Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 412-426

Synergistic Effects of Biochar and Palm Fiber Amendments on Soil Water Retention and Pak Choi (*Brassica rapa subsp. chenensis*) Growth

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التأثيرات التآزرية للفحم الحيوي وألياف النخيل على أحتفاظ الماء في التربة ونمو نبات الباك تشوي(*Brassica rapa subsp. chenensis*)

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Received: 10-02-2026; Accepted: 22-04-2026; Published: 11-05-2026

Abstract:

This study evaluated the synergetic effects of coconut husk biochar and palm fiber as soil amendments on moisture retention and *Pak Choi (Brassica rapa subsp. chenensis)* growth under water-limited conditions. An experiment was performed through a completely randomized design pot with four treatments: control (T_0), 5% biochar (T_1), 5% palm fiber (T_2), and 5% biochar + 5% palm fiber (T_3) and restricted irrigation of about 200 mL poultice by pot every two days for the period of experimental phase which last for over duration of time up until n=3 pots were completed in milestone. At the final harvest, combined amendment T3 was significantly more effective than all treatments for plant height (15.67 ± 0.58 cm), leaf count (12.00 ± 0.00), fresh biomass (34.67 ± 0.58 g) and dry biomass (3.50 ± 0.00 g) representing an increase of 36.9% and 180% in fresh and dry biomass compared to the control, respectively. At Week 5, soil moisture was highest in T3 (32.67 ± 2.52%) while increased electrical conductivity in biochar-amended treatments reflected enhanced potassium availability not salinisation. These results demonstrate to validate that biochar and palm fiber work synergistically, as the biochar improves water and nutrient retention while the palm fiber enhances soil aggregate stability, representing a promising and inexpensive amendment for arid or semi-arid sandy loam under limited irrigation in many farming systems.

Keywords: biochar, palm fiber, soil water retention, *Pak Choi*, water-limited conditions, potassium availability, electrical conductivity.

الملخص:

قامت هذه الدراسة بتقييم التأثيرات التآزرية لكل (الفحم حيوي) قشور جوز الهند وألياف النخيل كمعدّلات للتربة على احتفاظ الرطوبة ونمو نبات الباك تشوي (*Brassica rapa subsp. chenensis*) تحت ظروف محدودة من الري. أُجريت التجربة باستخدام تصميم عشوائي كامل في أصص من أربعة معالجات: الضابطة(T_0) ، 5% الفحم حيوي(T_1) ، 5% ألياف نخيل (T_2)، و5% الفحم حيوي + 5% ألياف نخيل(T_3) ، مع ري مقيد يبلغ حوالي 200 مل لكل أصيص كل يومين طوال فترة التجربة حتى اكتمال ثلاثة أصص لكل مرحلة.

عند الحصاد النهائي، أظهر المعالج المشترك T_3 فعالية أعلى بكثير مقارنةً بجميع المعالجات الأخرى من حيث ارتفاع النبات (15.67 ± 0.58 سم)، وعدد الأوراق (12.00 ± 0.00)، والكتلة الحيوية الطازجة (34.67 ± 0.58 جم) والكتلة الحيوية الجافة (3.50 ± 0.00 جم)، ممثلاً زيادة بنسبة 36.9% و180% في الكتلة الحيوية الطازجة والجافة على التوالي مقارنة بالضابطة. في الأسبوع الخامس، كانت رطوبة التربة الأعلى في(T3 (32.67 ± 2.52% ، في حين أن زيادة التوصيلية الكهربائية في المعالجات التي أُضيف لها البيو تشار انعكست على تحسين توافر البوتاسيوم دون إشارة إلى ملوحة.

وتُظهر هذه النتائج أن الفحم حيوي وألياف النخيل تعملان بتآزر، حيث يحسن الفحم حيوي احتفاظ التربة بالماء والمغذيات، بينما تعزز ألياف النخيل استقرار تجمعات التربة، مما يجعلها تعديلًا واعدًا وغير مكلف للتربة الرملية الطينية الجافة أو شبه الجافة تحت ظروف ري محدودة في العديد من أنظمة الزراعة.

الكلمات المفتاحية: فحم حيوي، ألياف النخيل؛ احتفاظ ماء التربة، الباك تشوي؛ ري محدود، إتاحة البوتاسيوم، التوصيل الكهربائي للتربة.

1. Introduction

Soil-based agriculture has ever-increasing challenges in modernity, especially for arid and semi-arid areas with a very low crop productivity due to factors such as water scarcity, enhanced evapotranspiration rates, and little soil structure(Rao and Patra 2023; Sharina and Rosli 2023). Soil fertility degradation propelled by urbanization, climate change and the unchecked use of herbicides and pesticides makes these challenges even worse. In drought-prone environments, excessive soil water evaporation leads to high irrigation losses and limited crop yield. Herein lies the heartbeat of all food security internationally, as we lag behind in innovation towards new soil amendments that can improve both physical and chemical characteristics of the growth medium to counter these limitations and ultimately feed earth's growing population(Huang and Gu 2019). One of the most effective solutions is creating biochar and natural fibers. Which can alter soil structure for better water retention and efficiency in agricultural use(Garc et al. 2022; Xia et al. 2023).

