

Optimization of biochar and drip irrigation to improve chili yield and soil properties

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Abstract. *Widowati, Biru SM, Agastya IMI, Cahya UTW, Wilujeng R. 2025. Optimization of biochar and drip irrigation to improve chili yield and soil properties. Asian J Agric 9: 442-453.* Cayenne pepper (*Capsicum frutescens*) is an important horticultural crop in Indonesia; however, its yield remains below optimal despite rising demand. This study intends to (i) assess changes in soil bulk density, particle density, and porosity; (ii) evaluate the effects of irrigation techniques and the application of biochar on chili yields; and (iii) identify the best combination for optimizing resource usage and yield. Eight different treatment combinations, each repeated four times, were used in a nested randomized design study conducted in Tunggulwulung Village, Malang. As the primary factor, the treatments included two main irrigation techniques (conventional and drip), which were further subdivided with different rates of biochar application (0%, 2%, 4%, and 6%). There were 160 pots total, with five plants per treatment acting as experimental units. Rice husks that had been pyrolyzed for three to four hours at 600°C were the source of the biochar. According to the results, adding biochar to conventional irrigation increases fruit weight by 125% and yield by about 130%. Drip irrigation with 4% biochar, on the other hand, is the most successful technique and yields much larger improvements, increasing fruit weight by 764% and fruit yield by 324%. Drip irrigation is more effective and yields better results than conventional irrigation, especially when combined with rice husk biochar. Furthermore, soil porosity and water use efficiency are significantly increased when 4% and 6% doses of biochar are added to drip irrigation systems.

Keywords: Bulk density, drought stress, soil amendment, soil porosity, SEM analysis

INTRODUCTION

Chili peppers (*Capsicum* spp.) are essential crops but increasingly threatened by climate variability and declining soil fertility, leading to reduced productivity (Prajapati et al. 2024). The main constraints in chili cultivation are low fertility and water scarcity, which often induce drought stress and yield loss. Improving fertility with organic matter and applying efficient irrigation are crucial strategies (Ayaz 2021). Beyond conventional management, biostimulants and nanofertilizers offer sustainable alternatives. Biostimulants such as seaweed extracts and amino acids enhance growth and resilience, while nanofertilizers improve nutrient absorption and yields by up to 13% (Chaitra et al. 2024; Goyal et al. 2025; Singh et al. 2025).

However, the integration of organic amendments with efficient irrigation to address climate and water challenges remains limited. Low soil organic matter and nutrient deficiency constrain chili yield (Hussain et al. 2023). Biochar, a carbon-rich material from biomass pyrolysis (Wang et al. 2022; Li and Tasnady 2023), enhances fertility, sequesters carbon, and improves productivity (Kabir et al. 2023). Although not a fertilizer, biochar's high cation exchange capacity supports nutrient retention and uptake, while improving aggregation, aeration, and porosity (Mohan et al. 2018; Purakayastha et al. 2019; Alkharabsheh et al. 2021). These effects arise from its porous, chemically stable

structure, particularly beneficial in sandy soils (Knoblauch et al. 2021; Khan et al. 2024).

Biochar also enhances soil water retention and efficiency. It increases field capacity, wilting point, and available water (Baiamonte et al. 2020). Water use efficiency can reach 95-98% (Abdou et al. 2024b). Meta-analyses reveal the strongest effects in medium-textured soils, with long-term benefits in fine-textured soils (Wei et al. 2023). Higher dosages improve soil moisture and support water-saving irrigation (Acharya et al. 2024; Aleiadeh 2024). Biochar reduces evapotranspiration and prolongs soil moisture (Feng et al. 2023). A review of over 150 studies confirmed positive effects on porosity and plant-available water, though influenced by feedstock, pyrolysis temperature, and soil type (Amer et al. 2021). It also lowers bulk density, increases micropores, and strengthens aggregation (Abdou et al. 2024a).

The magnitude of these benefits depends on application rate and soil type. At 40-60 t/ha, bulk density declines 8-12% while porosity rises 15-20% (Pranagal and Piotr 2020). In sandy soils, 20 t/ha of hardwood biochar (<2 mm) increased porosity 2%, water retention 18%, and reduced bulk density from 1.52 to 1.38 g/cm³ (Botková et al. 2023). In China, 50 t/ha raised porosity 14-32% and decreased bulk density linearly (Jang et al. 2023). A meta-analysis of 59 studies reported reductions up to 29% in bulk density and increases up to 59% in porosity, especially in coarse

soils (Singh et al. 2022a). In Turkish clay soils, 80 t/ha reduced bulk density 4.2% and increased porosity 9.7% (Abdulwahhab and Cedvet 2021). Such improvements result from stable organic matter, micro-aggregate formation, and pore enhancement (Alma and Alperay 2021).

Overall, biochar enhances water retention, porosity, and aggregation while lowering bulk density (Kolambani and Widowati 2022). This sustains root-zone moisture and yield. Yet conventional irrigation often fails to maintain adequate water, leaving crops drought-prone (Touil et al. 2022). Drip irrigation is vital, delivering water directly to roots, increasing yields, minimizing evaporation, and maintaining soil moisture (Soko et al. 2019; Guo et al. 2023).

The synergy of biochar and drip irrigation is promising. Biochar absorbs and gradually releases water, complementing drip irrigation's precision. This combination boosts soil water storage and ensures gradual release based on plant demand (Jiang et al. 2024). Consequently, irrigation frequency and volume decline, nutrient leaching is reduced, and root stress is minimized. This integration conserves water and enhances yields, especially in semi-arid regions. Widowati et al. (2025) reported higher flower production and yields in cayenne pepper under biochar with irrigation. Nevertheless, the influence of biochar on soil characteristics and crop productivity is still variable, highlighting the need for additional research to better understand its long-term effects (Mukherjee et al. 2021).

Combining biochar with drip irrigation offers a holistic solution to improve soil structure, water retention, and chili yields under limited water conditions (Maida et al. 2020). Addressing both fertility and water scarcity, this strategy provides a sustainable pathway for chili production. Therefore, this study aims to (i) evaluate biochar and irrigation effects on yield, (ii) assess changes in bulk density, particle density, and porosity, and (iii) determine the best combination for improving productivity and efficiency.

