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Research Article

Effects of bagasse and its biochar on the leaching of solutes and water uptake by field pea (*Pisum sativum* L.) under controlled and free drainage conditions and irrigation with municipal wastewater

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ABSTRACT –This study examined the effects of sugarcane bagasse and its biochar on soil properties, field pea (*Pisum sativum* L.) yield, and nutrient absorption under different drainage conditions using municipal wastewater for irrigation. The experiment was conducted as a factorial design with two factors in a greenhouse. The first factor was drainage condition at two levels: controlled drainage (CD) and free drainage (FD). The second factor was the application of sugarcane bagasse and its biochar at four levels: 1% bagasse (BA1), 2% bagasse (BA2), 0.66% biochar (BIC0.66), and 1.32% biochar (BIC1.32). Municipal wastewater was used for irrigation throughout the study. Results showed that adding sugarcane bagasse and its biochar improved soil physical properties, particularly water holding capacity, with BIC1.32% being the most effective. In CD treatments, capillary rise provided additional water and nutrients, increasing irrigation water productivity for field pea by 1.8 times compared to FD. The controlled drainage also reduced water consumption by 22% and enhanced nitrate and phosphate absorption by 44.25% and 28.78%, respectively. However, it decreased nitrate leaching, phosphate leaching, and drainage water volume by 19.73%, 24.23%, and 31.23%, respectively. Additionally, nitrate and phosphate uptake by field pea increased by 75% and 13.3% under CD compared to FD. The interaction between additives and drainage treatments significantly affected plant weight, with the highest yield observed in the CD and BIC1.32% treatments. Overall, CD combined with BIC1.32%, BIC0.66%, BA1%, and BA2% increased plant dry weight by 26.2%, 13.2%, 25.8%, and 26%, respectively, compared to FD. These findings highlight the potential of sugarcane bagasse and biochar for enhancing soil quality, improving water-use efficiency, and boosting crop yields under various drainage conditions.

INTRODUCTION

Controlled drainage (CD), also known as drainage water management, is a technique used to regulate subsurface drainage systems so that more water is retained in agricultural fields during certain periods of the year. The system is adjusted during times when drainage is not necessary—for example, in winter when no crops are present, or in summer when crop water demand is high. Both field studies and modeling research have shown that CD effectively reduces discharge flow and nitrate-N export downstream (Skaggs et al., 2012; Ross et al., 2016). By regulating the water table, CD achieves drainage objectives while minimizing water and nutrient losses and reducing pollutant transfer (Skaggs et al., 2012; Wesstrom et al., 2014). The benefits of CD include reduced drainage water loss, decreased fertilizer leaching and nitrogen losses, greater moisture retention in the root zone, reduced moisture stress, increased plant transpiration, and ultimately higher crop yields. By retaining water and nutrients in the soil, CD allows plants to make better use of these resources, particularly during drought conditions. Without an effective drainage system, the only alternative is to construct underground drainage networks. However, the design and maintenance of such systems are critical, as defects can result in soil salinization, fertility decline, and

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yield losses (Nozari et al., 2017; Javani Jooni et al., 2018). Several studies have demonstrated the effectiveness of CD in reducing nutrient losses and improving water management. Helmers et al. (2022) investigated the regional and seasonal impacts of CD compared to free drainage (FD), finding that reductions in nitrate-N load were directly linked to the decreased discharge flow. Similarly, Jia et al. (2006), in a study conducted in the Yin Nan region of China, reported that CD reduced drainage flow by up to 94% in aquatic crops and rice. On a smaller scale, Rozemeijer et al. (2016) examined chemical variations in drainage water under CD and conventional systems. They found that CD not only reduced drainage flow and increased soil water storage but also lowered phosphorus concentrations in the drainage water. Alongside CD, biochar has attracted considerable interest as a soil amendment. Biochar is a carbon-rich product derived from plant biomass through pyrolysis under anaerobic or semi-aerobic conditions. Recent research highlights its potential to improve soil fertility and mitigate both organic and inorganic pollution (Sohi et al., 2010). Ouyang et al. (2013) investigated the role of biochar in soil aggregate formation, stability, and hydraulic properties, reporting that biochar improves soil water holding capacity directly through its porosity and indirectly by increasing soil organic matter.

While most prior studies have focused on biochar's effects on pollutant leaching, little is known about its interaction with CD. The present study addresses this gap by examining the combined effects of bagasse-derived biochar and CD on soil leaching, solute absorption, and crop yield. Specifically, it evaluates field pea growth, solute absorption, irrigation management, and water use efficiency under both CD and FD conditions.

MATERIALS AND METHODS

Specifications of the treatment

This greenhouse experiment was arranged in a factorial design with two factors, i.e., drainage and soil additives, using a completely randomized design with three replications. The first factor consisted of two drainage treatments: controlled drainage (CD) and free drainage (FD). In the CD treatment, the water table was maintained 23 cm below the soil surface, whereas in the FD treatment, drainage water was positioned at a depth of 57 cm (the bottom of the soil column). The second factor involved the addition of soil amendments: two levels of biochar (0.66% and 1.32%), two levels of sugarcane bagasse (1% and 2%), and one control without additives, resulting in a total of 10 treatments (Table 1). To establish the experimental setup, 30 PVC columns were constructed, each with a volume of 9.8 L, a diameter of 10 cm, and a height of 62 cm (Fig. 1a and Fig. 1b). Each column was filled with a 3 cm layer of coarse gravel at the bottom, followed by 54 cm of soil. Sugarcane bagasse, collected from fields in Ahvaz, was used as the feedstock for biochar production. Prior to pyrolysis, the bagasse was first air-dried, then oven-dried at 70 °C for 24 hours to further reduce moisture. The dried material was crushed (Fig. 2a) and sieved to < 4 mm particle size. Pyrolysis was carried out by heating the biomass in a furnace at a rate of 3 °C per minute until the target temperature of 300 °C was reached, after which the material was held at this temperature for 120 minutes. The furnace was then gradually cooled, and the resulting biochar was collected (Fig. 2b). The biochar yield (BY) was calculated after pyrolysis using Eq. (1), where FM is the mass of the feedstock before pyrolysis and BM is the mass of biochar produced.