Biochar is a carbon rich processed material, made by pyrolysis of agricultural wastes like manure or wood residues in oxygen limited conditions (Ali et al. 2025; Shyam et al. 2025). Its recalcitrant composition and highly porous nature made biochar resistant to microbial degradation and provided a large surface area for nutrient and water storage(Ndede et al. 2022; Razzaghi, Bilson, and Arthur 2020). In arid and semi-arid soils, in which water accessibility is limited due to rapid drainage and significant evaporation rates, biochar has shown great potential to retain soil water holding capacity and minimize moisture loss(Edeh and Buss 2020). The application of biochar has been reported to increase the WHC by about 10-30 % based on reviews and meta-analyses, while enhancing effects were found increasingly in soils with coarse texture or drought-prone conditions(Ramesh and Raghavan 2024; Shyam et al. 2025). Besides its physical advantages, biochar leads to a better soil chemical state. Studies have reported that biochar amendment increases cation exchange capacity (CEC) and slowly releases essential nutrients such as K into the soil, directly raising EC as a reflection of increased ionic availability(Osman et al. 2022; Wang and Wang 2019b). Hence, monitoring EC together with moisture is crucial. The EC effect in soils under water-stress conditions takes into account both the nutrient-enrichment effect of biochar and the risk of solute concentration under limited irrigation (Shyam et al. 2025).

Similarly, soil K availability under amendment is physiologically important too for crops under water-deficit conditions. K helps regulate stomatal closure and maintain cell turgor pressure (Song et al. 2020). The overall synergistic effects are led to improved soil fertility, especially water-use efficiency in scenarios such as irrigation deficiency situations. Moreover, meta-analytical evidence shows that application of biochar leads to up to 9% reduction in soil bulk density and enhances both the field capacity and plant available water conten(Osman et al. 2022; Razzaghi and Arthur 2020). These benefits are particularly pronounced in sandy soils, where plant-available water can increase by up to 45 percent(Razzaghi and Arthur 2020). Other studies reported increases of 165-191% and for soils amended 5-10% (v/v) with biochar it was observed that there is significant increase in readily available water(Razzaghi and Arthur 2020).

Nonetheless, increased application rates can negatively influence water availability suggesting a need to tailor biochar dosage based on specific soil conditions.

Biochar improves chemical and moisture-retention elements, while palm fiber is emerging as an environmentally friendly soil enhancer where residues from palm substrates are in plentiful supply. In contrast, in the area of dryland agriculture, palm fiber adds mechanical reinforcement that enhances soil structure, porosity distribution and resistance to compaction(Alhakim et al. 2023; Kusumastuti et al. 2019). Fiber reinforcement improves bearing capacity, and assists both infiltration rates and surface runoff to mitigate erosion for arid conditions(Abanda et al. 2024). Under limited water, palm fiber plays an important role in keeping moisture within the root zone for longer by increasing soil aggregation and stability(Chen, Ding, and Li 2023).

Pak Choi (Brassica rapa subsp. chenensis) as a leafy vegetable cultivated for human consumption. Nutrition-wise *Pak Choi* is a highly sought-after variety rich in vitamin A, C and K along with calcium, potassium and magnesium (Nazrul et al. 2024). It also has antioxidants and sulphur-containing compounds (Jinglei et al. 2023). This species has high nutrient (nitrogen and potassium) requirements, as well as sensitivity to water stress, such that the species could be employed to assess any soil amendments under limited water conditions (Song et al. 2020). Also, biochar application has been reported to increase the retention of water-soluble nutrients such as nitrate (NO_3^-) and K, plant metabolic responses and nutrient uptake (Song et al. 2020), but studies on yield response or weight usually relate these effects with biochar rate. The low doses of biochar positively impacted plant growth and also improved water productivity as compared to control, whereas the high dose of biochar may reduce growth(Suharyatun et al. 2024).

However, previous experiments have proposed single contributions of biochar on biomass and described mere structural advantages from palm fiber in soil, little is understood of the synergistic action that these materials may exert for improving the capacity to retain water in soils to favour plant growth; especially important within arid and semiarid environments where both high temperatures and scarcity of water can limit crop production This study aims to assess the synergistic effect of biochar and palm fiber amendments on soil water retention and growth performance of *Pak Choi* (Brassica rapa subsp. chenensis) grown in water limited condition. As well, soil potassium availability, pH and EC. These findings could have important implications for sustainable soil management practices in arid and semi-arid regions, as the combination of moisture- and nutrient-retention properties from biochar with the structural benefits provided by palm fiber can lead to improved water-use efficiency and potentially enhanced agricultural productivity.

2- Materials & Methods

2.1 Soil Sampling and Characterization

The soil used in the pot experiments were classified as sandy loam, a type of light-textured soil characterized by low water-holding capacity. Sieve and hydrometer particle size analysis showed that the soil was coarse, porous, and well-drained. The soil was approximately 75% sand, 20% silt and 5% clay. Gravimetric field capacity (FC) and wilting point (WP), in addition to saturation hydraulic parameters were measured. A column vadose chamber was also employed according to the methods detailed in Dane and Topp (2020). Soil pH and EC of the initial soil were measured using the HANNA HI 9829 multiparameter meter on soil-water extracts recording a moderate EC (232 µS/cm) and neutral to slightly alkaline pH (6.60). Hydraulic conductivity (K) was measured using constant head and estimated 0.0033 cm s^{-1} indicating high permeability. The physical and chemical properties of the soil before amendment application are summarised in Table 1

Table 1: Initial Physical, hydraulic, and chemical properties of the soil used in the experiment.