MATERIALS AND METHODS

Study site and experimental design

The experiment was carried out from July to November 2024 in Bawang Hamlet, Tunggulwulung Village, Lowokwaru District, Malang, East Java, Indonesia. The average temperature is 22.7–25.1°C and humidity is 79–86%, with a maximum temperature of 32.7°C and humidity up to 99%. Soil and plant samples were analyzed at the Soil Laboratory of the Science Techno Park, Universitas Tribhuwana Tunggaladewi, Malang, Indonesia. The chemical compositions of chicken manure fertilizer, rice husk biochar, and soil samples before treatment and after a 7-day incubation period were detailed by Widowati et al. (2025).

Eight treatments were tested in four replicates using a nested randomized block design (RAK), with irrigation method (drip and conventional) as the main factor and biochar dose (four levels) as a nested factor within the main factor. Drip irrigation (coded as T) and conventional irrigation (coded as K) were applied. For drip irrigation, the treatment codes were TB0, TB2, TB4, and TB6, while for conventional irrigation, the codes were KB0, KB2, KB4,

and KB6. The letter B indicates the level of biochar application, where B0: 0%, B2: 2% equivalent to 120 g, B4: 4%; 240 g, and B6: 6%; 360 g. For each treatment, 5 plants were used as experimental units, resulting in 160 polybags, 80 of which were used for drip irrigation and the remaining 80 for conventional irrigation.

Procedures

Planting media and biochar preparation

All treatments received 200 g of chicken manure per polybag in addition to NPK Mutiara 16:16:16 fertilizer applied at half the recommended rate. The soil used in this study had a loamy texture with a pH of 5.95. Widowati et al. (2025) give comprehensive details on the initial chemical composition of the soil as well as the properties of the soil after applying biochar and allowing it to incubate for seven days. Biochar was produced by pyrolyzing rice husk at 600°C for a duration of three to four hours. In accordance with the specified treatment levels, biochar was added to the planting media at the beginning of preparation. Each polybag containing 6 kg of soil was thoroughly mixed with biochar, irrigated with 1 L of water, and allowed to incubate for 7 days prior to the relocation of the chili seedlings.

Chili cultivation

After being cultivated for 25 days, chili seedlings of the superior Ori 212 variety (from the farm store) were moved at a 50×50 cm interval. The chili seedlings are tended to by fertilization, weeding, pest control, drip and conventional watering, and routine inspections until harvest after being transferred to the planting medium.

The Ori 212 chili pepper variety is a superior variety with upright plants, many branches, and resistance to pests and diseases such as thrips and anthracnose. The fruit is about 4.5 cm in size, orange-red when ripe, with a high level of spiciness and good shelf life. This variety is suitable for cultivation in lowland areas with a potential yield of up to 10 tons per hectare within 90 days after planting. Ori 212 has official certification and is widely used by farmers as a productive and easy-to-maintain option.

Setting up irrigation

The water reservoir stands at a height of 50 cm, and water distribution is facilitated through 0.5-inch PVC pipes, positioned to maintain a 5 cm slope for optimal flow. Installation involves placing 6.7 m bamboo poles along each row of plants. Water is delivered from the main hose to individual emitters in each polybag, aided by secondary and tertiary hoses secured to these poles. Each polybag is supported by a bamboo stake to keep the hoses in the proper position and steady.

Drip irrigation

Through a valve on the main pipe, drip irrigation controls the flow of water, enabling accurate delivery to the emitters via attached hoses. Typically, the 400-L storage tank fills in 20.4 minutes at a rate of about 7 seconds per L. With this system, 500 mL of water can be dispensed in approximately 1 hour and 15 minutes. Every 2–3 days, 500–1,500 mL of water is applied (for 1.25–3.75 hours), usually

in the late afternoon. During the growing season, the amount of water is scheduled based on the needs of the plants.

Following the preset irrigation schedule, the drip system's water delivery volume was meticulously calibrated based on the estimated water requirements of chili plants (Widowati et al. 2025). The daily water needs of chili plants (ETc) were specified for different growth stages: 173 mL per plant during the early phase, 341 mL during the growth phase, 606 mL during fruit formation, and 598 mL during ripening. It was found that the average potential evapotranspiration (Eto) was 3.91 mm per day. Widowati et al. (2025) give thorough explanations of how the drip irrigation system works and how it is used, along with the traditional watering technique.

Conventional irrigation

Traditional irrigation involves manually applying water with a watering can or other comparable implements. Every plant receives between 200 and 400 mL of water per day, which is adjusted to match the amount provided by the drip system. Adjustments are made based on the specific water requirements of the chili plants.

Measured parameters

The soil physical properties measured at harvest included bulk density (BD), particle density (PD), and soil porosity. Fruit weight per plant at harvest (14-17 WAP), dry shoot and root biomass at week 17, and the quantity of fruits at 10, 12, 14, and 17 weeks after planting (WAP) were all plant parameters that were monitored.

Data analysis

The collected data were subjected to Analysis of Variance (ANOVA), and where significant treatment effects were detected, the Least Significant Difference (LSD) test was applied at a 5% significance level to determine differences between means.

RESULTS AND DISCUSSION

The results of this study indicate that the combination of rice husk biochar with drip irrigation significantly improves chili growth and yield. Biochar is likely effective not only due to its physical properties that enhance water retention capacity and soil porosity but also because of the presence of bioactive compounds such as organic acids, phenolics, and micronutrients that can stimulate soil microbial activity and improve nutrient availability for plants (Samyukta et al. 2024). These improvements were observed in vegetative growth parameters and fruit productivity, consistent with the findings of Abdou et al. (2024a) on sugar beet and El-Mageed et al. (2020) on *Capsicum annum*, which demonstrated the role of biochar in enhancing water and nutrient uptake efficiency.

In addition, the application of drip irrigation has been shown to significantly improve water use efficiency and chili yields, supporting the findings of Guo et al. (2023). The combination of these two treatments appears to be synergistic, where biochar enhances the soil's water-

holding capacity while drip irrigation provides a more controlled water supply, resulting in lower water stress and improved photosynthetic efficiency in plants.

