Synergistic effects of biochar and poultry manure improve soil water availability and drought tolerance in Ananas comosus

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Abstract

Enhancing soil water availability is critical for improving the drought resilience of crops in coarse-textured tropical soils. This study aimed to evaluate the effects of charcoal fines and poultry litter on pineapple (*Ananas comosus*) water status, comparing a process-based, flux-based model (FBM) with the traditional FAO-56 method for a mechanistic assessment. The experiment was conducted in a greenhouse using a completely randomized factorial design with nine treatments and four replications. Treatments included various combinations of biochar and/or poultry litter added at 5% and 10% on a volume-per-volume (v/v) basis. Soil hydraulic properties, root distribution, and potential transpiration were measured and estimated to determine plant water availability and drought stress. The combined application of charcoal fines and poultry litter was essential for significantly increasing both total (TAW) and readily available water (RAW). In contrast, the sole application of charcoal fines was detrimental, reducing RAW by up to 16.5%. Modeling revealed that the direct enhancement of soil hydraulic properties, rather than increased root growth, was the dominant mechanism driving these improvements. Furthermore, RAW calculated via the FBM proved to be a more sensitive indicator of plant performance, showing significant correlations with biomass and water use efficiency, which traditional metrics failed to capture. We conclude that for industrial byproducts like charcoal fines, co-application with an organic source is a necessary strategy to improve soil water retention and mitigate crop water stress.

1 Introduction

Brazil is the third-largest fruit producer in the world [1]. Among fruit crops, pineapple stands out due to its high productive potential and significant capacity to generate employment. In 2023, Brazil cultivated approximately 64,000 hectares of pineapple, with an average yield of 37 tons per hectare, reaching a total production of 2.4 million tons and USD 800 million to the national agricultural GDP [2].

Despite its economic importance, achieving optimal pineapple yields and reducing the yield gap depends intrinsically on water availability [3]. The total water requirement for a full crop cycle typically ranges from 1,200 to 1,400 mm, with daily water use reaching 3.5 to 4.6 mm during the active growth stage [4, 5]. Drought stress at critical growth stages can significantly reduce leaf size and chlorophyll content, impairing photosynthesis and ultimately limiting yield [6, 7].

Given these substantial water requirements, physiological mechanisms that enhance water-use efficiency are critical for sustainable pineapple cultivation, especially in regions with seasonal water deficits [8]. While the crassulacean acid metabolism (CAM) pathway provides an innate physiological advantage, pineapple's resilience to drought can be further enhanced through soil management practices that improve the root-zone environment. For instance, application of soil conditioners is a key strategy to change soil physical and hydraulic properties, thereby directly influencing plant growth and water availability [9]. Among these materials, charcoal (e.g. biochar) has garnered significant attention as a promising amendment. Its effectiveness arises from its physicochemical properties, particularly its highly porous structure and large surface area, which enhance soil water retention and improve aggregation [10].

Brazil is the world's largest producer of charcoal. The production process, particularly within the iron and steel industry, generates a considerable volume of byproducts, most notably charcoal fines [11]. Often regarded as industrial waste, this material constitutes a readily available and agronomically valuable feedstock for use as a soil amendment [12]. Their agricultural potential includes mitigating greenhouse gas emissions, reducing soil contamination, and improving soil hydrophysical and chemical properties [13, 14].

The inherent variability of charcoal, associated with its source and composition, directly influences its effects on soil properties and plant growth [15]. This variability is particularly pronounced in materials such as charcoal fines, which tend to be heterogeneous, especially when applied to different soil types [16, 17].

Biochar application has been consistently reported as beneficial in coarse-textured soils, where meta-analyses indicate increases of 28.5–45% in plant-available water due to fine particles filling large pores, thereby enhancing microporosity and water retention [18, 19]. In contrast, in fine-textured soils, while some studies report modest gains, others show negligible or even negative effects [20, 21]. These contrasting findings highlight that the efficacy of biochar is not universal but depends strongly on the interaction between charcoal properties and the inherent soil texture.

Combining biochar with organic matter sources can enhance soil improvement through synergistic effects. In a tropical Alfisol, Adekiya et al. [22] found that biochar plus poultry manure improved soil physical properties more than either amendment alone, reducing bulk density and increasing porosity and moisture. Similarly, Sharma et al. [23] reported higher water use efficiency and crop yield when biochar was combined with poultry manure compared to sole biochar application.

Investigating these interactions requires methods that accurately quantify plant-available water. However, assessments of readily available water (RAW)—a key indicator of drought stress—are often inconsistent, relying on arbitrary pressure heads or variable definitions of soil field capacity and limiting points. In response, Melo et al. [24] proposed a process-based model that uses matric flux potential to define the onset of drought stress [25]. This approach integrates soil hydraulic properties, root length density, and plant transpiration to calculate both total available water (TAW) and RAW within the soil–plant–atmosphere continuum [26].

Although the synergistic effects of biochar and organic amendments are recognized, the underlying mechanisms remain unclear, particularly for industrial byproducts such as charcoal fines. It is uncertain whether improvements in plant drought resilience result primarily from enhanced water availability or from stimulated root growth. A flux-driven model was employed to provide a more mechanistic assessment of plant water availability, and its results were compared with those of the traditional FAO model. The objective of the present study was to quantify the effects of charcoal and poultry manure application on soil water dynamics, thereby clarifying the mechanisms underlying improved drought resilience.

2 Material and methods

2.1 General description of experiment

The study was conducted at the Embrapa Cassava and Fruits research station in Cruz das Almas, Bahia State, Brazil (12º40’19” S, 39º06’22” W; 220 m above sea level). The region is characterized by a humid tropical climate, with average monthly maximum temperatures typically ranging from 30–33°C and minimums from 20–22°C and an average annual relative humidity of approximately 78%. The experiment was conducted in a naturally ventilated greenhouse without active climate control; therefore, internal conditions generally tracked the external climate.

The soil was classified as a Typic Hapludox with a sandy clay texture (sand: 471 g kg^{-1}; silt: 93 g kg^{-1}; clay: 436 g kg^{-1}), and presented the following chemical properties: pH (H_2O) 4.8; available P = 1 mg dm^{-3}; exchangeable K^+ = 0.04 $cmol_c$ dm^{-3}, Ca^{2+} = 0.37 $cmol_c$ dm^{-3}, and Mg^{2+} = 0.25 $cmol_c$ dm^{-3}; exchangeable Al^{3+} = 1.2 $cmol_c$ dm^{-3}; potential acidity (H^++Al^{3+}) = 4.95 $cmol_c$ dm^{-3}; sum of bases = 0.67 $cmol_c$ dm^{-3}; and cation exchange capacity = 5.62 $cmol_c$ dm^{-3}; base saturation = 12%; and organic matter content = 8.0 g kg^{-1}. For treatment establishment, soil acidity was corrected by liming, increasing the base saturation to 50% according to crop recommendation [27].