Property	**Soil Type**			**(FC, %)**	**(WP, %)**	**Saturation** θs	**K (cm/s)**	**EC (µS/cm)**	**pH**
	Sand (%)	**Silt (%)**	**Clay (%)**						
Estimated Value	75	20	5	15	5	30	0.0033	232	6.60

2.2 Coconut Husk Biochar Preparation

The feedstock for biochar production was derived from coconut husks, a local organic agricultural waste. The coconut husks were washed to eliminate surface impurities and air-dried at room temperature for 48 hours. The biomass was then slow-pyrolysed in the laboratory-scale pyrolyzer under oxygen-limited conditions at 500 °C for a residence time of 2 hours as previously describes by Lehmann and Joseph (2009).The biochar was then allowed to cool down to room temperature (23 ± 1 °C), ground, and sieved (<2 mm) to classify it into a range that would ensure its even distribution when mixed with the soil. The prepared biochar was kept in hermetically sealed containers, stored in dry conditions until the time of use.

2.3 Palm Fiber Preparation

data palm residues (palm fronds) were used to obtain palm fiber as a natural soil amendment. Collected fibers were washed with tap water to remove adhering dust and impurities, and then air-dried at room temperature for 48 h to reduce moisture content. The dry material was then chopped into pieces (1-3 cm) to obtain homogenous distribution in soil matrix. The palm fibers which were prepared as described above, were stored in a dry room at room temperature before applying on the scales. The adopted size and preparation method aimed to enhance homogeneous soil mixing, thus providing a uniform experimental condition for all treatments.

2.4 Experimental Design

A controlled pot trial was executed to assess the effects of biochar and palm fiber amendments on soil water retention and the growth performance of Pak Choi under water-stress conditions. The arrangement of the experiment was in completely randomized design (CRD) consisting of four treatments: Control (T_0): Soil without amendment. Biochar (T_1): Soil amended with biochar. Palm fiber (T_2): Soil amended with palm fiber. Biochar + Palm fiber (T_3): Soil treated with biochar and palm fiber

Biochar and palm fiber were added to the soil in a concentration of 5% (w/w) for single treatments, whereas the combined treatment consisted of 5% biochar + 5% palm fiber. The amendments were mixed into the soil thoroughly so that each area received even amounts. All experiments were performed in triplicate (three replicates for each treatment), such that the overall experimental units consisted of 12 total. All plants were grown in standard size plastic pots of equal volume containing the same amount of prepared soil mix. *Pak Choi* seeds were directly sown in each pot, and seedlings were thinned after germination to obtain one plant per pot for uniform plant density. The experiment was performed in controlled environmental conditions and all pots had the same irrigation regime, to simulate water-limited conditions. To maintain consistency in the treatments, a constant volume of water was applied uniformly to each pot at regular intervals.

2.5 Irrigation and Growth Conditions

This experiment was conducted at the same environmental conditions to ensure identical plant growth. All pots were kept in natural daylight conditions with ambient temperature (25–30°C) suitable for lettuce cultivation. Two-day interval between watering: in order to mimic water-limited conditions, a constant volume of only 200 mL per pot every 48 hours was applied every 48 hours for the entire period of the experiment. Irrigation water had an EC of approximately 1.0 dS m^{-1}, indicating low-salinity water conditions. To isolate the effects of added amendments on soil moisture retention and plant growth, the irrigation regime was maintained uniformly across treatments. Waterlogging was avoided as care was taken to maintain uniform distribution of water across all experimental units.

2.6 Measurements and Analysis

2.6.1 Soil moisture and water retention

Volumetric soil moisture content (%) was performed with the help of a portable soil moisture meter, capable of providing water volumetric content measurements quickly and non-destructively. Measurements were taken at 48 hours after each irrigation event and was used as an indicator of soil water retention capacity under water-limited conditions. Mean values for each treatment were used to represent soil moisture conditions under water-limited conditions. Soil moisture was monitored over time to assess water-holding behaviour and allow a comparison of the effect performed by biochar and palm fiber amendments on soil desiccation.

2.6.2 The physicochemical properties (pH, EC, temperature and potassium) of the soil

Monitoring the soil physicochemical parameters include pH, EC, temperature and nutrient-related indicators were performed with portable hand-held soil multi-parameter meter (Gemho soil smart sensor). It provides direct in situ readings of soil pH, EC, temperature, and macronutrient content estimation K, based on built-in calibration algorithms. All measurements were performed at the same day of week every 48 h in order to reduce diurnal change (09:00). Soil temperature (°C) was obtained at a depth of 5 cm. EC (µS cm^{-1}) was used as a measure of ionic activity in the soil solution. K was expressed as mg kg^{-1} in relation to the device output and interpreted in relative abundance rather than as absolute laboratory-grade concentration. All measurement were performed from the same stationary point in each pot, and results are given as means of three replicates per treatment.