Comparisons with other studies on chili peppers or similar horticultural crops reinforce these findings. For example, Baiamonte et al. (2020) and Han et al. (2023) reported increases in biomass and yield in *C. annum* with the application of rice husk-based biochar, while Amer et al. (2021) emphasized the importance of biochar interaction with soil quality to support root growth and plant productivity. Specific differences may arise due to soil type, climatic conditions, and biochar dosage, highlighting the need for local adaptation in practical implementation. In line with these findings, recent studies on *C. annum* also indicate that biochar consistently enhances plant growth and productivity. Kebede et al. (2023) reported that the combination of biochar and compost on chili pepper fields increased pH, soil organic matter, and nutrient availability, resulting in the highest chili pepper yield at a dose of 4 t/ha. Similar results were also demonstrated by Zheng et al. (2023), where the co-application of biochar and vermicompost in a sustainable chili intercropping system increased fresh yield by 24-89% and improved nitrogen, phosphorus, and potassium fertilizer efficiency. Furthermore, Gaber et al. (2024) found that in sandy soils under drought conditions, the application of 2% biochar improved growth, root distribution, and fruit nutrient content (N, P, K, Ca, Mg), making plants more resistant to water stress. This mechanism is supported by the findings of Hareem et al. (2024), who showed that biochar increases chlorophyll content, antioxidant enzyme activity, and the accumulation of phenolic compounds and flavonoids in chili peppers under stress conditions, indicating biochar's role in modulating bioactive compounds while enhancing product quality.

Variations in responses across studies can be explained by differences in soil type, climatic conditions, and biochar quality, including feedstock and pyrolysis temperature, as demonstrated by Sanchez et al. (2024) and Xie et al. (2023), who found that biochar derived from pistachio shells at 450°C and biochar with high specific surface area yielded more optimal pepper outcomes. The consistency of these findings with research on other vegetables, including the use of rice husk biochar proven to improve water retention and soil pore connectivity (Williams et al. 2023), further strengthens the argument that biochar not only acts as a soil conditioner but also enhances the physiological and bioactive quality of horticultural crops.

Examination of rice husk biochar using Scanning Electron Microscopy (SEM)

With an accelerating voltage of 20 kV, the SEM analysis provided enough resolution to clearly show the microstructural properties of rice husk biochar. At 1000x magnification, the surface morphology was clearly visible. It was determined that 39.7 seconds of data acquisition time was sufficient to obtain a representative spectral profile.

Figure 1 is an electron microscope image showing the microstructure of plant tissue at a scale of 100 µm, used to analyze the condition and quality of tissue related to plant

productivity. The SEM image of the surface morphology (Figure 1) revealed that rice husk biochar possesses a porous and irregular surface, indicative of an effective formation process and distinct variations between micro- and macrostructures. The biochar's exceptionally high carbon content—77.2% by weight and 83.5% by atomic percentage—reflects its predominantly organic nature. Additionally, oxygen made up 17.1% of the weight, while silica made up 5.3%, most likely from oxide compounds, mineral residues, or contaminants. The water retention capacity and cation exchange ability of the biochar, which are critical elements impacting its surface qualities and long-term stability, are greatly influenced by these structural features.

Figure 2 is an EDS spectrum showing the elemental analysis of the sample with the horizontal axis representing energy in keV and the vertical axis representing count intensity. The peaks in the spectrum indicate the presence of elements such as carbon (C), oxygen (O), silicon (Si), and potassium (K), with the highest peaks representing the relative abundance of these elements in the sample. The eZAF quantitative results (Figure 2) detail the elemental composition of rice husk biochar, as summarized in Table 1. Table 1 shows a comparison of the elemental composition of rice husk biochar based on weight (%). Carbon (C) is the predominant element, comprising 77.2% by weight and 83.5% by atomic percentage, highlighting the biochar's organic nature and emphasizing carbon's critical structural role. In addition to reflecting the biochar's organic qualities, the high carbon content greatly improves soil quality, which promotes the growth of chilies (Yadav et al. 2023). Moreover, carbon is essential for improving the physical and chemical characteristics of soil as well as for sequestering carbon in the soil (Li et al. 2023).

Oxygen (O), which was probably derived from oxide or mineral compounds, was found at 17.1% by weight and 13.9% by atomic percentage. Photosynthesis and respiration are two biochemical processes in plants that depend on oxygen (Khorobrykh et al. 2020). At 5.3% by weight and 2.5% by atomic percentage, silica (Si) was found; it may have come from contaminants or was an inherent part of the

biochar matrix. Silica improves resistance to environmental stress and fortifies plant cell walls (Debona et al. 2017).

Potassium (K) content was relatively low, at 0.4% by weight and 0.1% by atomic percentage, indicating a minor structural contribution to the biochar. Nonetheless, potassium remains crucial for plant physiological functions, including water regulation, fruit quality enhancement, and protein synthesis (Hasanuzzaman et al. 2018). The substantial carbon content also imparts organic properties, mechanical strength, and reactivity of the biochar towards other elements (Sarfaraz et al. 2020; Li et al. 2023; Yang et al. 2025). The dominance of carbon underscores the biochar's organic framework and its pivotal role in improving soil fertility and water retention capacity.