$$BY = (\frac{BM}{FM}) \times 100 \quad \text{Eq. (1)}$$

The biochar yield obtained from sugarcane bagasse at 300 °C was 66%.

Location of the experiment

This research was conducted in the research greenhouse of Isfahan University of Technology, located at 51˚43' east longitude and 32˚39' north latitude, in the year 2022.

Soil properties

The physical and chemical characteristics of the soil are presented in Table 2.

Irrigation management

To determine the irrigation water depth for the field pea, Readily Available Water (RAW) in the columns must first be calculated. This was done based on the type of soil and plant via the following equation:

$$RAW = MAD \times (\theta FC - \theta PWP) \times Drz \quad \text{Eq. (2)}$$

where MAD is the maximum allowable depletion, which depends on irrigation management and the type of cultivation. In this research, MAD value was considered to be 0.5 based on the plant type and cultivation conditions (Allen et al., 1998), θ_{FC}, and θ_{PWP} are volumetric soil water content at field capacity and permanent wilting point (%), and D_{rz} is the plant root zone depth (mm).

After calculating RAW, the depth of irrigation, including the leaching requirement (LR), was obtained using the following equation:

$$IW = \frac{RAW}{1-LR} \quad \text{Eq. (3)}$$

where IW is the irrigation water depth (mm), and LR is the leaching requirement percentage, which was considered to be 15%.

Irrigation depth is defined when soil water content reaches θ_{irr}as follows:

$$I_{rrD} = (\theta_{FC}(\theta_{FC} - \theta_{pwp}) \times MAD) \times D_{rz} \quad \text{Eq. (4)}$$

where $I_{rrD}$is the irrigation depth (mm) and is defined for the time when the soil water content reaches θ_{FC}.Using the water balance in the root zone, evapotranspiration values over a specific period were determined using Eq. (5).

$$ET_a = IW - \Delta S - DP \quad \text{Eq. (5)}$$

where ET_a is the actual evapotranspiration rate (mm/day), ∆S is the change of equivalent water depth in soil column over a certain period (mm/day), and *DP* is the rate of drainage volume per column area (mm/day). This specific period refers to the growing season, during which the soil moisture generally fluctuates within a narrow range due to the regular irrigation and plant uptake. Therefore, ∆S is assumed to be negligible compared to the other components of the water balance.

Irrigation Water Productivity (WP_I)

Another important indicator in determining WP_I in the agricultural sector is the efficiency of water consumption. This index is the ratio of the amount of product being produced to the amount of water consumed (IW) by the plant. This metric is especially crucial in situations where water resources are limited. An increase in dry matter boosts WP_I because the production of dry matter occurs more rapidly than the loss of water.

Eq. (6) enabled the calculation of the WP_I value.

$$WP_I = \frac{Y}{IW} \quad \text{Eq. (6)}$$

where WP_I is the irrigation water productivity (kg/m^3, Y is the amount of dry product in kg/ha.)

Data collection

After every ten irrigation cycles, the drainage water collected from each column (three replicates per treatment) was measured separately. The water samples were then transferred to the laboratory for analysis of nitrate and phosphate concentrations using a spectrophotometer. Since these compounds degrade rapidly, all measurements were completed within 24 hours of sampling. At the conclusion of the experiment, soil samples were collected from each column, and their nitrate and phosphate concentrations were determined using the same spectrophotometric methods. Nitrate concentrations were measured according to the Standard Methods for the Examination of Water and Wastewater (4500-NO3), and phosphate concentrations were measured following the 4500-PD method. Following harvest, the aboveground biomass of field peas from each column was collected, packaged, and transported to the laboratory. The fresh weights of leaves, stems, and seeds were recorded separately. Subsequently, plant materials were oven-dried at 70 °C for 72 hours, after which the dry weights of leaves, stems, and seeds were measured for each column.

RESULTS AND DISCUSSION

Effect of sugarcane bagasse and its biochar on WHC

The analysis of variance indicated that treatments had a statistically significant effect on the soil WHC at the 1% level (Table 3). The greatest improvement in WHC was observed with biochar at 1.32% (BIC1.32%) and 0.66% (BIC0.66%), which increased WHC by 43.3% and 33.8%, respectively, compared with the CD control (C-CD). This enhancement can be attributed to the high porosity, large surface area, and structural stability of biochar, which promote soil aggregation and improve moisture retention (Ouyang et al., 2013; Laird et al., 2010). Sugarcane bagasse also improved WHC, with increases of 13.5% at 1% (BA1%) and 24.3% at 2% (BA2%) compared to C-CD. These improvements are likely due to the high organic matter content and slow decomposition of bagasse, which enhance soil structure and WHC (Doan et al., 2013).