2.6.3 Plant Growth Parameters and Measurement Schedule

Plant growth was assessed during the experimental period on *Pak Choi* which was used to determine whether biochar and palm fiber amendments improved soil properties under a water-limited condition. The following measures were recorded weekly from the time seedlings had 2–3 true leaves including plant height (cm) and number of leaves per plant. Fresh biomass (g) and dry biomass (g), measured at harvest plants were sampled after 35 days of sowing which is the mature leafy stage and suitable for yield assessment. Plants dry biomass was determined by oven drying at 70°C until constant weight. This design enabled evaluation of both temporal growth dynamics, as well as final yield response to soil amendments.

2.6.4 Statistical Analysis

All data are represented as mean ± standard deviation (SD) of triplicates measurements ($n = 3$). The effects of the treatments on plant growth parameters include plant height, number of leaves, fresh mass, and dry biomass. As well, soil physicochemical properties include moisture content, pH, EC, and K availability were examined. One way analysis of variance (ANOVA) was used to test the differences among treatments. Where ANOVA demonstrated differences, treatment means were separated by Tukey's HSD post hoc test. All analyses were considered statistically significant at $p < 0.05$. Statistical analyses and graphical representations were performed in microsoft excel (Version 2021) via data analysis Tool Pak add-in.

3. Results and Discussion:

3.1 Plant Growth Performance

Effect of biochar and palm fiber amendments on the growth of *Pak Choi* was evaluated on a weekly basis throughout the 35-day pot culture experiment under limited water conditions 200 mL per pot every 48 hr. The plants were observed for some important growth parameters including Plant height, leaf number, fresh biomass and dry biomass. Figures 1-3 shows that all growth parameters measured were significantly increased compared to the unamended control, in a consistent and progressive manner for amended treatments.

3.1.1 Plant Height

Over the course of five weeks experimental period plant height increased as observed for all treatments (Figure 1). Seedling height was not significantly different from the test treatments at Week 1 ($p = 0.512$), with similar initial germination conditions represented in all treatments mean heights: T_0, 1.67 ± 0.58 cm; T_3, 2.33 ± 0.58 cm. Height data indicated that combined amendment treatment T_3 achieved the highest final height of 15.67 ± 0.58 cm, significantly higher than T_1 (14.33 ± 0.58 cm) and both T_0 (11.67 ± 0.58 cm) and T_2 (6.67 ± 0.58 cm) by Week 5 ($p < 0.05$).

Importantly, T_2 generated the shortest plants throughout all weeks. This can be explained with a bulking agent in palm fiber is fibrous and bulky, which probably temporarily changes bulk density and aeration that delayed onboarding for newly seedlings root. But, leave production later compensate for T_2 (3.1.2) indicating a morphological trade-off. The higher T_3 clearly shows the additive effect of biochar with palm value, where biochar is a source of stable nutrient-rich micropores while palm fibre acts as a supportive structural backbone in the root zone consistent with earlier combined organic amendment influence findings by Razzaghi et al (2020) and Ali et al (2025).

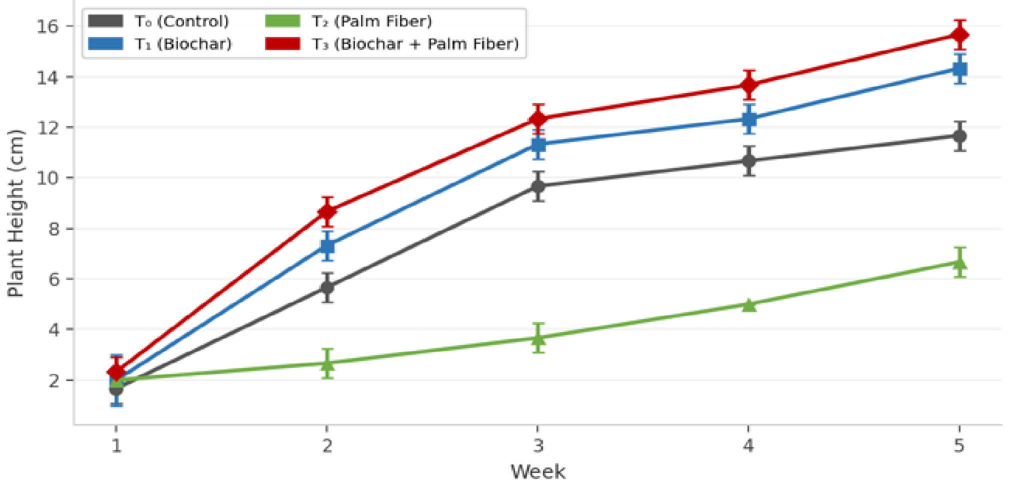

Figure 1: Weekly the plant height (cm) of *Pak Choi* in different soil amendment treatments (mean ± SD, n = 3). Error bars represent standard deviation.