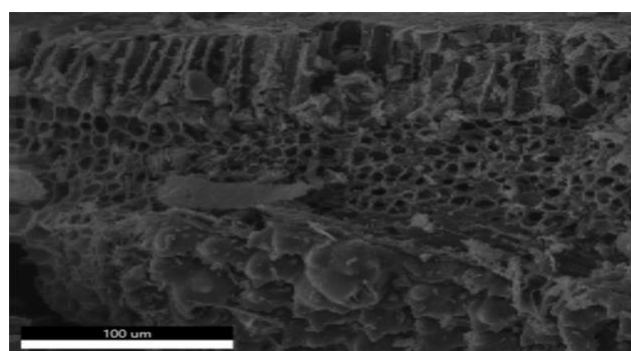


Figure 1. Surface morphology of biochar. Scale bar: 100 μm

Table 1. Elemental composition of rice husk biochar

Element	Weight (%)	Atom (%)
C	77.20	83.50
O	17.10	13.90
Si	5.30	2.50
K	0.40	0.10

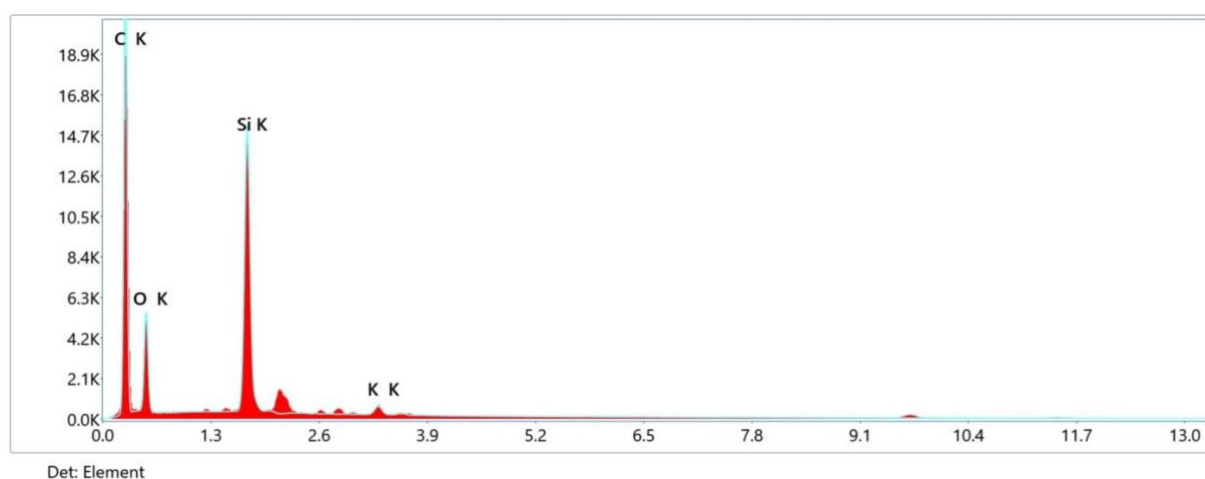


Figure 2. eZAF Quant result from SEM analysis on rice husk biochar

Effects of irrigation method and biochar application rate on chili yield

Both the fruit weight per plant (F value=73.67 > F table=7.82) and the number of fruits per plant at harvest (F value=56.96 > F table=7.82) were significantly impacted by the type of irrigation used. Similarly, adding biochar to the irrigation system had a statistically significant effect on both the number of fruits per plant (F value=18.27 > F table=3.67) and fruit weight per plant (F value=13.61 > F table=3.67). With an average fruit weight of 122.40 g and 62.84 fruits per plant, drip irrigation outperforms conventional irrigation by a significant margin. With traditional irrigation, 33.75 fruits and 37.27 g are produced. The best results were obtained when drip irrigation and 4% biochar were combined. The maximum fruit weight (193.68 g) and fruit number (94.25 fruits per plant) were observed, as presented in Figures 3 and 4, respectively. Furthermore, applying biochar continuously increased yield; higher dosages were associated with more fruit in terms of both weight and quantity. Together, drip irrigation and 4% biochar enhance soil quality and water distribution effectiveness, greatly boosting harvest yields.

According to Oktavia et al. (2025), using biochar and drip irrigation together can boost chili growth and yield while also enhancing soil quality. Even though adding biochar to conventional irrigation increases yields, drip

irrigation still produces better results. By supplying moisture straight to the root zone, drip irrigation improves the efficiency of water distribution (Banik et al. 2024) and maximizes the availability of water and nutrients to support plant growth (Arouna et al. 2023; Yang et al. 2023). Because of its porous structure, large surface area, negative charge, and intricate pore morphology (Purakayastha et al. 2021), biochar increases cation exchange capacity and adsorption potential (Liu et al. 2024), allowing nutrients to be released gradually (Zhang et al. 2023). These factors all contribute to increased chili productivity. When combined, these elements result in higher crop yields and more effective use of water and fertilizer. Figure 3 shows that drip irrigation treatment with 4% biochar (TB4) produced the highest fruit weight and was significantly different from all treatments, while conventional irrigation (KB) showed a lower increase.

The results of Amer et al. (2021) and Singh et al. (2022b), who showed that combining biochar with drip irrigation improves soil moisture retention and increases crop yields in sweet corn and chili peppers, are supported by this study. By increasing porosity and decreasing bulk density, the ideal biochar application enhanced soil structure and produced a more conducive environment for plant and root growth.

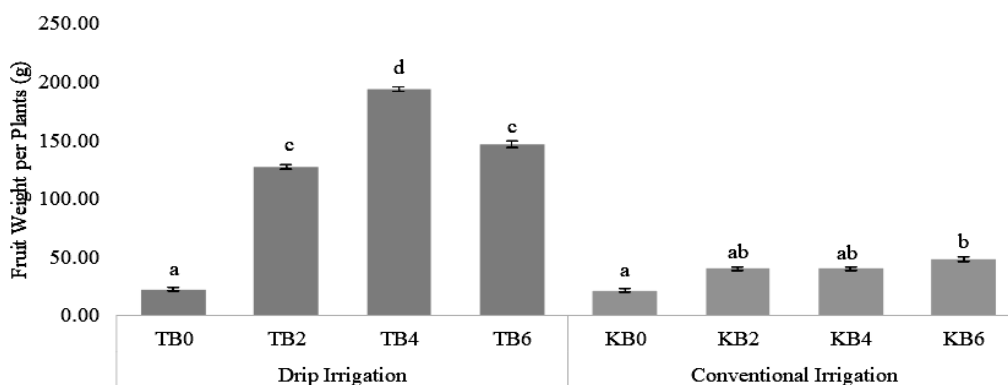


Figure 3. Impact of irrigation technique and biochar dosage on fruit weight per plant

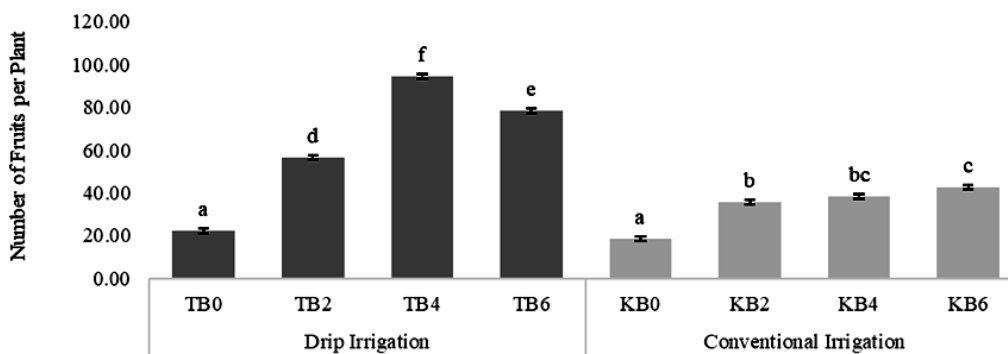


Figure 4. Impact of irrigation technique and biochar dosage on number of fruits per plant