The experiment was arranged in a completely randomized design with a factorial arrangement of nine treatments and four replications, totaling 36 plants. The pineapple (*Ananas comosus* (L.) Merr.) variety ‘Pérola’ was selected for this study due to its widespread commercial cultivation in the region. To ensure uniformity, all plantlets were derived from micropropagation and were acclimatized for 60 days prior to transplanting into 20 L polyethylene pots (34 cm upper diameter, 30 cm depth). An experimental setup of the experimental unit is presented in Fig. 1.

The evaluated treatments consisted of the soil amended with conditioners poultry litter and/or biochar at proportions of 5% and 10% on a volume-per-volume (v/v) basis, calculated relative to the total container volume of 20 liters (Table 1).

Table 1
– Proportions of biochar (B) and poultry litter (P) used as soil conditioners in relation to recipient volume

Treatments	Proportions (% of recipient volume)
B_0P_0	100% Soil (control)
B_5P_0	95% Soil + 5% B
$B_{10}P_0$	90% Soil + 10% B
B_0P_5	95% Soil + 5% P
B_0P_{10}	90% Soil + 10% P
B_5P_5	90% Soil + 5% B + 5% P
$B_{10}P_5$	85% Soil + 10% B + 5% P
B_5P_{10}	85% Soil + 5% B + 10% P
$B_{10}P_{10}$	80% Soil + 10% B + 10% P

The poultry litter was originated from the poultry industry and consisted of wood shaving, a commonly used bedding material due to its high water absorption capacity [28]. This material presented the following characteristics: moisture content of 24.9%, pH in $CaCl_2$ of 7.68, total organic carbon content of 37.3%, cation exchange capacity of 800 mmolc kg^{-1}, nitrogen content of 2.1%, C/N ratio of 18, total phosphorus (P_2O_5) of 2.6%, potassium (K_2O) of 4.2%, magnesium content below 0.5%, copper below 0.05%, manganese below 0.05%, calcium content of 1.16%, iron content of 0.05%, and sulfur below 1.0%.

The biochar was a byproduct of the steel industry, known as charcoal fines, with particles smaller than 10 mm. Charcoal destinated to steel industry was produced from renewable eucalyptus plantations, obtained by pyrolysis process under 550°C of temperature. Charcoal fines were generated from abrasion and mechanical impacts during transportation of charcoal. This material is a residual and it is not used in the steel production, and presented the following chemical characteristics: moisture content of 8.2%, pH in $CaCl_2$ of 6.25, total organic carbon content of 62.6%, cation exchange capacity of 285 mmolc kg^{-1}, total nitrogen below 0.50%, C/N ratio greater than 27, total phosphorus (P_2O_5) below 1%, potassium (K_2O) below 1%, magnesium below 0.5%, boron below 0.1%, copper below 0.05%, total manganese (Mn) below 0.05%, calcium below 0.5%, iron below 0.05%, and sulfur below 1.0%.

The actual evapotranspiration (ET_a) of the pineapple plant was estimated using the system's water balance, considering only the applied irrigation depth, as there was no precipitation, deep drainage, or capillary rise within the pots in the greenhouse. The calculation of actual transpiration was performed based on Allen et al. [29], according to

$$T_a = ET_a\left(1 - e^{-LAI}\right)$$

1

$$E_a = ET_a - T_a$$

2

where T_a (mm d^{-1}) is the actual transpiration, E_a (mm d^{-1}) is the actual evaporation and LAI is the leaf area index. The LAI was estimated using the allometric model developed specifically for the 'Pérola' variety by Santos et al. [30], which calculates total plant leaf area from biometric measurements of the 'D' leaf. For the purposes of this study, potential transpiration (T_p) was set at 0.55 mm d^{-1}, a value established for pineapple under non-stress conditions in this experiment [31, 32].

2.2 Soil hydraulic properties

Three undisturbed and one disturbed soil samples were collected from each treatment 505 days after planting the pineapple seedlings to assess soil physical properties, including particle size distribution and the soil water retention curve. The undisturbed soil samples were saturated and subjected to suctions of 0.1 cm and 100 cm on a tension table, and to pressures of 330 cm, 1000 cm, 3000 cm, and 15000 cm in a pressure chamber to determine the soil water retention curve.

The soil hydraulic properties—water retention curve and hydraulic conductivity (K)—were described using the Van Genuchten [33] with the Mualem [34] parametric restriction:

$$\Theta \;=\; \left[1 + |\alpha\, h|^{n}\right]^{\frac{1}{n}-1}$$

3

$$K \;=\; K_{sat}\Theta^{\,l}\left[1 - \;\left(1 - \Theta^{\,n/(n-1)}\right)^{1-\;\frac{1}{n}}\right]^{2}$$

4

where K_{sat} (m d^{-1}) is the saturated hydraulic conductivity of the soil, $\Theta = (\theta - \theta r)/(\theta s - \theta r)$ is the effective saturation, θ (m^3 m^{-3}) is the volumetric water content, θs (m^3 m^{-3}) is the saturated water content, and θr (m^3 m^{-3}) is the residual water content. α, n, and l are fitting parameters. The fitting of parameters θ_s, θ_r, α, K_{sat}, l and n to Eqs. 3 and 4, was performed using the RETC software [35]. *Ksat* was estimated based on soil bulk density, sand, silt, and clay fractions, and the water content at -330 cm and – 15000 cm pressure head, using the Rosetta 3 pedotransfer function [36]. The complete set of fitted hydraulic parameters for all nine treatments is provided in the Supplementary Information (Table S1)

2.3 Plant water availability models

Based on the soil water retention curves, both TAW and RAW were calculated using the FAO-56 method. TAW was defined as the difference between the water content at field capacity (θ_{FC}) and at the permanent wilting point (θ_{WP}). RAW, which represents the portion of TAW that plants can extract without drought stress, was calculated as the difference between θ_{FC} and the limiting soil water content (θ_{LP}). Field capacity was assumed at a pressure head of -60 cm, a commonly used value to represent the point at which rapid drainage has ceased, while the permanent wilting point was set at -15,000 cm. To calculate the limiting soil water content (θ_{LP}, $cm^3\ cm^{-3}$), the FAO-56 method was used according to

$$\theta_{LP} = \theta_{WP} + (1 - p)\,(\theta_{FC} - \theta_{WP})$$

5

$$p = (a_1 G + a_2)\,ET_0 + (b_1 G + b_2)$$

6

where the value of p is tabulated in the model and depends on the reference evapotranspiration (ET_0) and the crop group *G*. Crops are classified into five groups, where group 1 is the most sensitive and group 5 is the least sensitive to water deficit. Pineapple belongs to group 3 [37]. The value of p can be found using Eq. 6, with a_1 = -0.00723 d mm^{-1}, a_2 = -0.04643 d mm^{-1}, b_1 = 0.142589, and b_2 = 0.453571 [38].