Table 1. Different treatments description

No.	Abbreviation	Drainage condition	Additive
1	C-CD	Control drainage	-
2	C-FD	Free drainage	-
3	BIC0.66-CD	Control drainage	Biochar (0.66%)
4	BIC0.66-FD	Free drainage	Biochar (0.66%)
5	BIC1.32-CD	Control drainage	Biochar (1.32%)
6	BIC1.32-FD	Free drainage	Biochar (1.32%)
7	BA1-CD	Control drainage	Bagasse (1%)
8	BA1-FD	Free drainage	Bagasse (1%)
9	BA2-CD	Control drainage	Bagasse (2%)
10	BA2-FD	Free drainage	Bagasse (2%)

C-CD: control drainage without additive, C-FD: free drainage without additive, BIC0.66-CD: biochar 0.66% and control drainage, BIC0.66-FD: biochar 0.66% and free drainage, BIC1.32-CD: biochar 1.32% and control drainage BIC1.32-FD: biochar 1.32% and free drainage, BA1-CD: bagasse 1% and control drainage, BA1-FD: bagasse 1% and free drainage, BA2-CD: bagasse 2%, and control drainage and BA2-FD: bagasse 2% and free drainage.

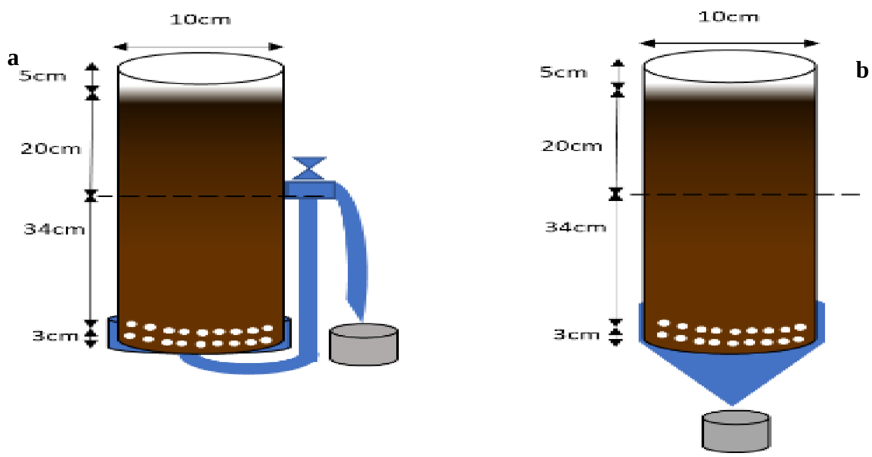

Fig. 1. Experimental column. (a) Controlled drainage and (b) free drainage.

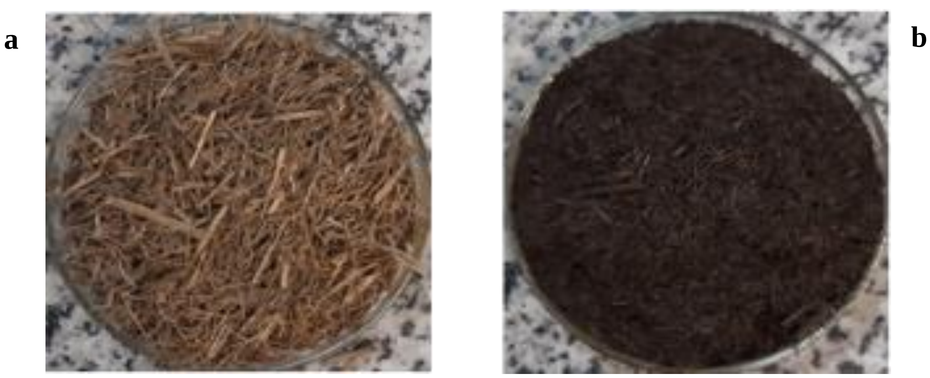

Fig. 2. Samples. (a) Sugarcane bagasse and (b) biochar of sugarcane bagasse.

Table 2. Properties of soil used in the study

Soil texture	Clay (%)	Loam (%)	Sand (%)	ρ_b (g/cm^3)	FC (%)	PWP (%)	pH	EC (dS/m)
Clay loam	32.8	28.4	38.8	1.22	23	15.5	7.2	2.85

ρ_b: Bulk Density, **FC**: Field Capacity, PWP: Permanent Wilting Point, and **EC:** Electrical Conductivity.

Table 3. Comparison of the effects of different levels of biochar and sugarcane bagasse on soil water holding capacity (WHC)

Treatment	Control	BIC0.66	BIC1.32	BA1	BA2
WHC (%)	7.4^{d}	9.9^{ad}	10.6^{a}	8.4^{cd}	9.2^{bc}

Different letters in each row indicate differences between treatments ($P < 0.05$, LSD test).

FC: field capacity, PWP: permanent wilting pint, EC: electrical conductivity, WHC: water holding capacity, BIC0.66: biochar 0.66%, BA1: bagasse 1%, BA2: bagasse 2%, and ρ_b : bulk density.