In contrast to conventional irrigation, which only produced a 101.10% increase, Table 2 shows that drip irrigation significantly increased the average fruit weight per chili plant by 594.23%, or nearly six times. While the greatest increase under conventional irrigation was only 125.8% at a 6% biochar application rate (KB6), the most significant gain—nearly eightfold—was seen in the TB4 treatment. In the TB6 treatment, the bulk density decreased to 0.55 g/cm³, which promoted the formation of soil pores and improved root penetration and aeration (Zhang et al. 2024). Furthermore, porosity sharply rose, especially in TB6, reaching 77.4%. These results attest to drip irrigation's superior effectiveness in optimizing chili pepper yields. Furthermore, biochar improves fertilizer and water use efficiency and dramatically lowers greenhouse gas emissions, including CO₂ and CH₄, by 17.6-40.6% (Jia et al. 2024). The study found that a dosage of roughly 22 tonnes of biochar per hectare produced the best results. The effectiveness of biochar is influenced by its physical characteristics; fine particles (<1 mm) work best under 100% ETo irrigation, while coarse particles (>13 mm) work best under irrigation regimes that supply 120% ETo. Fine biochar enhances soil water retention and boosts water use efficiency by filling macro- and micropores (Amer et al. 2021). In conclusion, adding the appropriate amount of biochar to drip irrigation greatly boosts chili pepper production while also promoting sustainable farming practices by reducing greenhouse gas emissions and enhancing resource efficiency. Figure 4 shows that the combination of drip irrigation with a 4% biochar dose (TB4) produced the highest number of fruits per plant and was significantly different from other treatments, while conventional irrigation (KB), even when supplemented with biochar, still produced fewer fruits.

Table 3 demonstrates that drip irrigation greatly outperforms traditional irrigation in terms of increasing fruit yield. Fruit yield increased more than threefold under drip irrigation but only roughly twice under conventional irrigation when compared to the control. The TB4 treatment (drip + 4% biochar) showed the highest increase (323.37%) compared to the control, while the highest increase in conventional irrigation was found in KB6 (129.73%). This confirms that the combination of biochar and drip irrigation is superior in increasing chili productivity.

The results of this study support earlier findings that biochar greatly increases soil water retention capacity, especially when combined with drip irrigation. According to studies by Glab et al. (2016) and Murtaza et al. (2021), biochar's porous structure enhances soil porosity and water retention, which promotes microbial activity and root growth. Plants can maximize fruit production while reducing stress from water scarcity thanks to drip irrigation, which more effectively and directly delivers water to the root zone. For chili plants that are sensitive to drought, biochar helps to create a stable and moist root environment. This positive impact is further enhanced by drip irrigation systems' constant supply of moisture. Similar research on irrigation technologies by Jia et al. (2024) and on chili cultivation by Purakayastha et al. (2021) emphasizes the synergistic advantages of combining biochar with effective

irrigation, leading to increased yields, improved water use efficiency, and decreased greenhouse gas emissions.

By improving soil aeration, water retention, and nutrient availability without upsetting the chemical equilibrium of the soil, applying biochar at an ideal rate of 4% significantly boosts chili yields. Additionally, biochar promotes plant productivity by improving photosynthetic efficiency, expanding leaf width, and facilitating nutrient uptake (Kamrunnahar et al. 2024), all of which lead to increased growth and yield (Sun et al. 2017). These benefits are further reinforced by increased soil microbial diversity (Tan et al. 2024) and improved physicochemical soil properties (El-Mageed et al. 2020). Furthermore, biochar increases plant productivity through greater photosynthetic efficiency, wider leaves, and easier nutrient uptake (Kamrunnahar et al. 2024), all of which result in higher yield and growth (Sun et al. 2017). Rodríguez-Vila et al. (2022) reported that applying high amounts of biochar can raise soil pH, which might affect the availability of key micronutrients such as Cu, Fe, and Zn. On the other hand, inadequate biochar application might not result in appreciable gains in crop yield or soil quality.

Limiting nutrient accessibility for plants, overapplication also runs the risk of pore blockage and nutrient adsorption by the biochar itself (Kocsis et al. 2020; Xu et al. 2023; Lin et al. 2024). This study suggests that 4% biochar is the ideal dosage for increasing chili yields, while 2% seems to be insufficient to noticeably improve productivity or soil conditions. In summary, the results go beyond raising yield and offer useful advice for improving soil quality and water conservation. Biochar has great potential for use as a soil amendment in intensive, water-efficient farming techniques such as drip irrigation. The positive effects of biochar on plants depend on finding a balance between increased porosity and water retention and potential pH and nutrient availability changes. Application of biochar must therefore be carefully adapted to particular soil types, crop needs, and irrigation techniques. For chili plants, which need a lot of moisture but are prone to waterlogging, drip irrigation provides the best soil moisture regulation, ensuring their long-term and productive growth.

This system is an excellent choice for dry and marginal lands because it can save up to 29% and double the amount of water compared to conventional irrigation (Ranomahera et al. 2020; Yang et al. 2023). Because biochar improves soil water retention, nutrient availability, and reduces nutrient loss, this system performs exceptionally well in arid and marginal lands (Singh et al. 2019; Ren et al. 2023). According to Jiang et al. (2025), both have been demonstrated to function best when combined at a dose of 10 tons of biochar per hectare and irrigation at 1.0 ETc, providing agronomic and financial benefits for sustainable agriculture.

These findings are highly relevant to global agricultural challenges, including the development of efficient, sustainable, and climate-resilient food production systems. When it comes to drought, shifting rainfall patterns, and land degradation, water use is the main issue. Innovations like drip irrigation provide solutions because they waste less water, and integrating biochar adds a layer of food

security because it helps mitigate climate change by storing carbon in the soil and lowering the need for chemical fertilizers.