To compare the water availability in treatments with biochar and poultry litter doses using a flux-based method (FBM) for available water, the FluxPAW software was used to calculate field capacity, limiting point, and permanent wilting point [26].

According to this method, θ_{FC} is determined using the polynomial expression derived by Inforsato and de Jong van Lier [39], which considers the soil's hydraulic parameters and the criterion of field capacity as a state of negligible drainage rate. This expression allows the calculation of the soil water content corresponding to field capacity according to a specific drainage rate, which in this study was set as q_{FC} = 1 mm d^{-1}.

To calculate the limiting point (θ_{LP}), the matric flux potential (*M*) is used, a soil hydraulic property defined as the integral of the hydraulic conductivity K(h) over pressure head h, starting at h_{WP} taken as -15,000 cm, according to

$$M = \int_{h_{WP}}^{h} K dh$$

7

De Jong van Lier et al. [40] proposed a linear relationship between the limiting matric flux potential (M_{LP}) and the transpiration rate T_p, indicating that the onset of water stress can be quantified using M_{LP}. This model was extended by Pinheiro et al. [25] to multilayer scenarios, proposing the following equation to determine M_{LP} in soils with k layers, each with thickness L_i (m) and root length density R_i (m^{-2}):

$$M_{LP} = \frac{pT_p}{\sum_{i=1}^{k} L_i R_i}$$

8

where p is a constant equal to 1.69. Simplifying for a scenario with a single-layer soil, it is possible to represent the onset of water stress conditions as described by

$$M_{LP} = \frac{1{,}69T_p}{ZR}$$

9

A root efficiency of 10% was adopted, based on previous studies [41] which observed that only 1 to 10% of the total root length is effective for water extraction.

In FluxPAW, the permanent wilting point (WP) is determined based on the residual transpiration rate criterion ($T_p \cdot f_{WP}$), where f_{WP} is the wilting factor taken as 0.01 and representing the ratio between maximum and minimum vapor conductance in the canopy. θ_{WP} is obtained from the calculated value of M_{WP} according to

$$M_{WP} = \frac{1.69T_p f_{WP}}{ZR} = M_{LP} f_{WP}$$

10

2.4 Plant biomass measurement and water use efficiency

At the end of the experiment, 505 days after planting, corresponding to the end of the vegetative stage, plants were destructively harvested and partitioned into shoots and roots. Aboveground dry biomass was determined by oven-drying the shoots at 65°C to a constant weight. For root analysis, roots were carefully separated from the soil of each pot by washing and sieving (2 mm mesh). The isolated roots were scanned, and the resulting digital images were analyzed using GSRoot software [42]. to determine total root length and calculate root length density (RLD). Following scanning, root dry biomass was determined using the same oven-drying procedure. Finally, water use efficiency (WUE) was calculated using

$$WUE = \frac{BM}{WU}$$

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where WUE (kg m^{-3}) is the water use efficiency, BM (kg) represents the total dry biomass of the plants, and WU (m^3) is the total water use, equivalent to the total volume of water applied during irrigation.

2.5 Statistical Analysis

All data related to plant growth (total biomass, aboveground biomass, root length density, water use efficiency) and soil water availability (TAW and RAW) were subjected to statistical analysis. Prior to the analysis of variance (ANOVA), the model residuals were checked for the assumptions of normality and homogeneity of variances using the Shapiro-Wilk and Levene's tests, respectively. When the F-test from the ANOVA was significant ($p < 0.05$), treatment means were compared using the Scott-Knott clustering test at a 5% significance level. Multivariate analyses were performed using the FactoMineR package in RStudio software [43].

3 Results and discussion

3.1 Impact of conditioners on root biomass and length

The application of soil conditioners influenced pineapple root development, though the effects varied by treatment. Compared to control, the $B_{10}P_5$ and $B_{10}P_{10}$ treatments increased root dry mass by 87.3% and 104.9% and root length density by 179.8% and 219.3%, respectively (Fig. 2). However, these changes were not statistically significant. The treatments with sole applications of either conditioner showed a slight, though not statistically significant, reduction in these root parameters.

This result suggests a synergistic effect on root development from the combined application of the amendments. This effect is likely attributable to complementary improvements in the root-zone environment. Prendergast-Miller et al. [44] demonstrated that biochar particles can form nutrient-rich microsites that attract roots and control nutrient uptake by retaining nitrogen and supplying phosphorus. We postulate that the poultry manure enriched the biochar particles with labile nutrients, creating zones of high nutrient availability that subsequently promoted root proliferation [45].

3.2 Changes in plant water availability through Soil Amendments

The FBM consistently estimated lower TAW and RAW values than the conventional FAO-56 approach (FC_{60}) across all treatments (Fig. 3). This discrepancy is primarily attributed to the lower field capacity values estimated by the FBM relative to the FC_{60} method. Additionally, the FBM yielded higher water content values at the permanent wilting point than the FC_{60} method, further contributing to the lower TAW estimations.

Similarly, the lower RAW values under the FBM were a consequence of its higher estimated lower θ_{LP} compared to FC_{60}. This factor, combined with the lower field capacity, resulted in a reduction in calculated RAW. On average, RAW estimated by the FBM constituted 43% of the corresponding TAW, a proportion that increased with the application of soil conditioners.

The combined application of biochar and poultry litter significantly increased TAW, with the $B_{10}P_5$ treatment exhibiting the greatest increase (68.3%) relative to the control. In contrast, the application of either amendment alone was not beneficial, as the B_5P_0 and B_0P_{10} treatments reduced TAW by 28.3% and 31.8%, respectively.

This finding is consistent with previous research demonstrating that while biochar can improve soil hydrophysical properties, its effectiveness as a sole amendment is often conditional. Mendonça et al. [13] working with a heavy clay soil, found that the increase in water retention induced by biochar was contingent upon an optimized application rate (approx. 50% v/v) and particle size (2–16 mm). Similarly, a long-term field study by Lucon et al. [14], reported that a significant increase in soil available water was confined to the 0.05–0.10 m soil layer. These studies indicate that optimizing the hydrophysical benefits of biochar as a sole amendment requires precise management of its application rate and physical characteristics. Therefore, the TAW increase observed in our study suggests that a synergistic combination with poultry litter may be a more robust strategy, potentially overcoming the conditional efficacy of biochar when used as a sole amendment.