Irrigation scheduling

The cumulative irrigation water applied to FD and CD treatments during the growth period is shown in Fig. 3a and Fig.3b. Under CD, the total irrigation amounts for BIC0.66%, BIC1.32%, BA1%, BA2%, and C-CD were 157.5, 140.8, 202.16, 189, and 227 mm, respectively. Under FD, the corresponding values for BIC0.66%, BIC1.32%, BA1%, BA2%, and C-FD were 206.77, 186.2, 254.26, 223.12, and 284.4 mm, respectively. As illustrated in the figures, C-CD and C-FD required the highest irrigation depths, while BIC1.32% consistently required the lowest. These results indicate that higher soil WHC reduces irrigation demand. Biochar plays a central role in this process, as its high specific surface area alters soil particle size distribution and porosity, thereby increasing WHC (Sun et al., 2014). Furthermore, a comparison between drainage systems showed that total irrigation water applied under CD was, on average, 22% lower than under FD. This demonstrates the effectiveness of CD in reducing irrigation water requirements, consistent with earlier findings (Skaggs et al., 2012). The actual evapotranspiration (ETa) during the growth period for CD and FD treatments, calculated using Eq. (6), is presented in Fig. 4.

Chemical characteristics of soil

Nitrate concentration

CD significantly increased soil nitrate concentration by 44.25% compared with FD (Table 4). Among the soil amendments, biochar treatments had the strongest effect: BIC0.66% and BIC1.32% increased nitrate levels by 28.1% and 46.3%, respectively, relative to the control. This result aligns with previous findings that biochar enhances nutrient retention by adsorbing nutrients and reducing leaching losses (Khademi et al., 2018; Zhang et al., 2014). Sugarcane bagasse also improved nitrate concentrations, with increases of 17.2% at 1% (BA1%) and 22.8% at 2% (BA2%), indicating that both biochar and bagasse contributed to improved nutrient availability in soil (Fig. 5).

Phosphate concentration

Phosphate concentrations showed a similar pattern. CD increased soil phosphate by 28.78% compared with FD. Biochar treatments again produced the largest improvements, with increases of 14.43% (BIC0.66%) and 18.83% (BIC1.32%) relative to the control. These effects are likely due to the biochar's ability to limit phosphate leaching through electrostatic interactions and surface adsorption (Li et al., 2016; Yao et al., 2012). Bagasse treatments also enhanced phosphate concentrations, though the effects were less pronounced than those observed with biochar (Fig. 6).

Quantity and quality of drainage water

The volume of drainage water

In this study, drainage water from each column was measured and analyzed throughout the growth period (Fig. 7). On average, drainage water volumes were lower under CD compared to FD (Fig. 7). As shown in Table 5, CD significantly reduced drainage water at the 5% level. significant.

Nitrate and phosphate uptake

Specifically, maintaining the water table at a depth of 34 cm decreased outflow by 31.23% compared to FD (Helmers et al., 2022; Wang et al., 2020). These results are consistent with previous findings. Helmers et al. (2022) reported that CD reduced drainage volume by 28%, 33%, and 52% under fresh, normal, and dry precipitation conditions, respectively. Similarly, a meta-analysis by Wang et al. (2020) concluded that CD reduces subsurface drainage by about 30% in dryland crops. In this experiment, CD reduced drainage water by 31.47% and 32.65% under BIC0.66% and BIC1.32%, respectively, compared with FD. Likewise, CD reduced drainage water by 33.79% and 30.74% under BA1% and BA2%, respectively, compared with FD. These reductions indicate that CD limits water loss from the root zone by raising the groundwater table, thereby enhancing the soil's capacity to retain moisture. Adjusting irrigation schedules under CD not only reduces plant stress but also improves water-use efficiency by minimizing drainage outflow. When comparing average FD values among treatments (Table 5), biochar also showed clear benefits. Relative to the control (C-FD), BIC0.66% and BIC1.32% reduced drainage water by 16.28% and 19.95%, respectively, reflecting the role of biochar in increasing soil water holding capacity. Similarly, BA1% and BA2% decreased drainage water by 9.52% and 13.69%, respectively, compared with C-FD.

Nitrate concentration of drainage water

C also reduced nitrate concentration in drainage water by 3.2% to 28.7% across different harvests (Fig. 8), mainly due to the reduced leaching and increased plant uptake. The reduction in drainage volume also contributes to nitrate retention (Shen et al., 2018).

Phosphate concentration of drainage water

Likewise, CD reduced phosphate concentration in drainage water by 3.13% to 24.23% (Fig. 9). This effect is attributed to the reduced drainage and improved retention of phosphate in the root zone, especially in treatments amended with biochar, which has high anion exchange capacity (Yao et al., 2012).

Fresh and dry biomass

Plant fresh and dry weights were higher under CD compared to FD, especially in BIC1.32%, which increased fresh weight by 84% and dry weight by 26.2% (Table 5, Fig. 10,11 and Fig. 12). This improvement is due to the better moisture availability and nutrient retention (Abbaspoor et al., 2018). In FD, differences among treatments were not statistically

CD treatments enhanced nutrient uptake by field pea plants. Nitrate and phosphate absorption increased by 75% and 13.75%under CD, respectively, compared to FD

(Fig.13a, Fig. 13b, and Table 6). The positive correlation between nutrient uptake and plant biomass (R^2 = 0.94 for nitrate and 0.82 for phosphate; Fig. 14a and Fig. 14b confirms the effectiveness of CD and amendments in improving nutrient use efficiency (Liang et al., 2006).

WP_I index (WP_I)

As shown in Fig. 17, CD and BIC1.32% significantly enhanced WPI by 43% and 145%, compared to C-CD and C-FD, respectively. This improvement is linked to the reduced water use, better nutrient availability, and increased biomass yield (Zhang et al., 2010). Although salt accumulation was observed in CD treatments, higher humidity levels mitigated its adverse effects, leading to an average 1.8-fold increase in WPI under CD compared to FD (Fig. 15).

