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RICE HUSK BIOCHAR AND WATER-APPLICATION PATTERNS SHAPE SHRINK–SWELL VERTISOL–MAIZE RESPONSES UNDER IDENTICAL CUMULATIVE WATER INPUTS

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ABSTRACT

Shrink-swell Vertisols persistently constrain crop growth because unstable pore conditions can limit root development and alter soil–water–nutrient relations. This study evaluated the main and interactive effects of rice husk biochar rate and water application method on Vertisol properties and early maize growth under identical cumulative water inputs. A 60-day greenhouse experiment comprised 24 experimental units arranged in a 2 × 4 factorial randomized complete block design with three blocks, combining surface-pour and drip water delivery with biochar rates of 0, 3, 6, and 9% (w/w). Because cumulative water input was identical between water-delivery treatments, the experiment isolated the effect of water-delivery Pattern rather than total irrigation quantity. Drip application produced higher post-harvest soil organic C, cation exchange capacity, available P, and total N than surface-pour application. Biochar significantly affected the same chemical properties, but not soil pH, with the 9% rate producing the clearest responses in organic C, cation exchange capacity, and available P. Plant-height responses were time-dependent, including a significant biochar rate × observation-time interaction, while drip application increased maximum root length from 66.8 to 76.9 cm. Post-harvest gravimetric water content and coefficient of linear extensibility (COLE) were interpreted descriptively because independent biological replication was unavailable; COLE declined numerically as biochar rate increased. Neither fresh nor dry biomass responded significantly to water-application method, biochar rate, or their interaction. These findings show that rice husk biochar and localized water application modified different functional components of the Vertisols–maize system, but improvements in soil chemistry, root elongation, shoot development, and biomass accumulation were not synchronized. Vertisols management should therefore be evaluated using multiple function-specific indicators rather than a single soil or plant response.

***Keywords*:** Coefficient of linear extensibility, Drip delivery, Expansive clay soil, Maize root development, Soil amelioration.

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1. INTRODUCTION

Vertisols are potentially productive agricultural soils, but expansive 2:1 smectitic clay minerals constrain their management (Wang et al., 2021). These minerals expand when wet and contract when dry, causing substantial volume changes, deep cracking, disrupted pore continuity, and changes in the soil's mechanical environment (Somasundaram et al., 2018). Consequently, Vertisols become sticky and plastic when wet but hard and resistant to Penetration when dry**,** restricting tillage, root penetration, and water uptake under unfavorable soil-water conditions (Zhu et al., 2024; Di Bert et al., 2026). These shrink–swell characteristics make crop performance dependent not only on the amount of water available but also on how repeated wetting and drying influence root-zone conditions and access to water and nutrients (Mbugua et al., 2019).

These constraints are particularly relevant to limestone-derived Vertisols in Jeneponto Regency, South Sulawesi, Indonesia, where montmorillonitic clay and carbonate-bearing parent materials contribute to pronounced shrink–swell behavior (Gargiulo et al., 2015; Juita et al., 2017). Under such conditions, water application may influence the root zone through both the quantity supplied and the spatial and temporal pattern of wetting (Novák & Hlaváčiková, 2019). Experimental studies have shown that drip application generates defined horizontal and vertical wetting fronts whose geometry varies with discharge rate, application duration, initial soil water content, and soil hydraulic

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properties (Cristóbal-Muñoz et al., 2022). In maize systems, localized drip fertigation has also been reported to influence soil water distribution, nutrient availability, and root development. Thus, contrasting delivery patterns may create different root-zone conditions even when cumulative water inputs are identical. Accordingly, the spatial pattern of water delivery may be particularly important in Vertisols, where root-zone conditions change during repeated wetting and drying cycles.

Rice husk biochar may complement such root-zone management by introducing stable carbon, providing reactive and exchangeable surfaces, modifying nutrient availability, and altering pore organization (Sang et al., 2021; Fatima et al., 2024; Al-Issa et al., 2026; Gavin et al., 2026). Its effectiveness, however, depends on feedstock composition, pyrolysis conditions, application rate, and the properties of the receiving soil (Bushra & Remya, 2024; Suyanto et al., 2026). Recent syntheses show that biochar-induced improvements in water retention are generally greater in coarse-textured than in clay-rich soils because clay matrices already possess considerable surface area and microporosity (Wei et al., 2023; Acharya et al., 2024). In fine-textured soils, biochar may instead affect interparticle contact, pore connectivity, and drying-induced cracking, although the magnitude and direction of these effects remain soil- and amendment-specific (Lu et al., 2022; Xia et al., 2025). Studies in non-expansive soils have reported that rice husk biochar combined with contrasting irrigation practices can modify soil chemical properties, water balance, crop growth, and water-use efficiency when these processes are measured directly (Turrodiyah et al., 2025; Widowati et al., 2025). Likewise, maize experiments show that biochar and irrigation regimes can alter nutrient availability, root morphology, shoot development, biomass, and yield (Wan et al., 2023; Yang et al., 2023; Ruan & Wang, 2024). However, most available evidence comes from soils without pronounced shrink–swell behavior and commonly evaluates treatment success through yield, water productivity, or isolated soil and plant variables. Consequently, it remains unclear whether responses documented in non-expansive soils transfer directly to montmorillonitic Vertisols, where wetting–drying cycles continuously reorganize pore space and root-zone mechanical conditions.

Recent studies have increasingly examined biochar application in fine-textured soils and water-limited agricultural systems, but responses in expansive soils remain highly context-dependent. Biochar addition has been reported to improve selected soil chemical properties, nutrient availability, and crop performance; however, improvements in soil quality do not always translate directly into greater biomass because responses depend on soil mineralogy, amendment characteristics, and the duration of plant development (Singh et al., 2022; Masud et al., 2024). In clay-dominated soils, where native mineral surfaces already provide substantial water and nutrient retention capacity, biochar effects may involve changes in soil structure and chemical functions rather than simple increases in water storage (Wei et al., 2023). Evidence from Vertisol systems further illustrates this context dependence. Field-grown maize in a Vertisol has shown variable growth and yield responses across biochar application rates (Nagaveni et al., 2024), while a greenhouse study using biochar-amended Vertisol reported differences in soil properties and vegetative maize responses under contrasting water-application levels (Masria et al., 2025).