The combined amendments also increased RAW. The treatments combining both amendments were particularly effective; $B_{10}P_5$ and B_5P_{10} increased RAW by 108.8% and 78.8% respectively, relative to the control (Fig. 3). These results support our hypothesis that combining biochar with poultry litter enhances RAW. In contrast, the sole application of biochar reduced RAW by 13.0% (B_5P_0) and 16.5% ($B_{10}P_0$). This reduction occurred despite a concurrent decrease in the lower limit of readily available water (θ_{LP}) in these treatments (Table S2). This finding indicates that for the sole biochar treatments, any potential benefit from a lower water stress threshold (θ_{LP}) was outweighed by a more substantial decrease in field capacity (θ_{FC}), leading to a net reduction in RAW.

While some studies report an increase in RAW with sole biochar application, our findings highlight that these benefits are highly conditional and material-dependent. Ndede et al. [21], in a study on sandy soils, found that the positive effect of biochar on RAW was optimal at low application rates (5–10%), with higher rates causing diminishing or even negative effects, being aligned with previous studies [46, 47]. These observations underscore the criticality of optimizing application rates, as excessive application can be counterproductive.

The negative effect observed in our study with sole charcoal fines, which contrasts with some literature, can be explained by the specific characteristics of the material and its interaction with the soil. Unlike more homogeneous, fully pyrolyzed biochars, the charcoal fines used here are an industrial byproduct of incomplete pyrolysis, characterized by high variability in particle size and a less-developed internal pore structure.

These properties can introduce to functional limitations. Fresh or unprocessed biochar often exhibits hydrophobicity, which can impede water infiltration into the soil matrix [48]. Ndede et al. [21] also reported that the mechanical processing of biochar can damage the intra-particle mesopore structure required to hold readily available water. Since the biochar used in this study is generated by mechanical abrasion, it is plausible that both hydrophobicity and a damaged mesopore structure contributed to the observed reduction in RAW. This effect may have been compounded by the high initial field capacity of the coarse-textured control soil, potentially masking any minor benefits from the sole amendment (Table S2).

This context underscores the critical role of poultry litter in the combined treatments. The organic manure likely overcame the biochar's limitations by coating its hydrophobic surfaces and acting as a binding agent. This process would have facilitated the formation of stable aggregates, thereby creating the favorable mesopore structure required for a significant increase in RAW [49].

Grouping the treatments into four categories control (soil only), sole biochar, sole poultry litter, and combined biochar and poultry litter, confirmed that the application of either amendment alone did not consistently increase plant-available water (Fig. 4).

In contrast, the combined application of biochar and poultry litter resulted in a significant increase in TAW and, more markedly, in RAW. This synergistic effect is likely associated with modifications in the soil's hydraulic properties and improved root growth. These changes can enhance water availability to plants and increase their water use efficiency [23]. Additionally, such amendments can improve the plant water balance and photosynthetic efficiency, thereby facilitating root water uptake [50], facilitating root water uptake. Similar synergistic effects on water availability have been reported for biochar from agricultural residues in a red clay soil [16] and for biochar derived from animal manure in a loamy sand soil [17].

3.3 Impact of rooting and soil properties on water availability

To quantify the individual contributions of root growth versus soil hydraulic properties, a modeling analysis was performed using the FBM. The model was run iteratively for each treatment: first, incorporating the observed changes in root length density (RLD) while holding hydraulic properties constant at control levels, and then incorporating the measured changes in hydraulic properties (θ_s, θ_r, α, K_{sat}, n) while holding RLD constant. This approach enabled the quantification of the individual impacts of each factor on TAW and RAW, with results presented in $cm^3\ cm^{-3}$ (Fig. 5).

The analysis revealed that modifications to soil hydraulic properties were the dominant factor driving the increase in water availability. On average, across all treatments, the impact of altered soil properties on RAW and TAW was 21.8% and 6.4% greater, respectively, than the impact of increased root growth alone. This effect was particularly pronounced in the combined amendment treatments (B_5P_5, $B_{10}P_5$, B_5P_{10},

$B_{10}P_{10}$), where the contribution from soil hydraulic properties to RAW and TAW was 43.5% and 26.3% greater, respectively, than that from enhanced root development.

Within the sole amendment treatments, the relative importance of root density versus soil hydraulic properties varied. For the 5% sole biochar application (B_5P_0), enhanced root density was the primary driver of changes in water availability. At the higher 10% rate ($B_{10}P_0$), however, improvements in soil hydraulic properties exerted a more dominant influence on TAW and RAW. Similarly, in the sole poultry litter treatments, the contribution of enhanced root density was more significant than the direct changes to the soil's hydraulic properties.

3.4 Drought stress mitigation

Relative transpiration (T_a/T_p), the ratio of actual (T_a) to potential transpiration (T_p), serves as a key indicator of plant water stress. When soil water supply is non-limiting, Ta approaches T_p, and the ratio is close to 1. As the soil's capacity to supply water diminishes, Ta falls below T_p, resulting in a ratio less than 1, which signifies an increasing level of water stress imposed by the soil (Fig. 6).

Biochar is recognized for its potential to mitigate water stress by improving soil physical properties, owing to its high surface area and negative charge [44, 51]. However, in our study, analysis of soil water dynamics during the pineapple vegetative growth period revealed that in several treatments, the soil water content dropped to the critical threshold (θ_{LP}) or near the permanent wilting point. This decline induced water stress and subsequently reduced plant transpiration.

The $B_{10}P_0$, B_0P_5, and control (B_0P_0) treatments were the most susceptible to drought. In these cases, the soil water content reached critical limits more rapidly, which reduced water uptake and impaired crop transpiration (Fig. 6).

The reduced transpiration in treatments $B_{10}P_0$, B_0P_5, and B_0P_0 can be attributed not only to lower soil water availability but also to the pineapple's physiological stress response. As a facultative CAM plant, pineapple adjusts its photosynthetic metabolism under water-limited conditions by reducing stomatal opening, which consequently decreases transpiration and biomass accumulation when subjected to a severe water deficit [32].

In contrast, the combined biochar and poultry litter treatments, as well as the sole 10% poultry litter application (B_0P_{10}), maintained T_a/T_p ratios close to 1 for a longer duration. This was observed despite the variability in TAW and RAW values among these treatments, indicating that they effectively enhanced soil water retention and delayed the onset of crop water stress.

Haider et al.[9] reported that biochar can mitigate drought stress by improving transpiration, increasing root length, maintaining water content in soil and leaves, and preserving plant turgor. Our findings, however, reaffirm that these benefits are highly conditional. The sole application of the biochar used in this study was detrimental to water availability, likely inducing significant water stress which can inhibit root proliferation, limiting both the length and volume of the root system [52]. Therefore, the synergistic combination with poultry litter was essential for creating the favorable hydrophysical conditions required to achieve these stress-mitigation effects.