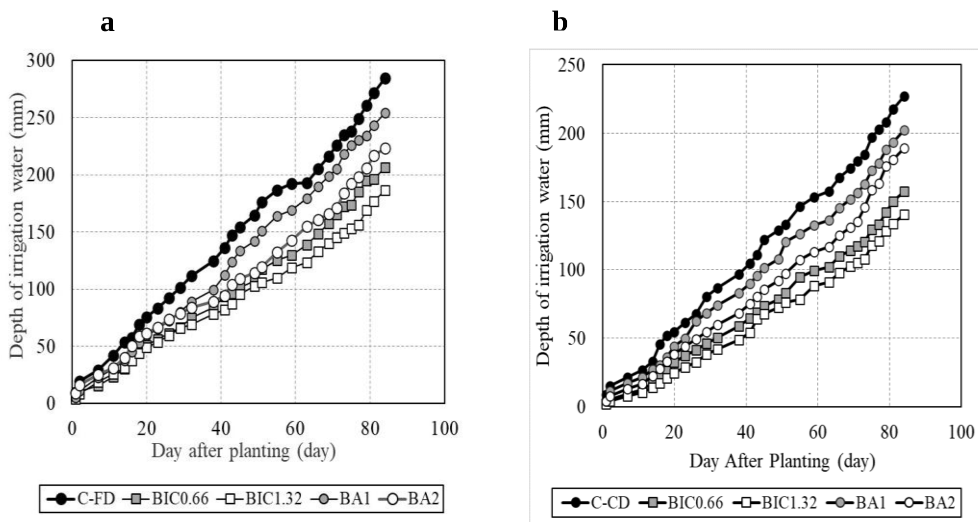

Fig. 3. Cumulative amount of irrigation water depth for samples with (a) free drainage and (b) controlled drainage. C-FD: free drainage without additive, C-CD: control drainage without additive, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

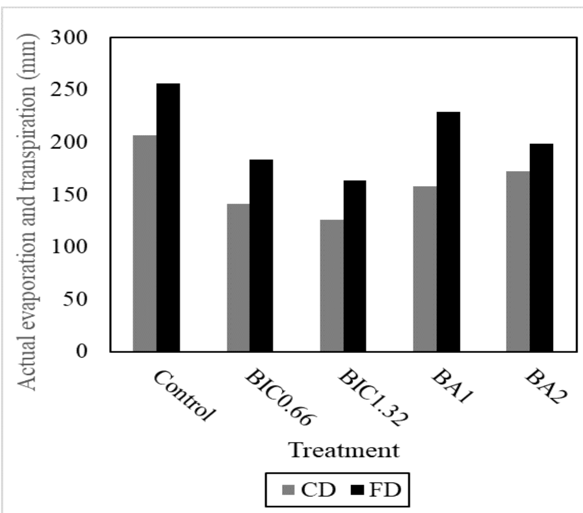

Fig. 4. Actual evaporation and transpiration rates during the growth period for treatments with controlled and free drainage. CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

Table 4. Effects of different levels of sugarcane bagasse and its biochar on nitrate and phosphate concentrations in soil and drainage water

		Solute concentration in soil (mg/g)				Drainage water concentration (mg/L)			
		NO_3		PO_4		NO_3		PO_4	
	Drain type treatment	**CD**	**FD**	**CD**	**FD**	**CD**	**FD**	**CD**	**FD**
Treatment	Control	5.7^{e}	4.4^{h}	8.18^{d}	5.7^{h}	4.5^{b}	5.8^{e}	0.35^{ab}	0.39^{a}
	BI0.66	7.3^{b}	4.9^{g}	9.36^{b}	7.61^{e}	1.6^{g}	1.94^{f}	0.12^{e}	0.19^{ed}
	BI1.32	8.34^{a}	5.4^{f}	9.72^{d}	8^{d}	1.2^{h}	1.5^{g}	0.11^{e}	0.15^{ed}
	BA1	6.6^{d}	4.6^{h}	8.42^{c}	6.4^{g}	2.8^{d}	3.2^{c}	0.18^{ed}	0.26^{cb}
	BA2	6.99^{c}	4.9^{g}	9.16^{b}	7.1^{f}	2.26^{e}	2.7^{d}	0.16^{ed}	0.39^{a}

Different letters in each row indicate differences between treatments ($P < 0.05$, LSD test). CD: controlled drainage and FD: Free drainage.

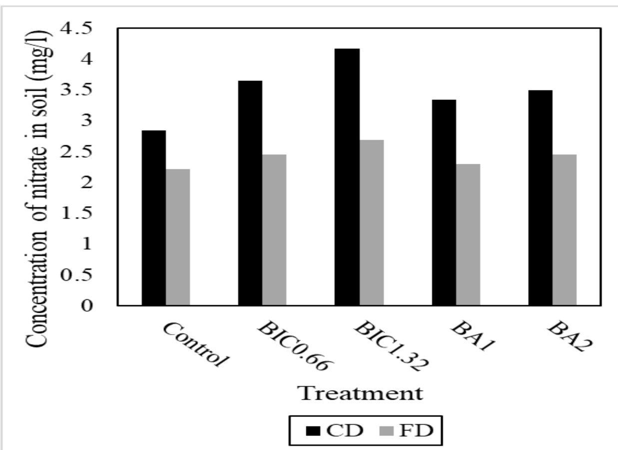

Fig. 5. Average nitrate concentration in soil (mg/L). CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