Impact of irrigation technique and biochar dosage on canopy and root dry weight

Impact of irrigation technique and biochar dosage on canopy and root dry weight. Similarly, the dry weight of the canopy increased significantly when biochar was added to the irrigation system (F value=8.17 > F table=3.67). The type of irrigation had a significant effect on root dry weight as well (F value=84.02 > F table=7.82), and the addition of biochar to the irrigation schedule significantly raised root dry weight (F value=8.17 > F table=3.67). With an average canopy dry weight of 31.93 g and root dry weight of 13.08 g, drip irrigation has outperformed conventional irrigation. Under conventional irrigation, these weights would have been 18.95 g and 7.39 g, respectively. When biochar was added at a dosage of 4% in combination with drip irrigation, both parameters notably increased; the highest canopy dry weight was 39.39 g (Figure 5), and the root dry weight was 14.27 g (Figure 6). On the other hand, treatments devoid of biochar had the lowest dry weights for the roots (5.69 g) and canopy (14.27 g). This increase in biomass implies that drip irrigation promotes better root system development and vegetative growth. Applying biochar at a rate of 4% encourages increases in plant height, leaf number, stem count, and flower production, according to Widowati et al. (2025). Compared to traditional irrigation techniques, drip irrigation supports optimal plant growth and yields more by minimizing water loss through evaporation and runoff, with water use efficiency ranging between 80% and 95% (Sirait et al. 2023). Figure 5 shows that drip irrigation (TB) with 4% biochar (TB4) produced the highest dry canopy weight and was significantly different from other treatments, while conventional irrigation (KB) produced lower dry canopy weight even with the addition of biochar.

Figure 6 shows that drip irrigation with a dose of 4-6% biochar (TB4 and TB6) produced the highest dry root weight and was significantly different from all other treatments.

Conventional irrigation (KB), even when biochar was added, still produced lower root weight.

When compared to traditional irrigation techniques, drip irrigation can save up to 40% of water usage during the vegetative stage and 37% during the generative stage (Cartika et al. 2023). Additionally, drip irrigation increases soil moisture content, which in turn stimulates the growth of advantageous microorganisms and improves soil nutrient availability (Wang et al., 2024). The highest harvest and fruit weight are obtained in conventional irrigation systems when biochar is applied at a rate of 6%. This is because the higher dosage helps to maintain soil moisture under a variety of environmental conditions.

Table 2. Comparison of drip and conventional irrigation on fruit weight gains per chili plant

Parameters	Drip irrigation (%)	Conventional irrigation (%)
Maximum fruit weight gain per plant	TB4 (763.49%)	KB6 (125.80%)
The least amount of fruit weight gain per plant	TB2 (465.89%)	KB4 (88.25%)
Fruit weight increase per plant on average	594.57%	101.10%

Table 3. Impact of irrigation methods on fruit production per chili plant

Irrigation type	Treatment	Increase in fruit yield (%) compared to the control
Drip irrigation	TB0	-
	TB2	153.49
	TB4	323.37
	TB6	253.03
Conventional irrigation	KB0	-
	KB2	91.89
	KB4	108.11
	KB6	129.73

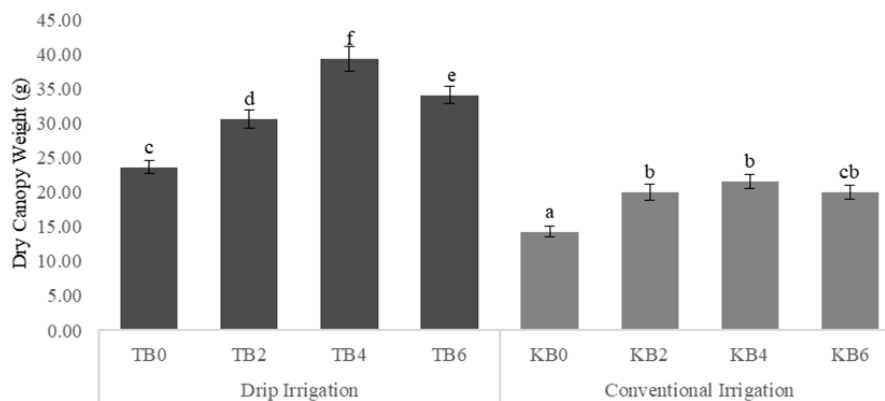


Figure 5. Impact of irrigation technique and biochar dosage on canopy dry weight

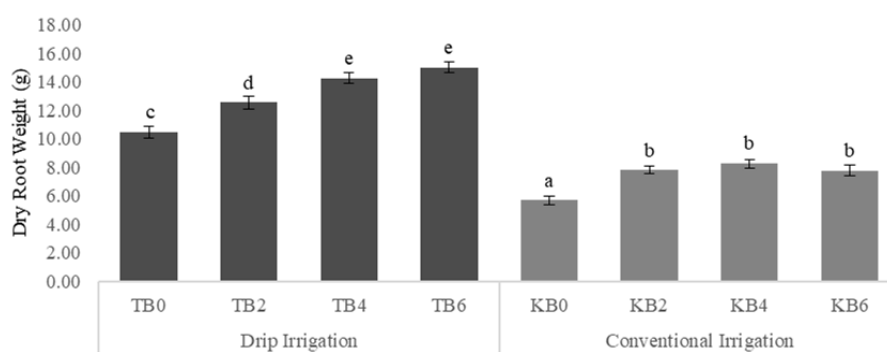


Figure 6. Impact of irrigation technique and biochar dosage on root dry weight

Effect of biochar dose and irrigation method on soil physical properties

According to statistical analysis, the irrigation method has no statistically significant impact on soil bulk density because the computed F-value of 3.85 is less than the critical F-value of 4.26. Similarly, the calculated F-value of 1.66, which is likewise below the critical value of 2.51, indicated no significant interaction effect between the type of irrigation and the application of biochar. Consequently, the bulk density of the soil is not statistically affected by the irrigation technique by itself or in conjunction with the application of biochar.