3.1.2 Number of Leaves

Based on Figure 2 shows that the overall number of leaves per plant tended to increase with week in all treatments. Notably, a prominent disjunction appeared at Week 5 as T_2 resulted in the third highest leaf count (10.33 ± 0.58), outpacing both T_1 (7.33 ± 0.58) and approaching T_3 (12.00 ± 0.00). This implies that palm fiber may preferentially encourage vegetative branching and leaf development possibly due to improved aeration and water retention in the root zone even when overall elongation growth is composted.

T_3 expressed the highest final leaf count (12.00 ± 0.00), correlating to its superior overall growth trajectory. At harvest, the number of leaves was 7.67 ± 0.58 for T_0. Increase in leaf number under amended treatments is ecologically important as canopy development and photosynthetic capacity are directly correlated to yield of leafy vegetables. Such response of T_2 in leaf production has been reported by (Chen and Li 2023) observed that soil reinforced with palm fibers stimulated lateral root production, which may facilitate wider canopy development.

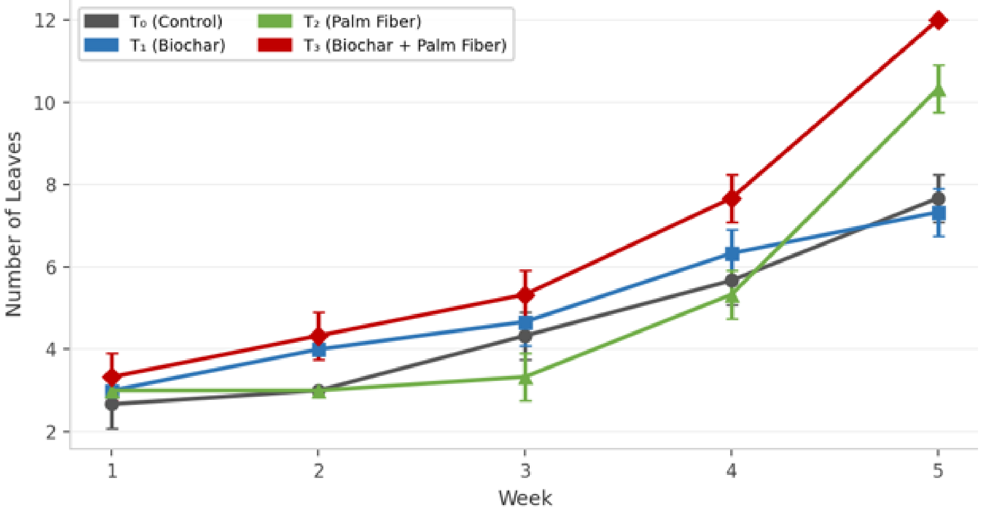

Figure 2: Weekly number of leaves per plant of *Pak Choi* under variance soil amendment treatments (mean ± SD, n = 3). Error bars represent standard deviation

3.1.3 Biomass Typology at Harvest (Fresh and Dry)

By the time of final harvest (Week 5), biomass accumulation differed significantly among treatments (Table 3; Figure 3). The highest fresh biomass (34.67 ± 0.58 g) and dry biomass (3.50 ± 0.00 g) values were found in T_3 increasing to about37 %and 180 %respectively when compared with control T_0(25.33 ± 0.58 g fresh; 1,25 ± 0,00 g dry). The total biomass was of 29.67 ± 0.58 g fresh and 1.50 ± 0.00 g dry for T_1 treatment, as well as for T_2 19.45±0,6g fresh and 1.,40± o.oo g dry biomass. The noteworthily greater dry biomass of T_3 as compared to its fresh biomass increase, indicate that the combination amendment stimulated not only vegetative mass but also dry matter content   a proxy measure for efficient carbon and nutrient use. T_3 biochar fraction likely contributed via greater nutrient retention especially K^+, while palm fiber assisted in structural stability, enabling root expansion. Those findings are also supported by Isaac (2020) who found that the use of low doses biochar significantly improved both water productivity and yield for many crops, in agreement with Garc et al (2022) who described increased growth of *lettuce* with biochar-amended peat substrates.

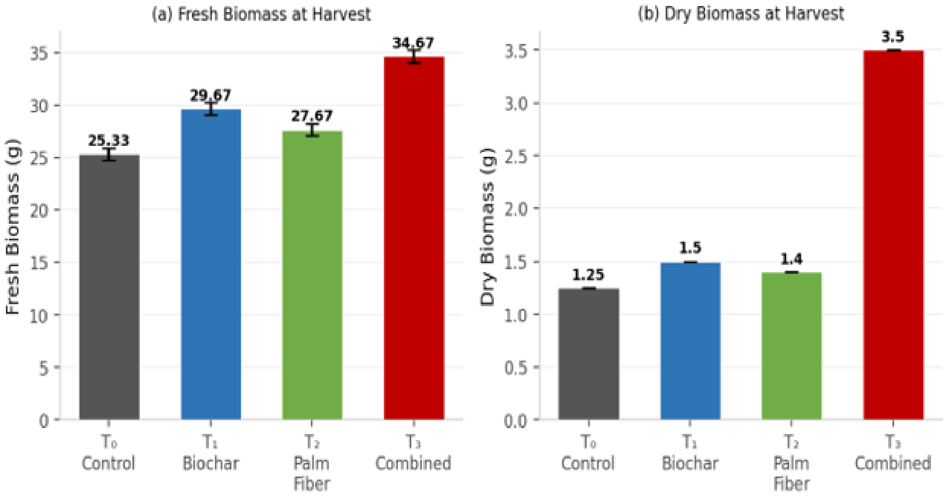

Figure 3: *Pak Choi* fresh biomass (a) and dry biomass (b) at weeks 5 harvests with different soil amendments (mean ± SD, n = 3).