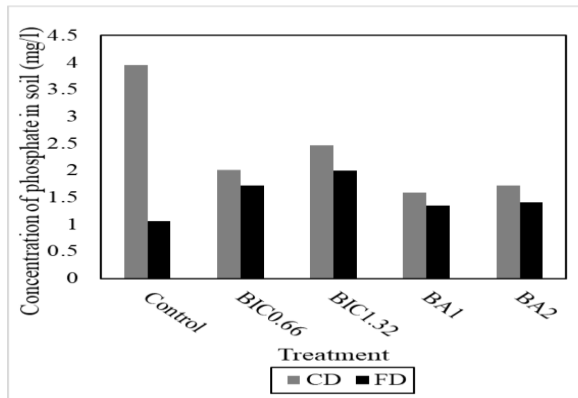

Fig. 6. Average concentration of phosphate in soil(mg/L). CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

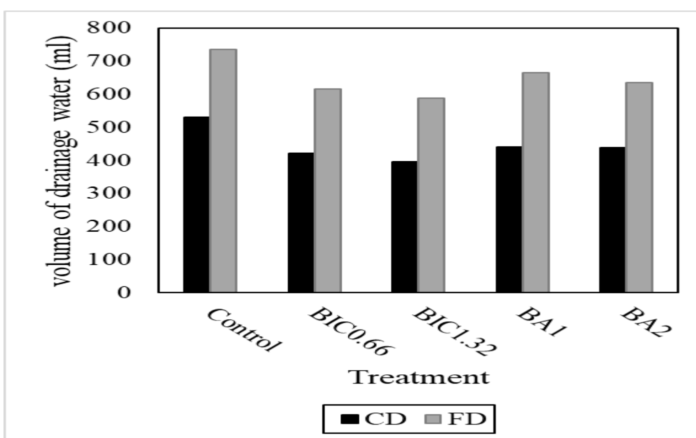

Fig. 7. Average volume of drainage water during the growing season (mL). CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

Table 5. Comparison of average effects of different levels of sugarcane bagasse and biochar on drainage water volume, fresh weight, dry weight, and irrigation water productivity index (WP_I)

		Volume of drainage water (mL)		Fresh weight (gr)		Dry weight (gr)		WP_I (Kg/m^3)	
	Drain type treatment	**CD**	**FD**	**CD**	**FD**	**CD**	**FD**	**CD**	**FD**
Treatment	Control	530^{d}	735^{a}	52.4^{a}	23.7^{cd}	24.5^{a}	10.3^{d}	1.7^{bc}	0.6^{f}
	BIC0.66	420^{e}	615b^{c}	35.6^{b}	24.7^{cd}	19.1^{abc}	16.9^{bc}	1.9^{ab}	1.2^{cde}
	BIC1.32	395^{e}	588^{cd}	46.6^{a}	25.3^{cd}	22.1^{ab}	17.5^{bc}	2.4^{a}	1.4^{bcd}
	BA1	440^{b}	665^{b}	32.3^{bc}	23.4^{d}	17.3^{bc}	13.8^{cd}	1.3^{cde}	0.8^{ef}
	BA2	439^{e}	634^{bc}	34.7^{b}	24.2^{cd}	17.8^{bc}	14.2^{cd}	1.5^{abcd}	0.9^{def}

Different letters in each row indicate differences between treatments ($P < 0.05$, LSD test), CD: controlled drainage and FD: Free drainage.

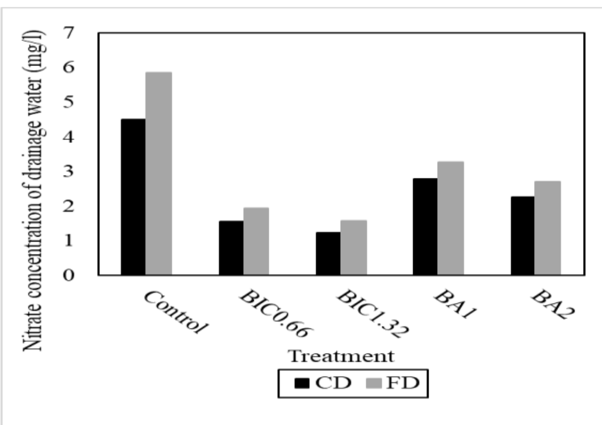

Fig. 8. Average of nitrate concentration of drainage water (mg/L). CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

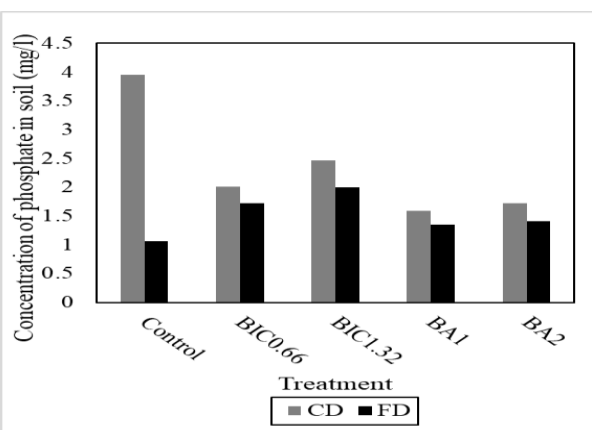

Fig. 9. Average of phosphate concentration of drainage water (mg/L). CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