Similarly, recent irrigation studies have shown that drip-based water delivery can modify maize root development and water acquisition by altering the spatial distribution of available moisture compared with conventional application methods (Li et al., 2023). However, most studies evaluate irrigation effects through total water supply, yield, or water productivity, making it difficult to separate the influence of water quantity from water-delivery pattern. Therefore, understanding how biochar amendment interacts with contrasting water-application patterns under equal cumulative water input is particularly important in shrink–swell Vertisols, where soil physical conditions fluctuate strongly during wetting and drying cycles.

Although these studies provide valuable evidence on biochar amendment or irrigation management separately, their combined effects under controlled, equal water-input conditions remain insufficiently understood in shrink–swell Vertisols. The central knowledge gap is therefore not whether biochar or water-application methods can independently influence soil properties or maize growth, but whether these management practices produce comparable changes across soil and plant components when total applied water is held constant. Specifically, this study tested whether rice husk biochar rate and contrasting water-application patterns under identical cumulative water inputs influence soil chemical properties, exploratory physical indicators, root elongation, shoot development, and biomass accumulation in a shrink–swell Vertisol. We hypothesized that rice husk biochar and contrasting water-application patterns would affect soil and plant responses differently, such that improvements in soil properties would not necessarily be accompanied by proportional increases in root development, shoot growth, or biomass accumulation.

2. MATERIALS AND METHODS

2.1. Study Site and Soil Collection

The study was conducted from April to August 2025 in the greenhouse of the Experimental Farm, Faculty of Agriculture, Hasanuddin University, Makassar, Indonesia. Greenhouse air temperature, relative humidity, and light conditions were not instrumentally recorded during the experimental period; therefore, measured greenhouse

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averages are unavailable. Because the experimental protocol did not incorporate a contemporaneous, site-specific outdoor meteorological dataset, we did not use retrospective outdoor values as proxies for greenhouse conditions. Soil analyses were performed at the Soil Physics Laboratory and the Soil Chemistry and Fertility Laboratory, Department of Soil Science, Faculty of Agriculture, Hasanuddin University. Vertisols were collected from the 0-20 cm soil layer of a maize field in Punagaya Village, Bangkala District, Jeneponto Regency, South Sulawesi, Indonesia, at 5.624871°S and 119.559544°E (Fig. 1). Soil was collected from five randomly selected points and homogenized for use as the experimental medium. Before treatment application, a representative subsample was collected to determine soil texture, pH, organic C, total N, available P, cation exchange capacity, gravimetric soil water content, and the coefficient of linear extensibility (COLE). The Results section presents the initial characteristics of the Vertisols.



Fig. 1: Location of the Vertisol soil-sampling site in Punagaya Village, Bangkala District, Jeneponto Regency, South Sulawesi, Indonesia (5.624871° S, 119.559544° E). The original cartographic labels are retained in Indonesian to preserve the source map. In the map, "Titik Pengambilan Sampel" indicates the soil-sampling Point, "Legenda" denotes the legend, "Inset Peta" denotes the inset map, and "Sumber Peta" denotes the map source.

2.2. Soil and Biochar Preparation

The soil was cleared of roots, gravel, and other foreign materials, air-dried at room temperature, gently crushed, and passed through a 2-mm sieve. Each 40 × 40 cm polyethylene grow bag, equipped with drainage holes, was filled with 5 kg of air-dried soil and designated as one experimental unit. We produced biochar from rice husks obtained from the area surrounding the soil sampling site. The rice husks were pyrolyzed under oxygen-limited conditions for 3 h at 500°C. The biochar was then cooled to room temperature, ground, and passed through a 2-mm sieve. This study did not determine the biochar's pH, electrical conductivity, ash content, total C and N, major nutrient content, porosity, or surface chemistry, and no archived biochar material or characterization data were available for retrospective analysis.

Biochar was subsequently applied at rates of 0, 3, 6, and 9% by mass of air-dried soil, corresponding to 0, 150, 300, and 450 g of biochar per 5 kg of soil, respectively. These rates followed the original greenhouse experimental protocol as an evenly spaced dose series of 150-g increments per 5 kg of soil and were not derived from a field-equivalent application recommendation. Controlled studies have used percentage-based rice husk biochar treatments, including 3% (w/w) in maize pot experiments (Boostani et al., 2023) and 10–20% (w/w) in greenhouse-soil incubation experiments (Tsai & Chang, 2020). These studies provide experimental context for percentage-based applications but were not the basis for the original treatment selection. Accordingly, the 9% rate is considered a high greenhouse experimental dose and should not be interpreted as a field recommendation or agronomic optimum.

2.3. Experimental Design and Treatments

The experiment was arranged in a 2 × 4 factorial randomized complete block design with three blocks. The blocks were established according to the position (row) of the greenhouse benches to control spatial variation in the experimental environment. Each block contained all eight treatment combinations, which were randomly assigned within the block. One grow bag containing one maize plant constituted one experimental unit.

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The first factor was the water-delivery method, consisting of surface-pour delivery using a graduated cylinder (A1) and drip delivery (A2). The second factor was the rice husk biochar rate: 0% (B0), 3% (B1), 6% (B2), and 9% w/w (B3). The two factors produced eight treatment combinations: A1B0, A1B1, A1B2, A1B3, A2B0, A2B1, A2B2, and A2B3. Each treatment combination was replicated three times, resulting in 24 experimental units. The experiment was designed to distinguish the effect of the water-application pattern from that of total water supply by keeping application volumes, schedules, frequencies, and cumulative water inputs identical across both water-application methods.

2.4. Maize Establishment and Maintenance

Three commercial hybrid maize seeds produced by Advanta Seeds Indonesia were planted in each grow bag. After germination, the seedlings were thinned to retain one uniformly growing plant in each experimental unit. Compound NPK fertilizer (16–16–16; Pak Tani NPK 16–16–16 Blue, CV Saprotan Utama, Semarang, Central Java, Indonesia) was applied once at a rate of 5 g grow bag^{-1} at 7 days after planting. the fertilizer was incorporated into the soil around the plant without direct contact with the stem. We removed weeds manually, and we did not apply pest and disease control because no infestations occurred.