3.2 Soil Moisture Content

Soil volumetric moisture content as percentage. The measured two days post each irrigation event declined progressively from week 1 to week 5. All treatments were under the imposed water-limited regime 200 mL every 48 h. This overall declining trend represents both the cumulative drying of soil moisture and/or plant uptake of water. There, however, were significant treatment-level differences Figure 4. In the WK1, T_0 had the highest initial moisture content (37.00 ± 1.73%) which likely represents no highly porous amendments and a relatively undisturbed soil structure. Nevertheless, T_0 manifested its greater decline overall though, dipping to 25.67 ± 2.08% by Week 5: A stark drop of approximately −11.33 percentage points. On the other hand, T_3 recorded relatively higher and more stable wet bulk densities than the rest of treatments starting from 30.00 ± 0.00% then retaining 32.67 ±2.52% at Week 5 which was also considered as the highest in moisture content alongside with final measured weights among all set of treatments used. This retention behavior is additionally consistent with the hypothesis that multi-indexing for the combined amendment produces a synergetic water-holding matrix, where biochar micropores trap water and palm fiber reinforces soil structure in effect reducing evaporative losses during periods of soil drying.

T_1 and T_2 also followed this trend with intermittently moderate moisture levels 26.67% and 26.67% at Week 5, respectively. But results did not show consistent superiority over each other overall. The gradual convergence of moisture values among treatments in Weeks 3–5 may indicate progressive equilibration of the soil-amendment system subjected to a fixed irrigation schedule. Additionally, in a meta-analysis Edeh and Buss (2020) reported that application of biochar increased soil water retention 10-30% in coarse-textured soils. Razzaghi et al (2020) also observed increases plant-available water to up 45% in sandy soils amended with biochar

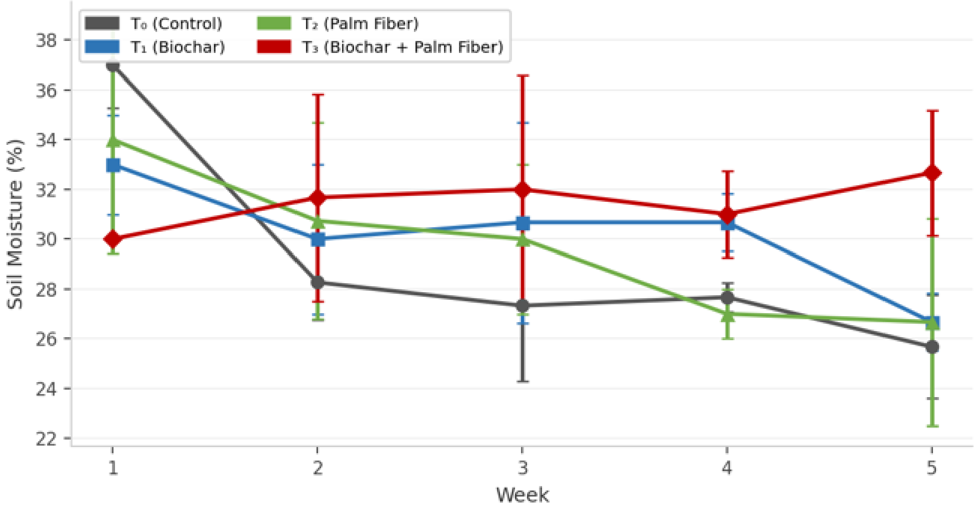

Figure 4: Weekly volumetric soil moisture content (%) after irrigation 48 hours, under variance soil amendment treatments (mean ± SD, n = 3).

3.3 Soil Electrical Conductivity (EC)

Soil EC (µS/cm) displayed strong patterns of treatment dependence throughout the study period Figure 5. T_3 starting with the highest EC of week 1 (327.00 ± 2.00 µS/cm) then gradually decreased by week 5 to 203.00 ± 1.00 µS/cm. Likewise, T_1 remained with the highest EC along the entire period (204.00 ± 1.00 µS/cm at week 1, increased to 264.33 ± 4.51µS/cm until Week 5. While T_0 presented a lower trajectory for EC throughout time, decreasing from139;00 ± 1;00 µS/cm to 62;00±4;00 µS/cm during five weeks of growing.

It is a recognized property of biochar that it can increase ionic availability in the soil solution by releasing soluble salts. Moreover, improving general cation exchange capacity (CEC), thus accounting for the higher EC of these treatments. As reported by Osman et al(2022) and Jianlong and Wang (2019) biochar addition increased EC as a function of nutrient enrichment rather than salinization, especially K, Ca, and Mg . The decreasing EC in T_0 over time indicates that the physiological microorganism T_0 in the unamended control was subjected to progressively declining nutrients with repetitive irrigation. The fairly stable and intermediate EC of palm fiber in T_2 (135–105 µS/cm) implies a low contribution of ionic enrichment. However, it may improve nutrient storage by enhancing soil aggregation.