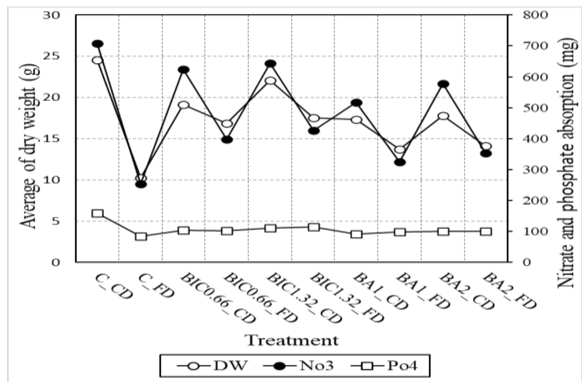

Fig. 10. The relationship between the performance of nitrate and phosphate absorbed by the plant. C-FD: free drainage without additive, C-CD: control drainage without additive, BIC0.66-CD: control drainage and biochar 0.66%, BIC1.32-CD: control drainage and biochar 1.32%, BA1-CD: bagasse 1% and control drainage, BA2-CD: bagasse 2% and control drainage, BIC0.66-FD: biochar 0.66% and free drainage, BIC1.32-FD: biochar 1.32% and free drainage, BA1-FD: bagasse 1% and free drainage, and BA2-FD: bagasse 2% and free drainage.

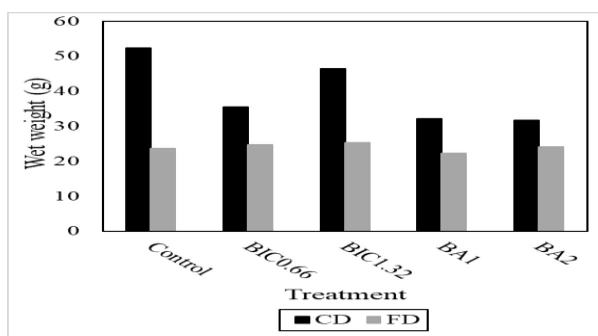

Fig. 11. Effect of product weight in controlled and free drainage with additives. CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

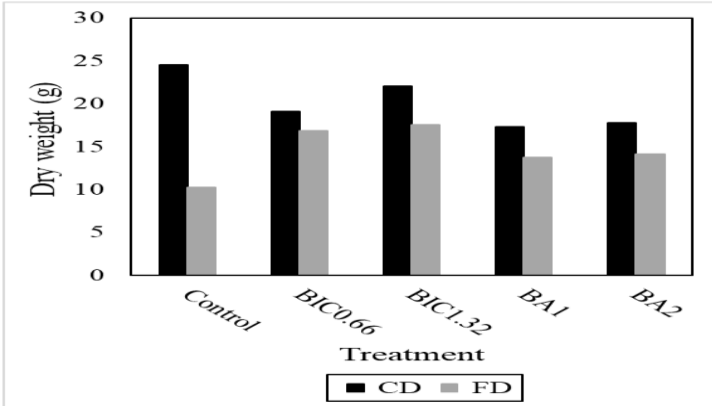

Fig. 12. Comparison of the dry weight of the product in controlled and free drainage with additives. CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

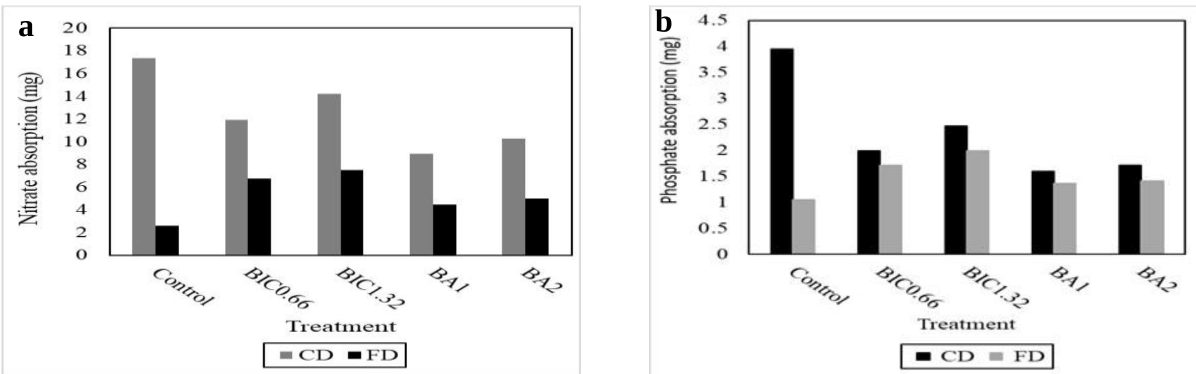

Fig. 13. Average (a) nitrate and (b) phosphate absorbed by field pea. CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

Table 6. Comparison of average effects of different levels of sugarcane bagasse and biochar on plant absorption of nitrate and phosphate

Absorption		**Field pea (mg/plant)**			
		NO_3		**PO_4**	
	Drain type treatment	**CD**	**FD**	**CD**	**FD**
Treatment	Control	17.34^{a}	2.57^{g}	3.95^{a}	1.05^{c}
	BIC0.66	11.94^{cd}	6.74^{ef}	2^{bc}	1.72^{bc}
	BIC.32	14.24^{ab}	7.49^{efd}	2.47^{b}	2^{bc}
	BA1	8.96^{ecd}	4.47^{fg}	1.6^{bc}	1.36^{bc}
	BA2	10.28^{cd}	4.99^{fg}	1.72^{bc}	1.41^{c}

Different letters in each row indicate differences between treatments ($P < 0.05$, LSD test). CD: controlled drainage and FD: Free drainage.