2.5. Field Capacity and Water Delivery Treatments

We determined the initial field capacity of the Vertisols gravimetrically as 35.69% w/w. This value characterized the initial soil-water condition and was not used to maintain a constant target water content during the experiment. We supplied the water from a deep-groundwater storage tank connected to the greenhouse. During each two-day cycle, each grow bag received a total of 1,800 mL of water divided into two applications. The 1,800 mL volume represented the fixed operational watering amount used in the original greenhouse protocol and was applied identically to all experimental units. Because evapotranspiration was not quantified, this volume should not be interpreted as replacement of measured crop evapotranspiration or as a water-use-efficiency treatment. A volume of 900 mL was applied at 09:00 a.m on the first day, followed by another 900 mL at 4:00 PM on the second day. The application volume, timing, frequency, and total water input were identical for both water-delivery methods until 60 days after planting. Thus, both treatments received the same cumulative water input and differed only in how the water was delivered to the soil medium.

Under the surface-pour method (A1), water was applied slowly and evenly over the soil surface using a graduated cylinder. Under the drip method (A2), water was delivered through an infusion tube connected to a 1,500 mL container. The container was positioned about 100 cm above the grow bag surface, and the end of the tube was placed 3–5 cm from the base of the plant. The flow rate was set to 10 mL min^{-1}, resulting in an application duration of approximately 90 min for 900 mL per watering day. Water draining through the six drainage holes was allowed to flow out and was neither collected nor quantified, and the occurrence of drainage was not systematically recorded. Therefore, the experiment controlled equal applied water across the two water-delivery methods, but not necessarily equal water retained in the soil. Accordingly, the experiment did not quantify drainage, percolation, water loss, irrigation efficiency, or water-use efficiency.

2.6. Post-harvest Soil Sampling and Chemical Analyses

After plant harvest, soil samples were collected separately from each of the 24 grow bags for chemical analysis. The sampling location and depth within each grow bag were kept as consistent as possible among experimental units. Soil samples from different grow bags were not combined for the determination of pH, organic C, total N, available P, or cation exchange capacity. The samples were placed in labeled plastic bags and air-dried for 3–4 days under room conditions in the soil bank of the Department of Soil Science. After air-drying, the soil was gently crushed, passed through a 2-mm sieve, and stored separately until analysis. Initial soil texture was determined using the hydrometer method. Soil pH was measured in a 1:2.5 soil-to-water suspension. Organic C was determined using the Walkley–Black method, total N using the Kjeldahl method, available P using the Olsen method, and cation exchange capacity through extraction with 1 M NH_4OAc at pH 7.0. Potassium was not analyzed. All post-harvest soil chemical Properties were analysed separately for each of the 24 experimental units.

2.7. Post-harvest Gravimetric Soil Water Content

Post-harvest gravimetric soil water content was determined from one soil sample representing each of the eight treatment combinations. From each treatment-combination sample, three 5-g moist-soil subsamples were weighed separately to obtain the moist soil mass (W_m). The subsamples were then oven-dried at 105 °C to constant mass to obtain the oven-dry soil mass (W_d). Gravimetric soil water content was calculated separately for each technical determination using Equation (1):

$$\theta_g = \frac{W_m - W_d}{W_d} \times 100 \qquad (1)$$

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Where θ_g is gravimetric soil water content (%), W_m is the moist soil mass, and W_d is the oven-dry soil mass. The three technical values were averaged to obtain a single gravimetric soil water content value for each treatment combination. Their standard deviation was used only to describe variability in technical measurements. Because these determinations were not independent biological replicates, post-harvest gravimetric soil water content was not subjected to inferential statistical analysis.

2.8. Exploratory Assessment of Linear Extensibility

COLE was determined after the experiment using a procedure adapted from Franzmeier & Ross (1968) for disturbed and remolded soil. After air-drying, gently crushing, and sieving the samples from each experimental unit, we combined equal-mass subsamples from the three replicates of each treatment combination. This procedure produced eight composite samples representing A1B0, A1B1, A1B2, A1B3, A2B0, A2B1, A2B2, and A2B3. The granite mold was trough-shaped, resembling a pipe split lengthwise, and was fitted with four metal pins that served as fixed reference points. Water was gradually added to each composite sample until a homogeneous and moldable soil paste was obtained. The paste was placed in the mold, and the sample length under moist conditions (L_m) was measured immediately after molding using the reference-pin positions. The samples and molds were then oven-dried at 105°C for 72 h. After drying, the oven-dry sample length (L_d) was measured using the same reference points. Sample condition and visible crack patterns after drying were documented photographically but were not analyzed quantitatively. COLE was calculated using equation (2):

$$COLE = \frac{L_m - L_d}{L_d} \qquad (2)$$

Where L_m is the sample length under moist conditions and L_d is the sample length after drying. Because the three experimental replicates were combined before measurement, each treatment combination produced only one composite COLE value. The data therefore did not retain variation among experimental units and were presented solely as an exploratory descriptive assessment without error estimates or inferential statistical analysis.

2.9. Plant Measurements

Plant height was measured on the same plants at 16, 32, 48, and 60 days after planting. Measurements were taken from the soil surface to the tip of the highest fully extended leaf. The 60-day endpoint was selected because the study focused on early vegetative growth and root development before reproductive growth; consequently, grain production was outside the scope of the experiment. At 60 days after planting, the plants were harvested, and the roots were separated from the shoots. The roots were carefully washed to remove adhering soil, and excess surface water was removed using absorbent material. Maximum root length was defined as the linear distance from the stem base to the tip of the longest individual root and was measured using a standard ruler graduated at 1-cm intervals. This measurement represented the maximum root extent, not the total root-system length or architecture. Total fresh biomass was determined immediately after harvest by weighing the roots and shoots together. The same plant material was then oven-dried at 60 ± 5°C to a constant mass to determine total dry biomass. Plant height and root length were expressed in centimetres, whereas fresh and dry biomass were expressed as g plant^{-1}.