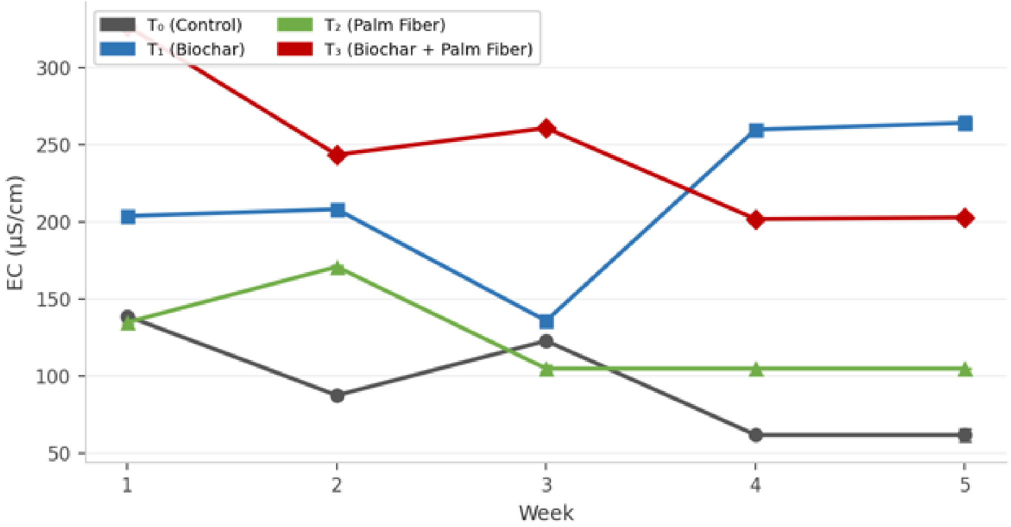

Figure 5: Weekly soil electrical conductivity (EC, µS/cm) as measured under the 3 variance soil amendment treatments (Mean ± SD, n = 3).

3.4 Soil Potassium (K) Availability

Soil K (mg/kg) was strikingly differentiated across amendments over the study Figure 6. T_3 exhibited the highest initial K of 46.00 ± 1.00 mg/kg for week 1, and decreased steadily by seven days to 30.33 ± 0.58 mg/kg at five weeks presumably indicating progressively increasing plant uptake. K was continuously released from that produced by torrefaction T_1 and increased with time, ranging from 32.00 ± 1.00 mg/kg to 42.33 ± 0.58 mg/kg at weeks 1 and 5 respectively Figures 2, indicative of a nutrient slow-release dynamic from biochar within the intermittent flooded root zone conditions imposed through wetting cycles during the experimental period.

Only T_0 had the lowest K availability which diminished quickly from 21.33 ± 1.53 to 11.33 ± 0.58 mg/kg. Thus, supporting nutrient depletion in the water-limited but amendment-free conditions imposed on these study units. However, with moderate but very stable K levels 23.00 to 15.00 mg/kg. As well, T_2 had no effect on increasing K availability indicating that palm fiber is not a primary k source it does not contain any K by its own. Therefore, the main reason of improvement- soil structure, slow down leaching and prolonging the time for k to liberate into a way which could be taken by plants. rather than its microbial decomposition since there is relation between K sources with soil services. These K dynamics are similar to those of Osman et al(2022).

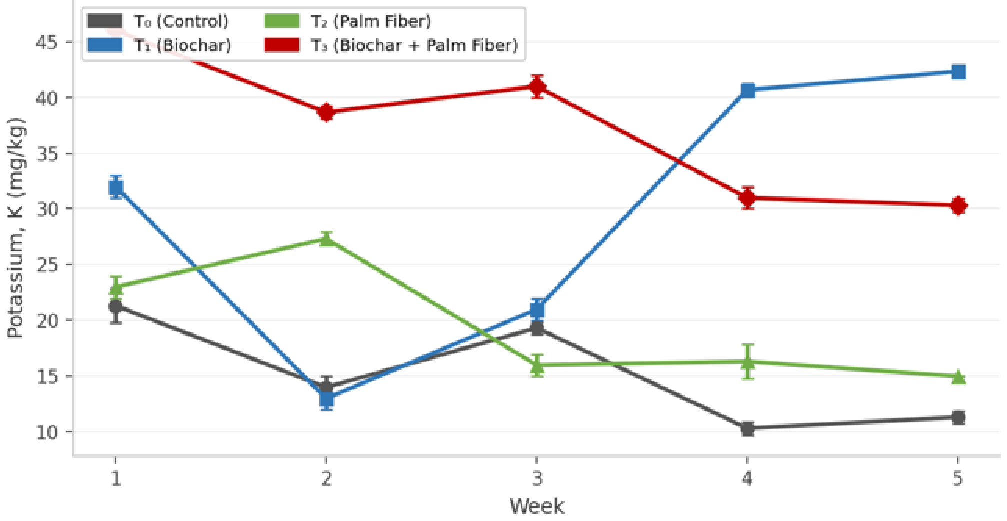

Figure 6: Soil potassium (K, mg/kg) weekly monitoring under each soil amendment treatment (mean ± SD, n = 3).