3.5 Water Use Efficiency and Biomass Response

Water use efficiency (WUE) and pineapple biomass production varied significantly among the treatments. The $B_{10}P_{10}$ treatment resulted in the highest dry biomass accumulation (0.519 kg m^{-3}) and the greatest WUE (16.48 kg m^{-3}), representing increases of 417.1% and 464.4%, respectively, relative to the unamended control. Similarly, the B_5P_{10} treatment yielded substantial increases in biomass (362.1%) and WUE (446.2%) (Fig. 2).

These results suggest that the $B_{10}P_{10}$ and B_5P_{10} treatments promoted more efficient water utilization, enabling greater plant growth without a proportional increase in water consumption. These findings are consistent with previous studies demonstrating that biochar, particularly when combined with organic matter, can improve WUE [23, 53].

3.6 Water Availability Metrics and Plant Performance

Pearson's correlation analysis indicated a significant correlation ($p < 0.01$) between the water availability metrics estimated by the FAO-56 and FBM approaches ($p < 0.01$). However, the metrics derived from the FBM showed a stronger relationship with pineapple biomass production than those from the conventional FAO-56 method. Specifically, TAW_{60} and RAW_{60} showed no significant correlation with either WUE or biomass production (Fig. 7).

Similarly, within the flux-based method, TAW_{FBM} did not correlate significantly with these plant performance variables. In contrast, RAW_{FBM} showed significant positive correlations with water use efficiency (WUE, $p < 0.05$), biomass (BM, $p < 0.05$), actual transpiration (T_a, $p < 0.05$), and root length density (RLD, $p < 0.05$).

This discrepancy can be attributed to the different underlying assumptions of the two concepts. The TAW concept assumes a constant rate of water extraction from field capacity (θ_{FC}) down to the permanent wilting point The RAW concept, however, posits that this constant rate occurs only down to a lower limit of readily available water (θ_{LP}). Below θ_{LP} water uptake is assumed to decline nonlinearly as the plant experiences increasing water stress. Consequently, RAW is a more sensitive indicator of incipient water stress than TAW, which explains its stronger correlation with plant performance metrics [24].

4 CONCLUSIONS

This study demonstrated that the efficacy of soil conditioners for improving water availability in pineapple is critically dependent on a synergistic interaction between materials. Key findings from this research include:

- The combined application of charcoal fines and poultry litter increasing both TAW and RAW. In contrast, the sole application of either amendment was ineffective and, in the case of biochar, proved detrimental to the readily available water fraction.
- Modeling revealed that the primary mechanism for this improvement was the direct enhancement of the soil's hydrophysical properties, which had a greater impact on water availability than the secondary benefit of increased root growth.
- The flux-based model (FBM) proved to be a more sensitive indicator of plant performance. Specifically, readily available water calculated by this method (RAW_{FBM}) showed significant correlations with biomass and water use efficiency, whereas traditional metrics did not.

These findings have practical implications for the management of coarse-textured soils. Our results suggest that for industrial byproducts like charcoal fines, co-application with a nutrient-rich organic matter source is an efficient strategy to improve soil water retention and enhance crop resilience to drought. Specifically, the $B_{10}P_5$ and $B_{10}P_{10}$ formulations proved to be the most effective treatments for increasing water availability, mitigating drought stress, and ultimately enhancing pineapple biomass production. Further studies exploring the interactions between different biochar types and organic amendments are also needed to optimize formulations for various soil types and agricultural systems. In addition, field studies are indispensable to establish the applicability of these findings beyond controlled conditions.

Declarations

Competing interests:

The authors declare no competing interests.

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Author Contribution

GMVQ was responsible for writing—review & editing, writing—original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. RRBS was responsible for writing—review & editing, writing—original draft, methodology, investigation. RBTN was responsible for methodology and investigation. FASX was responsible for installing the experiment in a greenhouse, standards and measurements for each treatment, the harvesting system and the anatomy of the plants, writing, review & editing. LDS was responsible for installing the experiment in a greenhouse, standards and measurements for each treatment, the harvesting system and the anatomy of the plants. QdJvL was responsible for writing, review & editing, visualization, investigation, conceptualization, formal analysis, methodology, and project administration.

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Data Availability

The data supporting the study's findings will be available on the corresponding author upon reasonable request.

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Figures

Figure 1

Experimental setup illustrating the preparation of soil substrates, planting of Ananas comosus, and subsequent plant and tensiometer management during the greenhouse experiment