2.10. Statistical Analysis

Data on soil pH, organic C, total N, available P, cation exchange capacity, maximum root length, fresh biomass, and dry biomass were analyzed using factorial analysis of variance (ANOVA) in a 2 × 4 randomized complete block design with three blocks. Water-delivery method, biochar rate, and their interaction were treated as treatment effects, whereas block was included as the blocking factor. The individual grow bag containing one plant constituted the experimental unit (n = 24). Plant height was measured repeatedly on the same experimental units at 16, 32, 48, and 60 days after planting. The temporal plant height response was evaluated using repeated-measures ANOVA for the same randomized complete block design, with observation time as the within-subject factor, water-delivery method and biochar rate as between-subject treatment factors, and block included as the between-subject blocking factor. Each individual grow bag/plant constituted the subject measured repeatedly over time. Because we used the IBM SPSS GLM repeated measures procedure rather than a linear mixed-effects model, we did not specify a separate random-effects term or covariance structure. Sphericity of the within-subject time factor was evaluated, and Greenhouse–Geisser-adjusted P-values were used when the sphericity assumption was violated. In addition, factorial randomized-block ANOVA was performed separately at each observation time to evaluate water-delivery method, biochar rate, and their interaction at 16, 32, 48, and 60 days after planting. Residual normality was assessed using the Shapiro–Wilk test and Q–Q plots, whereas homogeneity of variance for variables measured once was assessed using Levene's test. Analyses were conducted on the original measurement scales without data transformation. When the water-delivery method × biochar rate interaction was significant, treatment-combination means were compared using

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Tukey's HSD test at the 5% significance level. When the interaction was nonsignificant, but the main effect of biochar rate was significant, marginal means were compared using Tukey's HSD test at the 5% significance level. Results were presented as means ± standard errors. Post-harvest gravimetric soil water content and COLE were excluded from inferential statistical analysis because they did not retain independent biological replication at the treatment-combination level. All analyses were performed using IBM SPSS Statistics version 25.0.

3. RESULTS

3.1. Initial Soil Characteristics

The experimental soil contained 54% clay, 37% silt, and 9% sand and was therefore classified as clay according to the USDA textural triangle. Before treatment application, the soil had a neutral pH of 7.09, an organic C content of 1.66%, a total N content of 0.11%, an available P concentration of 10.08 mg kg^{-1}, and a cation exchange capacity of 19.75 cmol (+) kg^{-1}. The initial gravimetric soil water content was 10.8%, whereas the initial coefficient of linear extensibility (COLE) was 0.10 (Table 1).

Table 1: Initial physicochemical characteristics of the Vertisols before treatment application

Soil property	Unit	Value
Sand	%	9.00
Silt	%	37.00
Clay	%	54.00
pH H_2O	-	7.09
Organic C	%	1.66
Total N	%	0.11
Available P	mg kg^{-1}	10.08
Cation exchange capacity (CEC)	cmol (+) kg^{-1}	19.75
Gravimetric soil water content	%	10.80
COLE	-	0.10

3.2 Post-harvest Soil Chemical Properties

The interaction between water-application method and rice husk biochar rate was not significant for soil pH, organic C, cation exchange capacity, available P, or total N (Table 2). Accordingly, we interpreted the main effects of the water-application method and biochar rate independently. The water-application method significantly affected organic C (P=0.001), cation exchange capacity (P=0.039), available P (P=0.019), and total N (P<0.001), but did not significantly affect soil pH (P=0.054). Compared with surface-pour application, drip application increased the marginal mean organic C content from 1.94 to 2.48%, cation exchange capacity from 22.75 to 24.98 cmol (+) kg^{-1}, available P from 11.56 to 13.49 mg kg^{-1}, and total N from 0.213 to 0.313%.

Table 2: Main effects of water-application method and rice husk biochar rate on the post-harvest chemical properties of Vertisols

Factor and treatment level	pH H_2O	C-organic (%)	CEC (cmol (+) kg^{-1})	Available P (mg kg^{-1})	Total N (%)
Water-application method (A)					
A1	7.15 ± 0.01	1.94 ± 0.10	22.75 ± 0.69	11.56 ± 0.51	0.213 ± 0.011
A2	7.19 ± 0.01	2.48 ± 0.10	24.98 ± 0.69	13.49 ± 0.51	0.313 ± 0.011
P-value A	0.054	0.001	0.039	0.019	<0.001
Biochar rate (B)					
B0	7.14 ± 0.02	2.02 ± 0.13^{b}	20.62 ± 0.98^{b}	11.76 ± 0.73^{b}	0.202 ± 0.016^{b}
B1	7.19 ± 0.02	2.13 ± 0.13^{ab}	24.17 ± 0.98^{ab}	12.18 ± 0.73^{ab}	0.280 ± 0.016^{a}
B2	7.16 ± 0.02	2.08 ± 0.13^{ab}	24.65 ± 0.98^{a}	11.11 ± 0.73^{b}	0.277 ± 0.016^{a}
B3	7.19 ± 0.02	2.61 ± 0.13^{a}	26.02 ± 0.98^{a}	15.05 ± 0.73^{a}	0.292 ± 0.016^{a}
P-value B	0.274	0.028	0.010	0.009	0.005
P-value A × B	0.143	0.113	0.332	0.278	0.121
CV (%)	0.61	14.92	10.05	14.23	14.69

Note: Values are marginal means ± SE. Within each column of the biochar-rate section, means followed by different superscript letters differ significantly according to Tukey's HSD test at *P*<0.05. A1 = Surface-pour water application; A2 = Drip water application; B0, B1, B2, and B3 = Rice husk biochar rates of 0, 3, 6, and 9% (w/w), respectively; CEC = Cation exchange capacity; CV = coefficient of variation.