Particularly under drip irrigation with a 6% biochar dose (TB6), where bulk density decreased to 0.55 g/cm³ compared to 0.65 g/cm³ in the control treatment without biochar (TB0), there is a definite descriptive trend of decreasing soil bulk density with increasing biochar application rates (Figure 7). Figure 7 shows that high doses of biochar (TB6) reduced soil bulk density, but not significantly in drip irrigation (TB). In conventional irrigation (KB), the application of biochar did not significantly change soil bulk density. A looser, less compact soil structure is the result of an expansion of the soil's pore space, which is reflected in this decrease in bulk density. These circumstances promote root penetration and improve soil aeration, two factors that are critical for the best possible plant growth (Zhang et al. 2024).

These findings are corroborated by additional research, which shows that biochar can improve soil aggregate stability (as shown by a 9% increase in Mean Weight Diameter, or MWD), decrease bulk density by up to 18%, and have a positive impact on soil cohesion and penetration resistance (Zhang et al. 2024). Additionally, it has been demonstrated that applying biochar can reduce bulk density by up to 21% while increasing soil microbial activity and water content (Zhang et al. 2025).

Similar findings were found in studies on sweet corn that combined drip irrigation and biochar, which improved plant water availability by reducing bulk density by about 4%, increasing soil porosity by about 4%, and increasing volumetric water content in both saturated and field capacity conditions (Singh et al. 2022a).

In summary, although the statistical analysis did not reveal significant effects, biochar application at various

dosages consistently tends to improve soil physical properties by lowering bulk density and increasing porosity, thereby potentially supporting enhanced plant growth.

The analysis of variance results indicate that the type of irrigation did not have a statistically significant effect on soil particle density, as the calculated F-value of 1.34 was lower than the critical F-value of 4.26, demonstrating no meaningful difference between the irrigation methods employed. Additionally, with an F-value of 2.13—below the crucial threshold of 2.51—the interaction between the type of irrigation and the application of biochar did not significantly affect the density of soil particles. As a result, the density of soil particles was not significantly affected by either treatment. Figure 8 shows that soil particle density remained relatively stable in all treatments, both with drip irrigation (TB) and conventional irrigation (KB), as well as in all biochar doses. The soil particle density, which ranged from 2.38 to 2.51 g/cm³, stayed largely consistent across all treatments (Figure 8). Conversely, the irrigation type exerted a highly significant effect on soil porosity, as evidenced by an F-value of 16.81, exceeding the critical value of 7.82. Similarly, the addition of biochar in conjunction with irrigation type significantly influenced soil porosity, with an F-value of 11.32, surpassing the critical threshold of 2.74.

Soil porosity reflects the soil's capacity to retain water and provide adequate space for oxygen and moisture. In both conventional and drip irrigation systems, increasing the rates at which biochar was applied generally resulted in increased soil porosity, with the effect of drip irrigation being more noticeable. The TB6 treatment, for example, had a porosity of 77.40%, which was higher than the KB6 treatment's 76.15%. This improvement is probably due to drip irrigation's better moisture retention efficiency and more even water distribution. It has been demonstrated that drip irrigation and a high dose of biochar (6%) greatly increase soil porosity, which in turn encourages plant growth and improves water use efficiency in farming operations.

Figure 9 shows that high doses of biochar (TB6 and KB6) can significantly increase soil porosity. Drip irrigation (TB) is more consistent in increasing soil porosity than conventional irrigation (KB). Soil porosity tends to increase as bulk density decreases, as demonstrated by the highest porosity values in the KB6 (76.15%) and TB6

(77.40%) treatments (Figure 9). Greater porosity indicates increased pore space within the soil, which is essential for air and water availability, both critical factors for plant health and productivity. These results demonstrate that by increasing pore space and improving aeration, efficient irrigation management can improve the physical characteristics of soil, which are essential for the best possible plant growth and land productivity. However, depending on the type of soil and the amount of biochar applied, the impact of biochar on bulk and particle density of the soil frequently varies or is negligible.

Because biochar is porous, it can hold water in its pores, increasing the soil's overall moisture retention. The pore space in the soil acts as a reservoir for both air and water. Furthermore, by increasing the number of available water pores and decreasing the frequency of rapid drainage pores, biochar greatly improves the ability of soils, even sandy ones, to retain water. By increasing the quantity and size of soil pores, biochar's porous structure makes the soil looser and enhances its ability to retain air and water. Together, the macropores and micropores in biochar

produce more spaces between soil particles, improving the physical characteristics of the soil.

Higher rates of biochar application typically result in more pore space and higher soil porosity; however, at certain dosages, this effect may be lessened or even reversed. By allowing air and water to flow more easily, increased porosity improves soil structure and encourages the growth of roots. On the other hand, biochar particles smaller than 0.5 μm may decrease soil porosity at low application rates, like 2%, by filling existing soil pores and thereby lowering the total pore volume (Glab et al. 2016).

Drip irrigation systems tend to lower the bulk density of soil by delivering water at low flow rates and high frequency straight to the root zone, maintaining ideal soil moisture levels without compaction or waterlogging. This method tends to maintain favorable porosity and reduce bulk density of the soil. On the other hand, waterlogging, soil compaction, increased bulk density, and decreased soil porosity can result from the massive amounts of water applied all at once during conventional irrigation.

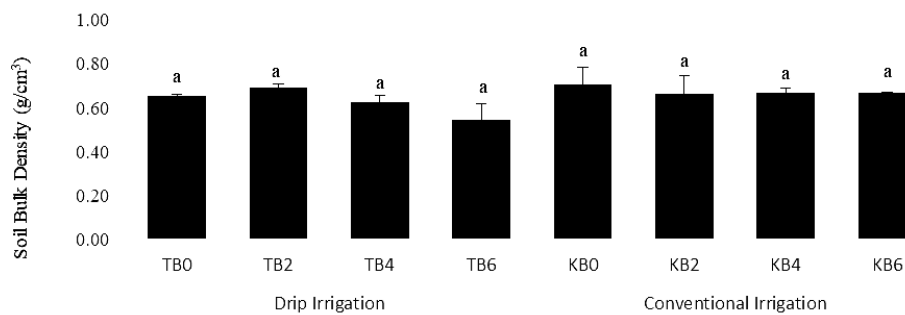


Figure 7. The effect of irrigation and biochar application on soil bulk density

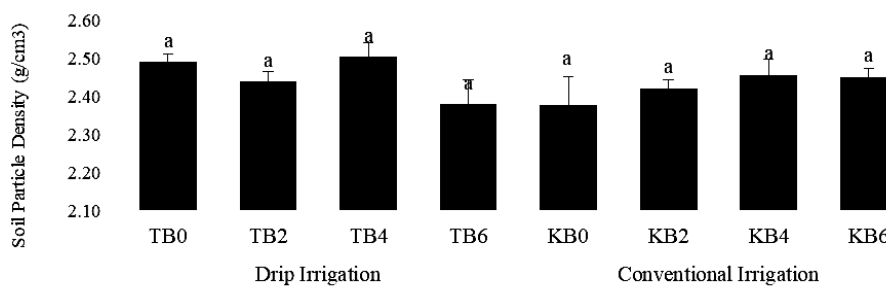


Figure 8. The effect of irrigation and biochar application on soil particle density