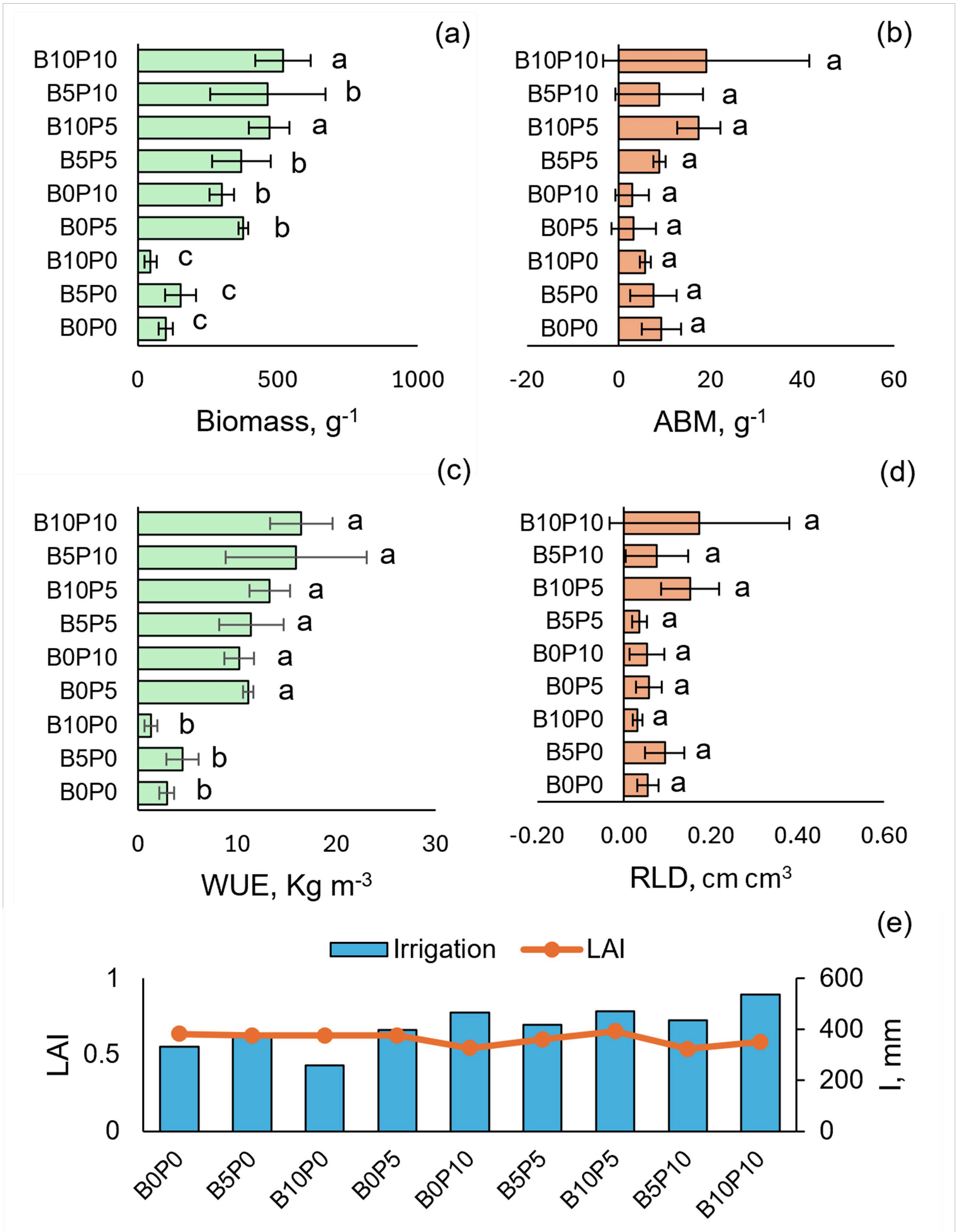

Figure 2

Effects of biochar and poultry litter on (a) total biomass, (b) aboveground biomass (ABM), (c) water use efficiency (WUE), (d) root length density (RLD), and (e) leaf area index (LAI) and cumulative irrigation (I). Error bars represent the standard deviation. Different letters indicate statistically significant differences ($p < 0.05$).

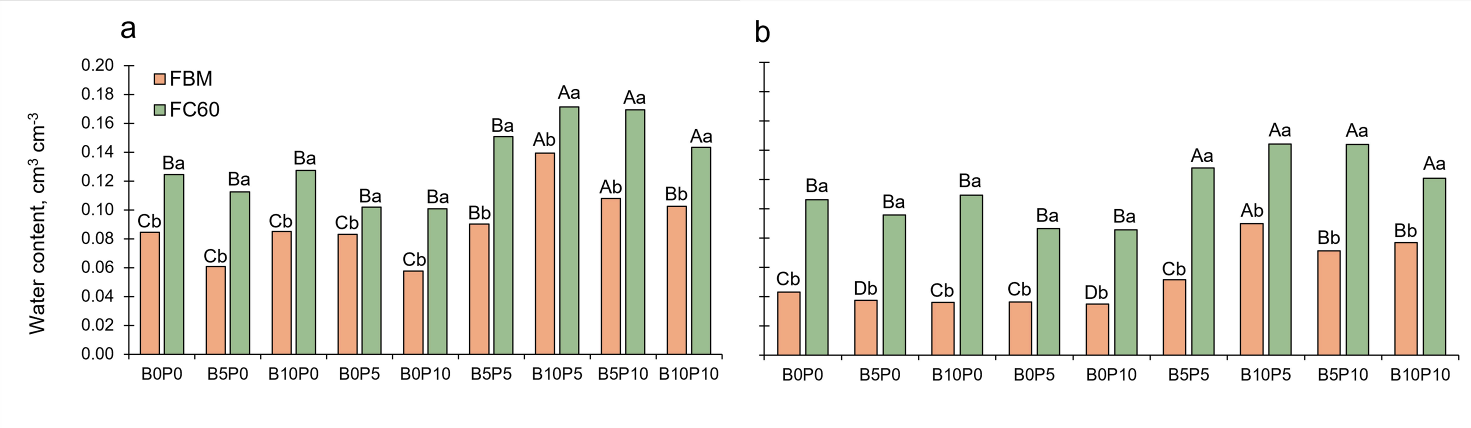

Figure 3

Effect of biochar and poultry litter on totally available water (TAW) (a) and readily available water (RAW) (b), comparing two water availability criteria: flux-based method (FBM) and field capacity at 60cm (FC_{60}). Uppercase letters indicate differences between treatments, while lowercase letters indicate differences between methods