Rice husk biochar rate significantly affected organic C (P=0.028), cation exchange capacity (P=0.010), available P (P=0.009), and total N (P=0.005), whereas soil pH was not significantly affected (P=0.274). Organic C was higher at the 9% biochar rate than in the no-biochar treatment, whereas the 3% and 6% rates did not differ significantly from either treatment. Cation exchange capacity at the 6 and 9% biochar rates was higher than in the no-biochar treatment. Available P at the 9% biochar rate was higher than that at the 0 and 6% rates, whereas the 3% rate did not differ significantly from the other rates. Total N was higher in all biochar-amended treatments than in the treatment without biochar, but did not differ significantly among the 3, 6, and 9% rates. Relative to the treatment without biochar, the 9% biochar rate increased organic C by 29.2%, cation exchange capacity by 26.2%, available P by 28.0%, and total N by 44.6%.

3.3. Post-harvest Gravimetric Soil Water Content and Coefficient of Linear Extensibility

Post-harvest gravimetric soil water content ranged from 10.22 to 14.51% among the eight treatment combinations

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(Fig. 2a). The lowest mean value was observed in A1B1, whereas the highest was observed in A2B3. Error bars represent the standard deviation of three technical determinations obtained from a single soil sample for each treatment combination and therefore reflect analytical rather than biological variability. Consequently, we did not subject soil water content to inferential statistical analysis.

Post-harvest COLE values ranged from 0.02 to 0.09 (Fig. 2b). Under surface-pour water application, COLE decreased descriptively from 0.09 without biochar to 0.05 at the 9% biochar rate. Under drip water application, COLE decreased from 0.08 without biochar to 0.02 at the 9% rate. A2B3 recorded the lowest COLE value. All post-harvest COLE values were numerically lower than the initial value of 0.10. However, because each treatment combination was represented by a single composite sample, the COLE data were presented descriptively and not subjected to inferential statistical analysis.

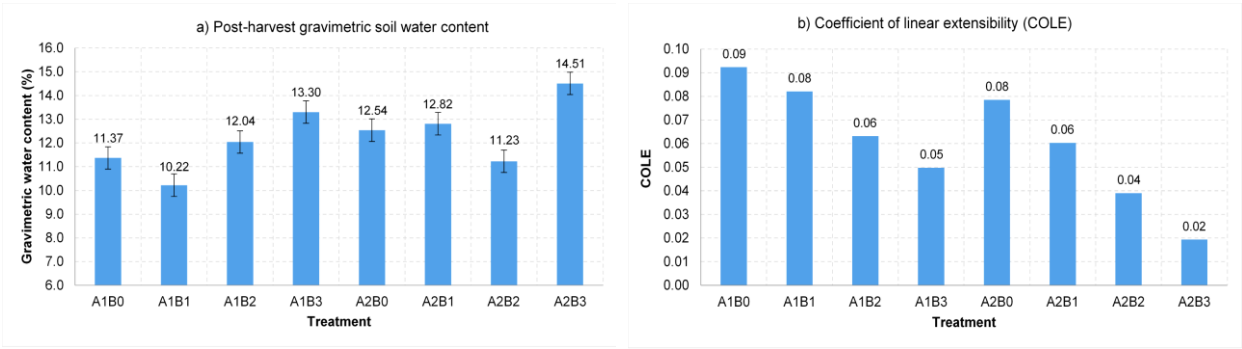


Fig. 2: Post-harvest gravimetric soil water content (a) and coefficient of linear extensibility (COLE) (b) under different combinations of water-application method and rice husk biochar rate. Bars in Panel (a) represent the mean ± standard deviation of three technical determinations obtained from one soil sample for each treatment combination. These technical determinations describe analytical variability and were not treated as independent biological replicates; therefore, inferential statistical comparisons were not performed. COLE values in Panel (b) were calculated from one composite soil sample for each treatment combination and are presented descriptively without error bars. A1 and A2 represent surface-pour and drip water application, respectively; B0, B1, B2, and B3 represent rice husk biochar rates of 0, 3, 6, and 9% (w/w), respectively. The y-axis in Panel (a) begins at 6% and is shown with an axis-break indicator to make the truncated scale explicit.

3.4. Temporal Response of Maize Plant Height

Plant height increased throughout the observation period. Repeated-measures analysis showed a significant effect of observation time ($P<0.001$) and biochar rate ($P=0.029$). The biochar rate × observation-time interaction was also significant after Greenhouse–Geisser correction ($P=0.043$), indicating that plant height responded differently to biochar across growth stages. The effects of water-application method, water-application method × observation time, water-application method × biochar rate, and the three-way interaction were not significant. Analysis at individual observation times showed that water-application method, biochar rate, and their interaction did not significantly affect plant height at 16 or 32 days after planting (DAP) (Table 3). At 48 DAP, biochar rate ($P=0.002$) and the water-application method × biochar rate interaction ($P=0.036$) significantly affected plant height, whereas the main effect of water-application method was not significant ($P=0.549$).

At 48 DAP, plants in A2B2 were shorter than those in A1B3, A2B0, A2B1, and A2B3, but did not differ significantly from those in A1B0, A1B1, or A1B2. This treatment-specific response was temporary because the water-application method × biochar rate interaction was no longer significant at 60 DAP. At 60 DAP, only the main effect of biochar rate was significant ($P=0.034$). The marginal mean plant height at the 9% biochar rate was 167.2 cm, which was 22.2% greater than the 136.8 cm recorded without biochar. However, plant height at the 9% rate did not differ significantly from that at the 3 or 6% rates.

3.5. Maximum Root Length and Plant Biomass

Water-application method significantly affected maximum root length ($P=0.040$), whereas biochar rate ($P=0.106$) and the water-application method × biochar rate interaction ($P=0.242$) were not significant (Table 4). Drip water application produced a marginal mean maximum root length of 76.9 cm, compared with 66.8 cm under surface-pour application, representing an increase of 15.1%. Water application method ($P=0.479$), biochar rate ($P=0.327$), and their interaction ($P=0.744$) did not significantly affect fresh biomass. Water-application method ($P=0.802$), biochar rate ($P=0.467$), and their interaction ($P=0.924$) also did not significantly affect dry biomass.