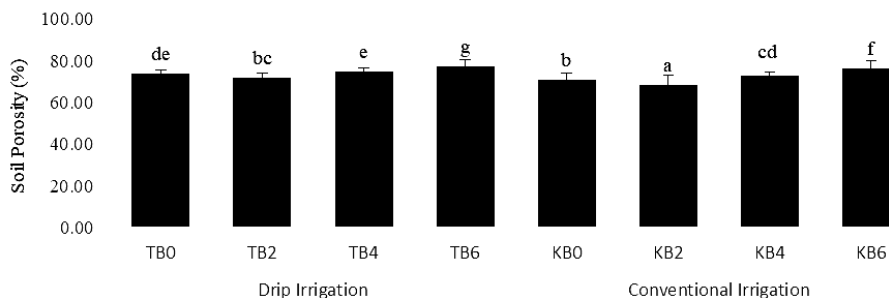


Figure 9. The effect of irrigation and biochar application on soil porosity

Table 4. Soil porosity and chili yield, shoot, and root biomass correlation

	Number of fruits	Fruit weight per plant	Dry shoot weight	Dry root weight
Porosity	0.48**	0.41*	0.54**	0.53**

Relationship between soil porosity and cayenne pepper yield and biomass

The analysis presented in Table 4 indicates a moderately significant correlation ($r=0.480$) between soil porosity and the number of cayenne pepper fruits produced per plant. This suggests that by improving the soil's capacity to retain water and oxygen, increasing soil porosity through the use of drip irrigation or the application of biochar can boost crop yield. Table 4 also shows that soil porosity and fruit weight ($r=0.410$), dry shoot weight ($r=0.504$), and dry root weight ($r=0.527$) have statistically significant correlations ($p<0.05$). Higher soil porosity promotes the best possible plant growth, according to these moderate correlations. Despite the lack of a significant correlation, cayenne pepper productivity can be increased by controlling soil porosity with drip irrigation or biochar.

Significant correlations were confirmed by linear regression analyses between soil porosity and dependent variables (fruit weight, number of fruits, dry shoot weight, and dry root weight). The data met the requirements for linearity, homoscedasticity, and normality (Kolmogorov-Smirnov test, Asymp. Sig. >0.05). According to the coefficient of determination (R^2), soil porosity accounted for 27.8% of the variation in dry root weight, 25.4% in dry shoot weight, 16.8% in fruit weight, and 23.1% in fruit number. The regression models' predictive reliability was confirmed by the F and t tests, which also validated their significance ($p<0.05$).

According to the regression analysis, the equation $Y = 251.888 + 4.100X$ ($p=0.005$) indicates that for every 1% increase in soil porosity, the number of fruits produced by a cayenne pepper plant rises by roughly 4.1. Likewise, $Y = -559.797 + 8.737X$ ($p=0.020$) indicates that for every 1% increase in soil porosity, fruit weight rises by an average of 8.737 g, underscoring the critical role porosity plays in raising yield. Furthermore, dry shoot weight improves by 1.375 g for every 1% increase in porosity ($Y = -75.260 + 1.375X$, $p=0.003$), and dry root weight increases by 1.312 g for every 1% increase in porosity ($Y = -9.503 + 1.312X$, $p=0.002$).

Collectively, these correlation and regression findings confirm that soil porosity plays a vital role in the growth and productivity of cayenne pepper. Managing soil porosity through the application of biochar and the use of drip irrigation has been demonstrated to enhance crop yields by improving the physical soil environment, which supports both shoot and root development. Because it controls the soil's ability to hold onto water and provide oxygen to the roots, soil porosity is essential for plant growth. Increased porosity promotes cayenne pepper plants' ideal growth by enhancing aeration and water availability. By increasing

the soil's capacity to hold water and oxygen, biochar or drip irrigation can improve soil porosity, which encourages healthy root development and raises biomass from both shoots and roots. When comparing treated and untreated controls, higher soil porosity is also linked to higher fruit weight and quantity. High doses of biochar (6%, for example) greatly increase soil porosity, which is in line with increases in cayenne pepper shoot and root biomass that have been observed. Furthermore, effective drip irrigation promotes better soil porosity and plant development.

In conclusion, using biochar and drip irrigation together greatly improves soil quality and chili yield. Specifically, employing drip irrigation enhanced with 4% biochar (TB4) resulted in an incredible 324% increase in fruit number and a remarkable 764% increase in fruit weight when compared to the control. Compared to using 6% biochar in combination with traditional irrigation (KB6), which only resulted in a roughly 130% increase in fruit weight and a 125% increase in fruit number, this performance was noticeably better. Significant increases in plant biomass were also observed under TB4; peak root dry weight was 14.27 g, compared to 5.69 g in the control, and the highest dry canopy weight was 39.39 g, compared to 14.27 g in the control. With bulk density decreasing from 0.69 g/cm³ in the control to 0.55 g/cm³ and soil porosity increasing to 77.40% under the TB6 treatment, notable improvements in soil physical properties were also observed. Therefore, drip irrigation combined with 4% biochar is the most effective way to maximize chili.

These findings suggest that adding 4% biochar to drip irrigation can both sustainably improve soil quality and practically increase chili yields in arid areas. The study's shortcomings include the lack of data on long-term impacts on nutrient availability and soil microbes, as well as the variation in plant responses across soil types and climates. Thus, additional study is needed to evaluate the technology's use and long-term impacts in various agroecological settings.

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