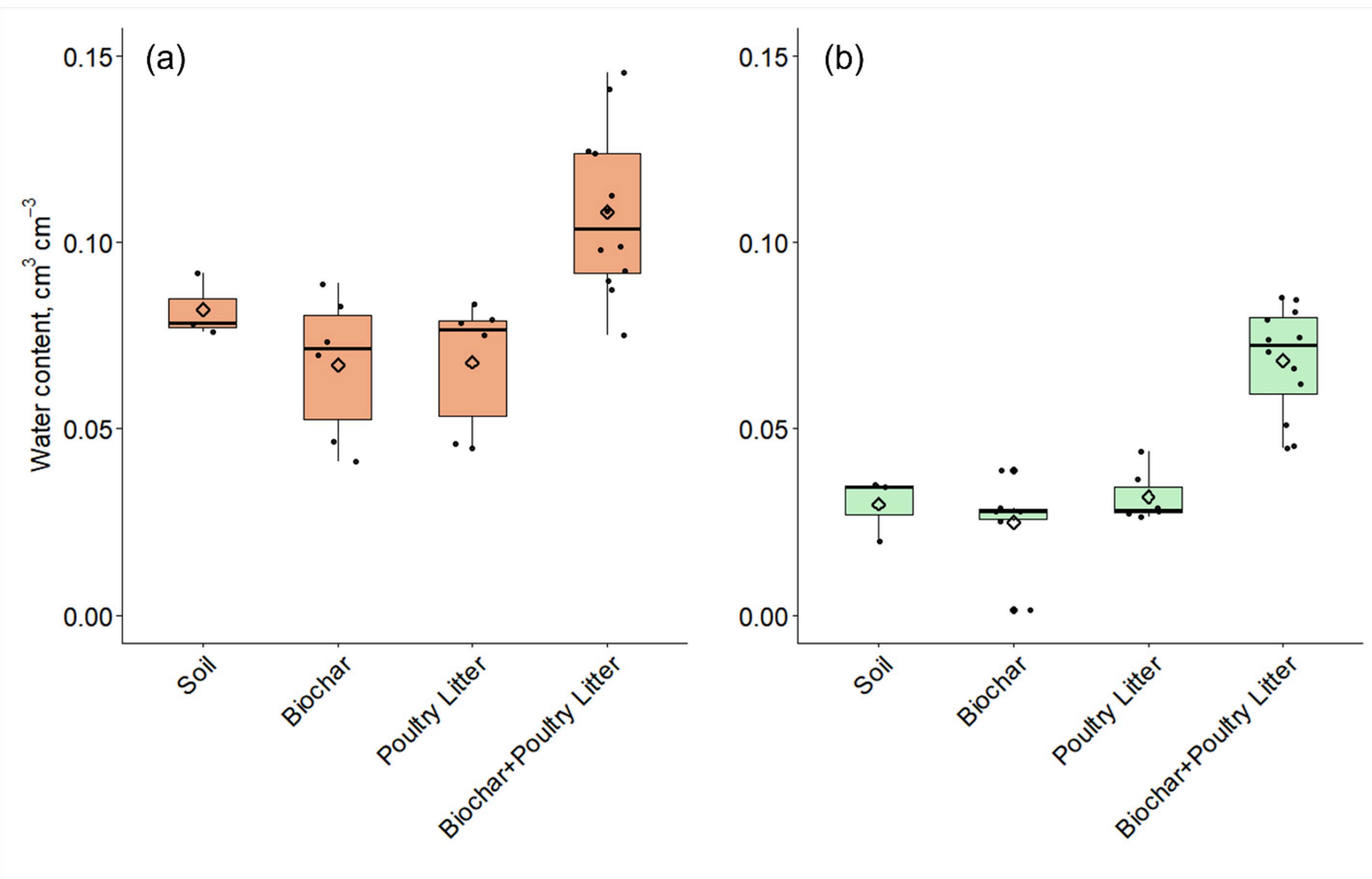

Figure 4

Effect of Grouped Soil Amendment Treatments (Biochar, Poultry Litter, and Combination) on (a) TAW and (b) RAW in Pineapple crop

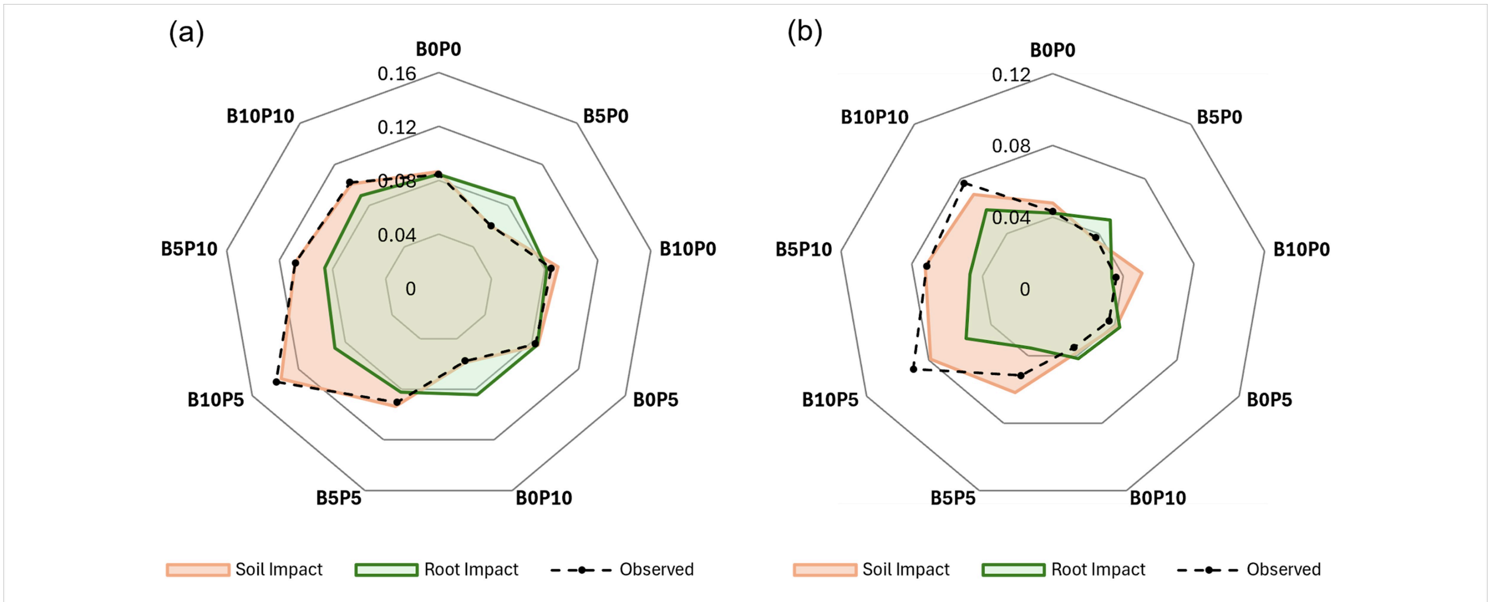

Figure 5

Modeling the soil impact and root impact on (a) totally available water (TAW) and (b) readily available water (RAW) in soil amendment with biochar and poultry litter