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Table 3: Maize plant height at different growth stages in response to water-application method and rice husk biochar rate

Factor and treatment level	16 DAP	32 DAP	48 DAP	60 DAP
Treatment combinations				
A1B0	52.4	64.2	88.6^{ab}	132.3
A1B1	51.4	65.7	86.5^{ab}	147.3
A1B2	55.7	68.3	86.8^{ab}	154.0
A1B3	52.7	70.4	91.2^{a}	163.0
A2B0	51.8	66.5	91.4^{a}	141.3
A2B1	49.7	67.4	91.3^{a}	153.0
A2B2	50.5	67.3	80.3^{b}	122.0
A2B3	52.7	69.3	93.2^{a}	171.3
P-value for water-delivery method (A)	0.521	0.859	0.549	0.759
P-value for biochar rate (B)	0.927	0.662	0.002	0.034
P-value for A × B	0.922	0.953	0.036	0.175
Pooled SE	4.06	3.71	1.80	10.19
Marginal means of biochar rate at 60 DAP				
B0	-	-	-	136.8^{b}
B1	-	-	-	150.2^{ab}
B2	-	-	-	138.0^{ab}
B3	-	-	-	167.2^{a}
SE of marginal means	-	-	-	7.21

Note: Treatment-combination values are unadjusted arithmetic means of three independent experimental units. The Pooled SE is the model-derived standard error from the factorial randomized-block ANOVA. Mean-separation letters are shown only where supported by the corresponding significant effect. Within the 48-DAP column, means followed by different superscript letters differ significantly according to Tukey's HSD test at $P<0.05$ because the water-application method × biochar rate interaction was significant. Mean separation was not performed at 16 and 32 DAP because none of the treatment effects were significant. At 60 DAP, the interaction was not significant; therefore, superscript letters are shown only for the marginal means of biochar rate. A1 = surface-pour water application; A2 = drip water application; B0–B3 = biochar rates of 0, 3, 6, and 9% (w/w), respectively; DAP = days after planting; SE = standard error.

Table 4: Main effects of water-application method and rice husk biochar rate on maize maximum root length and plant biomass at 60 days after planting

Factor and treatment level	Maximum root length (cm)	Fresh biomass (g Plant^{-1})	Dry biomass (g Plant^{-1})
Water-application method (A)			
A1	66.8 ± 3.18^{b}	105.0 ± 8.45	18.0 ± 1.39
A2	76.9 ± 3.18^{a}	113.7 ± 8.45	17.5 ± 1.39
P-value A	0.040	0.479	0.802
Biochar rate (B)			
B0	62.2 ± 4.50	112.0 ± 11.95	17.3 ± 1.97
B1	71.0 ± 4.50	121.4 ± 11.95	19.1 ± 1.97
B2	77.2 ± 4.50	90.2 ± 11.95	15.2 ± 1.97
B3	77.0 ± 4.50	113.8 ± 11.95	19.2 ± 1.97
P-value B	0.106	0.327	0.467
P-value A × B	0.242	0.744	0.924
CV (%)	15.3	26.8	27.2

Note: Values are marginal means ± standard errors. The total experiment comprised n = 24 independent experimental units. For the water-application method, each marginal mean represents n = 12 experimental units; for the biochar rate, each marginal mean represents n = 6 experimental units. Different superscript letters in the maximum-root-length column indicate a significant difference between water-application methods at $P<0.05$. Superscript letters are not shown for biochar rate or plant biomass because the corresponding effects were not significant. A1 = surface-pour water application; A2 = drip water application; B0–B3 = biochar rates of 0, 3, 6, and 9% (w/w), respectively; CV = coefficient of variation.

The coefficients of variation were 15.3% for maximum root length, 26.8% for fresh biomass, and 27.2% for dry biomass. Thus, variability among experimental units was greater for biomass than for maximum root length. Although numerical differences in fresh and dry biomass were observed among treatments, these differences were not statistically supported.

4. DISCUSSION

4.1. Soil Chemical Responses to Water Application and Rice Husk Biochar

The stability of soil pH, together with increases in organic C, cation exchange capacity, available P, and total N, indicates that chemical amelioration of the Vertisols occurred without a substantial change in soil reaction. In the Jeneponto Vertisols, dominated by montmorillonitic clay and developed from carbonate-influenced parent material, the soil's inherent buffering capacity may have limited pH changes during the experimental period (Juita et al., 2017). This interpretation is consistent with the global meta-analysis by Sun et al. (2022), which found that increases in soil organic C and cation exchange capacity were more consistent responses to biochar application than changes in pH. A recent study across contrasting tropical soils provides further soil-specific context. Blankson et al. (2025) reported that biochar increased organic C and available P in a Vertisol without a corresponding significant increase in soil pH,

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indicating that chemical responses to biochar can differ substantially among soil types. The increase in organic C at the highest biochar rate is consistent with incorporating a carbonaceous amendment, whereas the accompanying increase in cation exchange capacity indicates a change in the amended soil's exchange capacity. Potential mechanisms reported for biochar-amended soils include additional exchange sites, development of oxygen-containing functional groups during biochar aging, and organo-mineral interactions; however, these mechanisms were not measured directly in the present study. Thus, the present results demonstrate changes in soil carbon content and exchange capacity without establishing the specific processes responsible for those changes.

The responses of available P and total N indicate that individual soil chemical functions had different response thresholds. Available P did not follow a fully linear dose-response pattern, which may reflect processes such as P input, phosphate adsorption and desorption, interactions with Ca, biochar surface properties, and biologically mediated transformations. Because these processes were not measured directly, they should be regarded only as plausible explanations for the observed P response. Accordingly, the higher available P at the greatest biochar rate cannot be attributed specifically to direct P release or to any single soil–biochar mechanism. Moreover, soil P availability should not be equated directly with plant P acquisition. Plant P uptake and utilization involve additional morphological, physiological, and molecular processes, none of which were quantified in the present study. Therefore, the observed increase in available P is interpreted strictly as a soil chemical response rather than evidence of enhanced plant P uptake or utilization efficiency.