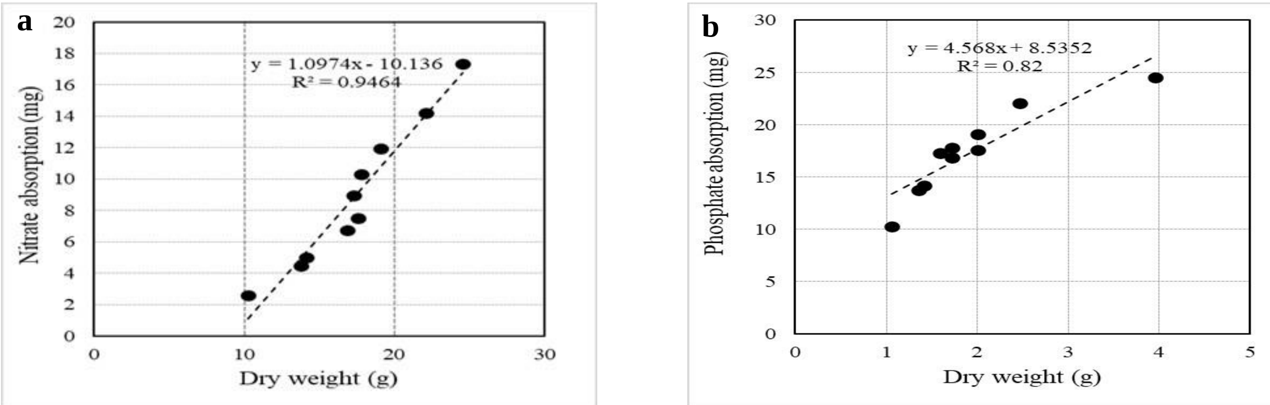

Fig. 14. The correlation coefficient of (a) nitrate and (b) phosphate compared to the dry weight of the plant.

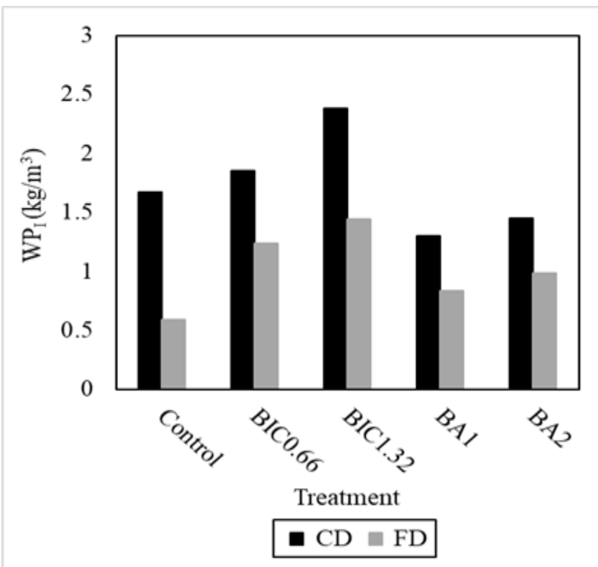

Fig. 15. Comparison of irrigation water productivity (WPI) in controlled and free drainage with additives. CD: control drainage, FD: free drainage, BIC0.66: biochar 0.66%, BIC1.32: biochar 1.32%, BA1: bagasse 1%, and BA2: bagasse 2%.

CONCLUSION

This research highlighted the significant benefits of CD, as well as biochar and bagasse used as organic additives on soil nutrient dynamics and plant growth. CD effectively reduced the concentration of nitrates and phosphates in the drainage water, thereby increasing their availability for plant uptake. This reduction in nutrient leaching is crucial for maintaining soil fertility and promoting sustainable agricultural practices.

Biochar and bagasse improved the soil's w(WHC), which helps in retaining more water and enhancing nutrient absorption by plants. Treatments with biochar (BIC0.66% and BIC1.32%) and bagasse (BA1% and BA2%) showed substantial increases in both fresh and dry weights of plants compared to FD treatments. This indicates that these organic additives can effectively mitigate water stress and nutrient loss, leading to better plant performance.

The study also underscores the importance of optimizing irrigation scheduling and water management practices. By controlling the water table and using organic additives, it is possible to reduce the volume of drainage water, thereby minimizing nutrient losses and improving water use efficiency (WP_I). The current research found that WP_I in CD treatments was significantly higher than in FD treatments, suggesting that CD can lead to more efficient water use and higher crop yields.

In conclusion, the combination of CD and the two organic additives, i.e., biochar and bagasse, can significantly enhance soil nutrient retention, improve plant growth, and increase agricultural productivity, thus offering practical solutions for sustainable farming practices.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Methodology: Tohid Balouchi Anaraki and Ali Reza Mokhtari Khozani; Investigation: Tohid Balouchi Anaraki and Ali Reza Mokhtari Khozani; Formal analysis: Tohid Balouchi Anaraki and Ali Reza Mokhtari Khozani; Writing—original draft preparation: Tohid Balouchi Anaraki and Ali Reza Mokhtari Khozani; Writing—review and editing: Mohammad Shayannejad, Mehdi Gheysari, and Hamid Reza Eshghizadeh; Supervision: Mohammad Shayannejad; Visualization: Tohid Balouchi Anaraki and Ali Reza Mokhtari Khozani; Funding acquisition: Mohammad Shayannejad.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

ETHICAL STATEMENT

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Isfahan University of Technology (Date:2025,27Sep.).

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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