave more plants, flowers, and fruits as well as higher phosphorus content of the biomass, while 6% gave taller plants with slightly improved water use efficiency. These differences were relatively minor and therefore based on the costs of producing and applying biochar to soil. A 2% application rate is recommended for chickpeas grown in sandy soil. The study demonstrates production of biochar from mixed vegetable and fruit wastes is an effective route for recycling food waste to reduce the burden of municipal solid waste management and enhance food security in water scarce regions. Based on this study, the authors recommend further study of even lower biochar application rates on soil to investigate improvements in fertility, plant growth, and water retention capacity.

Acknowledgements The authors would like to thank the Qatar National Research Fund (QNRF) for supporting this research work under the National Priorities Research Program (Grant Number: NPRP11S-0117-180328). The authors would like to thank Mr. Mohammad Danish of Gulf Organization for Research and Development for extending his support during the FTIR analysis of the sand sample and to Dr. Kamal Mroue and Mr. Mohamed I. Halal in Qatar Environment and Energy Research Institute (QEERI), Hamad bin Khalifa University for their support towards FTIR and SEM analysis of the biochar sample.

Author contribution Conceptualization: Snigdhendubala Pradhan, Hamish R Mackey, and Gordon McKay; methodology: Snigdhendubala Pradhan; formal analysis and investigation: Snigdhendubala Pradhan, Hamish R Mackey, and Gordon McKay; writing - original draft preparation: Snigdhendubala Pradhan; writing - review and editing: Hamish R Mackey, Gordon McKay, and Tareq Al-Ansari; funding acquisition: Gordon McKay, Hamish R Mackey, and Tareq Al-Ansari; resources: Gordon McKay and Hamish R Mackey; supervision: Hamish R Mackey and Gordon McKay.

Funding Open Access funding provided by the Qatar National Library. The authors would like to thank the Qatar National Research Fund (QNRF) for supporting this research work under the National Priorities Research Program (Grant Number: NPRP11S-0117-180328).

Data availability The article does not contain additional data resources.

Declarations

Competing interests The authors declare no competing interests.

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References

1. Gustavsson J, Cederberg C, Sonesson U (2011) Global food losses and food waste: extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome
2. Scialabba N, Jan O, Tostivint C et al (2013) Food wasteage footprint: impacts on natural resources. Summary Report. BIO-Intelligence Service, Food and Agriculture Organization of the United Nations (FAO)
3. Gowman A, Picard M, Lim LT et al (2019) Fruit waste valorization for biodegradable biocomposite applications: a review. Bioresources 14:10047–10092. doi:10.15376/biores.14.4
4. Alostaibi KD, Schoenau JJ (2019) Addition of biochar to a sandy desert soil: effect on crop growth, water retention and selected properties. Agronomy 9:327. https://doi.org/10.3390/agronomy9060327
5. Verheijen F, Jeffery S, Bastos A et al (2010) Biochar application to soils - a critical scientific review of effects on soil properties, processes and functions. European Commission, Report EUR 24099 EN, Luxembourg
6. Szymańska-Chargot M, Chylitiska M, Gdula K et al (2017) Isolation and characterization of cellulose from different fruit and vegetable pomaces. Polymers 9:495. https://doi.org/10.3390/polym9100495
7. Hossain MA, Ngo HH, Guo WS et al (2014) Performance of cabbage and cauliflower wastes for heavy metals removal. Desalin Water Treat 52:844–860. https://doi.org/10.1080/19443994.2013.826322
8. Rani B, Kawatra A (1994) Fibre constituents of some foods. Plant Food Hum Nutr 45:343–347. https://doi.org/10.1007/BF01088083
9. Kabenge I, Omugo G, Banadda N et al (2018) Characterization of banana peels wastes as potential slow pyrolysis feedstock. J Sustain Dev 11:14. https://doi.org/10.5539/jsd.v11n2p14
10. Waghmare A, Arya S (2016) Utilization of unripe banana peel waste as feedstock for ethanol production. Bioethanol 2:146–156. https://doi.org/10.1515/bioeth-2016-0011
11. Shahbandeh M (2022) Corn in the U.S. - statistics & facts. In: Statista. https://www.statista.com/topics/986/corn/ accessed 11 Dec 2020
12. Winarsh S (2019) The effect of NaOH concentration and microwave exposure time to the content of cellulose, hemicellulose and lignin of Corn Cob. Food Tech Halal Sci J 1:16. https://doi.org/10.22219/fths.v1i1.7543
48. Knoblauch C, Priyadarshani SHR, Haefele SM et al (2021) Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. Eur J Soil Sci 72:1885–1901. https://doi.org/10.1111/ejss.13088

49. Lusiba S, Odhiambo J, Ogola J (2018) Growth, yield and water use efficiency of chickpea (Cicer arietinum): response to biochar and phosphorus fertilizer application. Arch Agron Soil Sci 64:819–833. https://doi.org/10.1080/03650340.2017.1407027

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