In contrast, total N responded at the lowest biochar rate, indicating that N dynamics differed from those of organic C, cation exchange capacity, and P. The higher post-harvest organic C, cation exchange capacity, available P, and total N under drip application, despite identical cumulative water input, suggest that the water-delivery method affected these measured soil chemical properties. A possible explanation is that localized water delivery altered the spatial distribution of water and nutrients within the root zone, as reported in drip-fertigated maize systems by Li et al. (2023); however, water and nutrient distributions were not measured in the present study. Therefore, the absence of significant water-application method × biochar rate interactions indicates no statistical evidence of synergistic effects between the two factors for the measured soil chemical properties.

4.2. Post-harvest Soil Water Status and Exploratory Shrink–Swell Response

The relatively narrow range of post-harvest soil water content does not indicate that drip and surface-pour application produced equivalent hydrological conditions within the root zone. Soil water content measured at harvest represents only a single point in the watering cycle. Previous studies indicate that different water-application patterns can produce differences in wetting-front geometry, moisture duration, water redistribution, aeration, and soil–root contact during successive irrigation events. These variables were not measured in the present study and therefore represent literature-supported mechanisms rather than direct experimental evidence. These mechanisms could plausibly contribute to the contrasting soil chemical and root responses observed here, but the present data cannot determine their contribution. Biochar effects on water retention also depend strongly on soil texture, pore structure, amendment properties, and application rate (Zhang et al., 2024). Recent evidence from another Indonesian Vertisol system also indicates that biochar responses depend on water conditions. Masria et al. (2025) evaluated maize grown in Vertisol amended with 6% (w/w) corncob biochar under contrasting water-application levels and reported differences in soil chemical properties and vegetative growth among water treatments. Although their water treatments differed from the delivery-pattern comparison used here, the study further demonstrates the context dependence of biochar–water interactions in Vertisols. Acharya et al. (2024) emphasized that biochar–water interactions vary substantially among soils, while Razzaghi et al. (2020) and Wei et al. (2023) showed that improvements in water retention are generally more Pronounced in coarse-textured soils than in clay-rich soils, whose mineral matrices already possess considerable surface area and microporosity. Therefore, the lack of a strong separation in post-harvest water content does not mean biochar had no influence on the soil water environment; rather, it indicates that a single post-harvest measurement could not capture the full wetting dynamics of the Vertisols.

The initial COLE value indicated strong expansive behaviour, whereas its subsequent decline with increasing biochar rate suggests a possible modification of clay-matrix deformation during drying. Potential mechanisms reported in previous studies include changes in interparticle contacts, evaporation pathways, pore distribution, and tensile-stress development during drying; however, none of these processes were directly measured in the present experiment. Lu et al. (2022) demonstrated that biochar particle size and application rate affected desiccation-cracking characteristics in silty clay, while Lu et al. (2025) showed that the magnitude and direction of these effects varied among clayey soils and amendment conditions. The descriptive COLE Pattern observed here is therefore consistent with a possible modification of drying-related deformation, but it does not establish either a causal biochar effect or the mechanism responsible for the observed numerical decline. Soil water content describes the state of water at a Particular time, whereas COLE describes the dimensional response of soil to drying; consequently, the two indicators provide complementary information about different physical functions of Vertisols.

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4.3. Temporal Response of Maize Shoot Development

The emergence of plant-height responses during later growth stages indicates that biochar's influence was time-dependent. During early establishment, factors such as seed reserves, basal fertilization, and the initial soil environment may have contributed to the relatively uniform growth observed among treatments. As plants developed, increasing demand for water and nutrients could also have contributed to the later treatment responses; however, these processes were not measured directly in this study. Biochar responses do not always occur immediately after application and have been associated in previous studies with processes such as amendment aging, surface oxidation, soil–biochar interactions, microbial colonization, and progressive root development. These mechanisms were not evaluated directly here. Cong et al. (2023) showed that maize responses to biochar varied between newly applied and aged amendments, while Wan et al. (2025b) demonstrated that biochar effects on nutrient availability and maize performance changed with amendment type, irrigation regime, and successive growth cycles. The significant biochar rate × observation-time interaction therefore shows that plant-height responses to biochar varied across growth stages, although the underlying physiological or soil mechanisms cannot be identified from the variables measured in this study.

The temporary response under drip application combined with 6% biochar did not form a consistent dose-response Pattern and was not maintained until the final observation. It should therefore be regarded as stage-specific developmental variation rather than evidence of biochar toxicity or an inhibition threshold. The 9% biochar rate produced the clearest final-height response, but it cannot be identified as optimal because its effect was not statistically distinct from other biochar-amended treatments and was not accompanied by greater biomass. The inconsistent effect of water-application method on plant height also indicates that shoot development was less sensitive to wetting pattern than were soil chemical properties and root elongation during the vegetative period. Irrigation studies reporting improvements in yield and water productivity generally link changes in root development to plant physiology, biomass production, and grain yield. For example, Cho et al. (2025) found that optimized drip fertigation simultaneously improved the soil microenvironment, root growth, and maize yield. In the present study, however, we did not measure the root-zone microenvironment or plant physiological processes. Therefore, the water-application treatment can be interpreted only in terms of the measured responses, including soil chemical properties, plant height, maximum root length, and biomass, rather than as direct evidence of modification of the root-zone microenvironment.

4.4. Root Elongation under Contrasting Water Application Patterns

The increase in maximum root length under drip application demonstrates that plants receiving drip-applied water developed a greater maximum root extent than those receiving the same cumulative water input by surface-pour application. The mechanism underlying this difference was not directly measured. Slow, localized wetting could generate moisture gradients that influence root extension, as reported in previous drip-irrigation studies; however, the present experiment did not quantify wetting-front geometry or spatial soil-moisture gradients. Sampathkumar et al. (2012) demonstrated that drip-irrigation Patterns created uneven soil-moisture distributions and modified maize root development, with Particular irrigation arrangements promoting longer lateral roots and greater root dry mass. Thus, the greater maximum root length observed under drip application is consistent with a response to contrasting water-delivery patterns (Singh et al., 2023), but the present data do not demonstrate that moisture gradients or a change in root-exploration strategy caused this response.