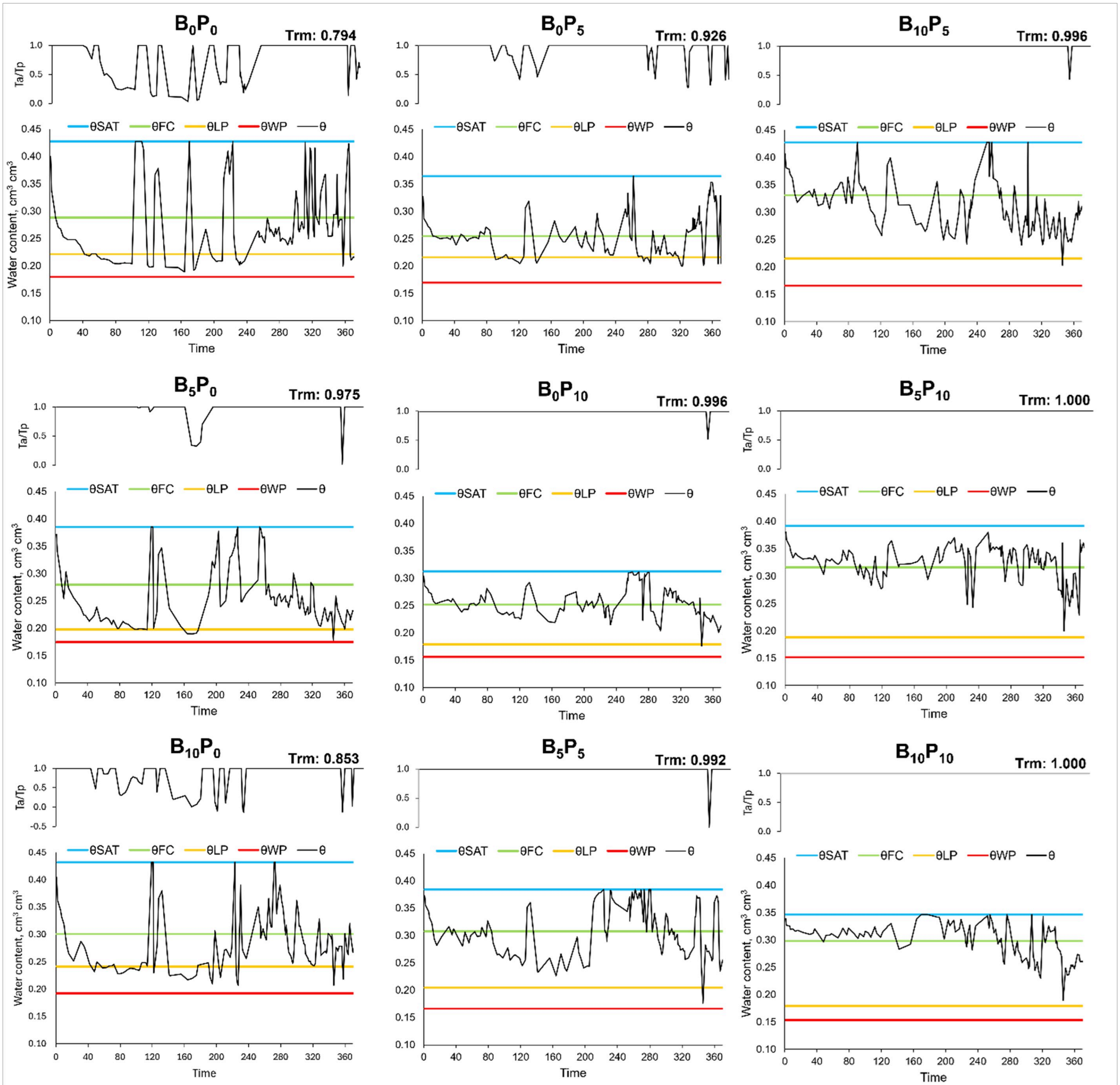

Figure 6

Temporal variation of soil water content and relative transpiration (T_a/T_p) under different treatments, together with the saturated water content (θ_{SAT}), field capacity (θ_{FC}), limiting point (θ_{LP}), and wilting point (θ_{WP}).

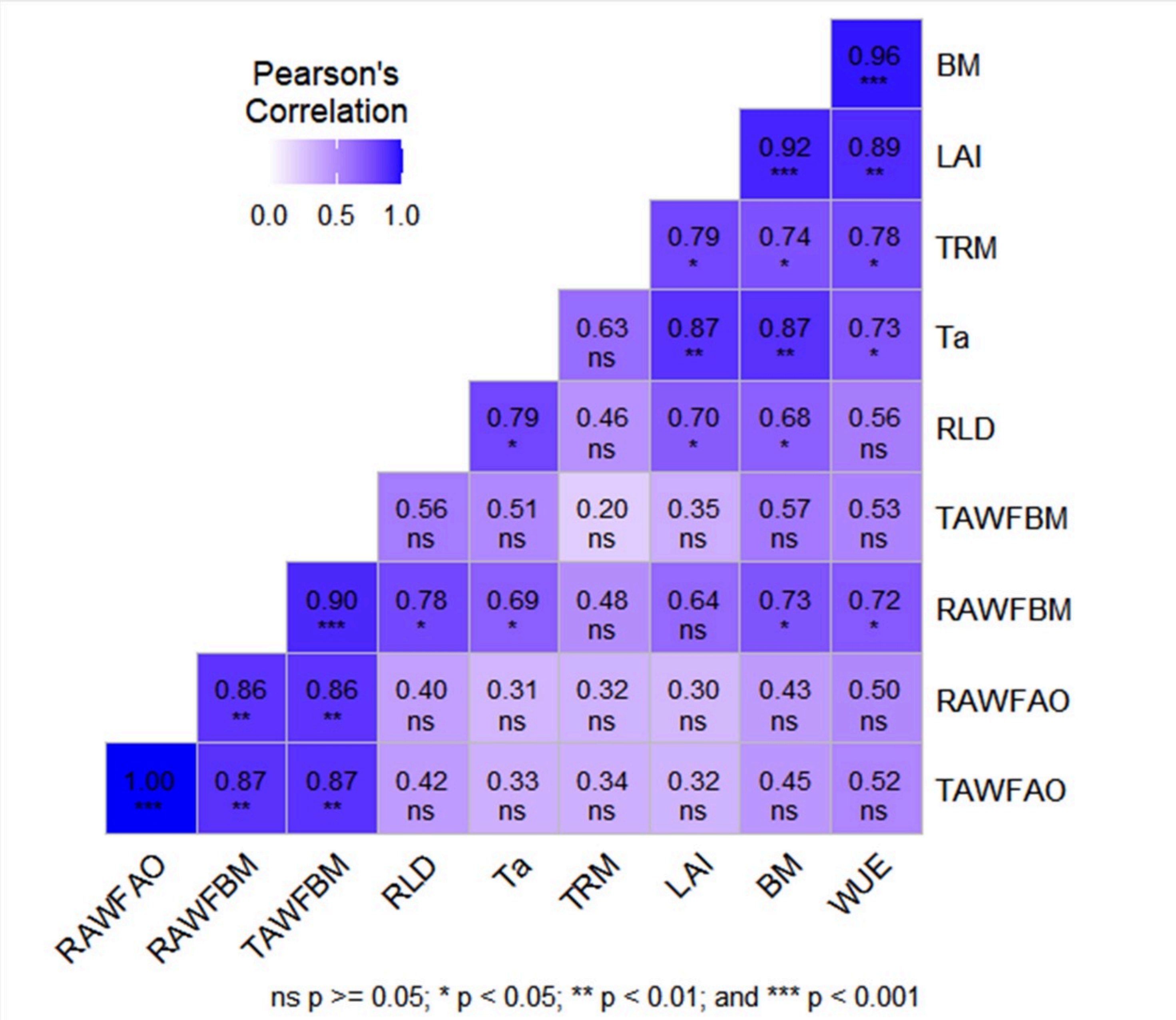

Figure 7

Pearson's correlation matrix between plant water availability, plant growth, and water use efficiency. The color gradient represents correlation strength and direction. Significant correlations are marked as $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***), non-significant correlations (ns) indicate $p \geq 0.05$

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