Maximum root length, however, represents only the farthest extent reached by a root and is not equivalent to the overall size of the root system. Longer roots do not necessarily possess greater biomass, surface area, fine-root density, branching intensity, or absorptive capacity. Lopez et al. (2023) showed that the root length, root biomass, root-length-to-shoot-biomass ratio, and root-to-shoot allocation can respond differently to soil resource conditions, confirming that a single root-length measurement cannot represent the complete functional architecture of the root system. Likewise, the absence of a biochar effect on maximum root length does not mean that the entire root architecture remained unchanged. Ruan & Wang (2024) demonstrated that biochar-induced root responses in maize were genotype-dependent and involved changes in lateral-root development, root anatomy, xylem characteristics, and plant water status. Because these additional root traits were not measured in the present study, the finding should be restricted to maximum root length and should not be interpreted as evidence of changes in complete root architecture or absorptive capacity.

4.5. Decoupling of Soil Improvement, Root Elongation, Shoot Growth, and Biomass Accumulation

The most important biological finding was that the responses of soil chemistry, roots, shoots, and biomass were not synchronized. Increases in organic C, cation exchange capacity, available P, and total N indicated improved soil chemical conditions, but nutrient uptake, photosynthesis, and other physiological processes were not measured; therefore, the observed chemical changes cannot be interpreted as direct evidence of improvements in these processes. Similarly, greater plant height and maximum root length represent specific morphological responses, whereas

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internode elongation, total root mass, root branching, and other aspects of shoot and root architecture were not quantified. The absence of a corresponding increase in fresh or dry biomass therefore demonstrates that the measured chemical and morphological responses did not translate into greater biomass accumulation during the 60-day experimental period. These findings differ from studies reporting simultaneous improvements in soil fertility, nutrient acquisition, maize growth, and biomass after biochar application. For example, Pandit et al. (2018) found that biochar increased maize growth principally by alleviating nutrient constraints in a moderately acidic, low-input soil. In another study, Masud et al. (2024) showed that biochars derived from different crop residues produced markedly different effects on soil pH, nutrient uptake, plant height, root biomass, and shoot biomass, reflecting differences in feedstock chemistry. These comparisons suggest that the translation of improved soil conditions into plant biomass may depend on the initial soil constraint and amendment characteristics; however, the physicochemical characteristics of the rice husk biochar used in the present study were not determined.

The absence of a biomass increase in the present study therefore does not invalidate the observed chemical and morphological changes; rather, it defines their functional boundary during the early vegetative period. This interpretation is consistent with Singh et al. (2022), who showed that biochar effects on soil properties and crop productivity varied with feedstock, soil texture, pyrolysis conditions, and experimental setting, and that improved soil chemical properties did not invariably produce equivalent gains in crop productivity. A similar functional decoupling has been reported under combined biochar and irrigation management. Wan et al. (2025a) reported that maize responses depended on both biochar type and irrigation regime, with changes in biomass and resource-use efficiencies not necessarily accompanied by proportional changes in total water consumption or N uptake. Taken together, the results show that biochar improved several soil chemical properties and later plant height, whereas drip application increased maximum root length; neither treatment increased fresh or dry biomass within 60 days. This divergence indicates that soil chemical, root, shoot, and biomass responses should be evaluated separately rather than assumed to change in parallel. Comparable context dependence has been reported across biochar studies differing in soil texture, amendment characteristics, and irrigation regime.

4.6. Study Limitations and Management Implications

Interpretation of this study is constrained by the greenhouse conditions and the 60-day experimental period, the absence of reproductive growth and grain-yield measurements, and the lack of physicochemical characterization of the rice husk biochar. The study did not measure drainage, nutrient movement, temporal moisture dynamics, or wetting-front geometry; soil water content and COLE also lacked independent biological replication, and root characterization was limited to maximum root length. The findings therefore cannot be used to establish water-use efficiency, reduced nutrient leaching, enhanced nutrient uptake, permanent modification of shrink–swell behavior, or an optimum field application rate. This distinction is particularly important for the 9% (w/w) treatment, which represents a greenhouse experimental dose rather than a field recommendation. For comparison, Nagaveni et al. (2024) evaluated biochar rates of 7.5–15 t ha^{-1} in field-grown maize on a Vertisol, illustrating the substantially different basis on which field application rates are commonly expressed and evaluated. Within these boundaries, the results support a function-specific management strategy: the 9% biochar rate produced the clearest chemical and final-height responses, whereas drip application increased maximum root length and improved several chemical properties under the same cumulative water input, but these benefits did not increase biomass. Further validation should use fully characterized biochar at more field-realistic rates, retain independent replication for soil physical measurements, and quantify water dynamics, nutrient losses, root architecture, plant physiology, nutrient uptake, grain yield, and economic feasibility under multi-season field conditions.

5. CONCLUSION

Rice husk biochar improved selected post-harvest soil chemical Properties, whereas drip application increased maximum root length under identical cumulative water inputs; neither treatment increased fresh or dry biomass during the 60-day greenhouse experiment. Post-harvest gravimetric soil water content and COLE were exploratory and descriptive because independent biological replication was unavailable, and these observations require validation using independently replicated measurements. The results do not support inferences about field productivity, water-use efficiency, nutrient-use efficiency, or a permanent reduction in shrink–swell behavior. Full-season field validation should therefore use well-characterized biochar at field-realistic rates and integrate measurements of soil-water dynamics, grain yield, and economic feasibility.

Declarations

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Ethics Statement: This study involved a greenhouse experiment using maize plants (*Zea mays* L.), Vertisol soil, and rice husk biochar. No human participants or animals were involved; therefore, ethical approval for human or animal research was not required.

Author's Contribution: RN: Conceptualization, methodology, supervision, validation, and writing-review and editing. DM: Data collection and laboratory analysis. MJ: Methodology, soil analysis, validation, and supervision. IRS: Plant-growth assessment, methodology, and validation. HI: Agronomic methodology, supervision, and interpretation of Plant responses. DR: Formal analysis, visualization, and writing-review and editing. All authors read and approved the final manuscript.

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