3.5 Soil pH

Soil pH displayed divergent treatment trajectories over the five-week period Figure 7. T_0 showed a progressive increase in pH from 4.60 ± 0.10 at week 1 to 6.00 ± 0.10 at weeks 4 and 5, approaching neutral conditions. This gradual alkalinisation in the control is likely attributable to the leaching of acidifying ions under repeated irrigation and natural soil buffering processes. In contrast, biochar-amended soils T_1 and T_3 maintained persistently acidic pH values approximately 4.00- 4.10 throughout the experiment. The acidifying effect of coconut husk biochar, pyrolyzed at 500°C, may reflect the inherent acidity of the feedstock and production conditions coconut husk biochar has been reported to have variable pH depending on pyrolysis temperature and ash content Lehmann and Joseph (2024) T_2 showed an intermediate pH trajectory (4.00-5.20), with slight alkalinisation over time. The consistently low pH in T_1 and T_3 warrants consideration in future studies. This is because pH below 4.5 may limit nutrient availability and beneficial microbial activity, particularly affecting phosphorus and molybdenum uptake. Despite this, T_3 achieved the highest growth and biomass. This suggesting that adequate moisture and K retention compensated for the sub-optimal pH conditions within the 35-day experimental window.

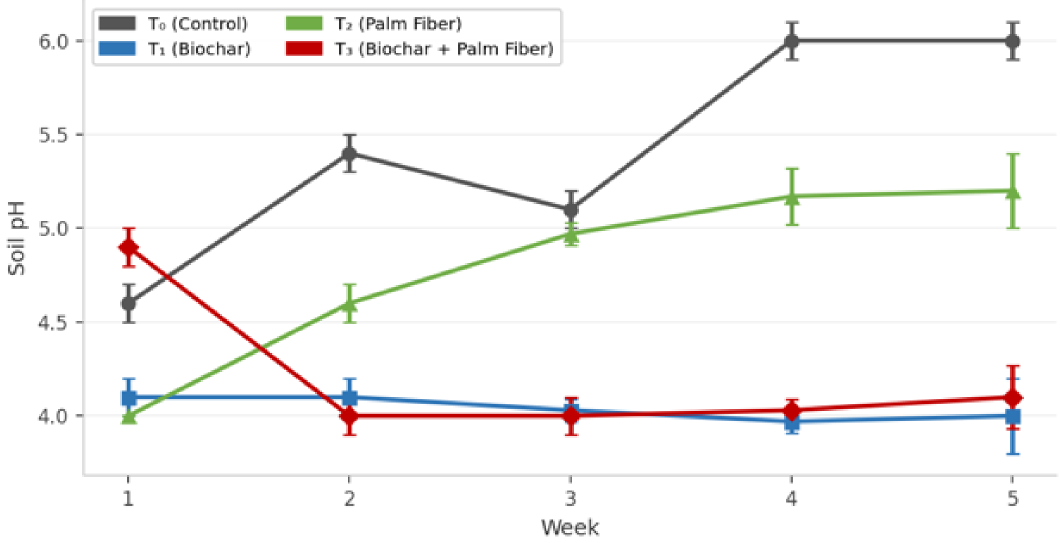

Figure 7: Mean weekly soil pH values under different treatments (Mean ± SD, n = 3)

3.6 Combined Amendments and Synergistic Effects

The general findings clearly demonstrated that the treatment with a combination of biochar and palm fiber T_3 provided significantly better results on all measured parameters. These included plant height, number of leaves, fresh biomass, dry weight ratio and moisture absorption. Such improvements occurred to a greater extent than in the individual amendment treatments T_1 and T_2. The performance of T_3 was also significantly better than the unamended control T_0. The appearance of this pattern is in line with the positive synergism between biochar and palm fiber as soil amendments. This is synergistic because of functional complementarity in the soil system. Overall, the high specific surface area of biochar provides a space for water and nutrient adsorption increases ionic availability reflected in increased EC and K and enhances microbial activity through improved microhabitat formation. On the other hand, palm fiber fortifies soil aggregates and thus it mitigates the risk of compaction-induced waterlogging whilst retaining air in the root zone. Altogether these attributes form an amendment matrix to correct the major deficiencies of sandy loam soils in water-limited conditions. This includes fast drainage, restricted moisture-holding capacity and nutrient leaching much more efficiently than either material alone.

The increase of 180% dry biomass T_3 over T_0 is consistent with a significant improvement in water-use efficiency agronomically. Under the irrigation regime of 200 mL per pot every 48-h simulating water-limited field condition the combined amendment-maintained crop yields at levels significantly greater than in the control. This indicating potential applicability for sandy soils typical to many tropical and semi-arid agricultural systems. These results expand the scope of previous conclusions derived from meta-analyses by Razzaghi et al (2020) and Edeh and Buss(2020) relating to biochar-mediated water retention. They further assess a new co-amendment system that includes natural fiber as an additional material. This condition for the indeed sustainment of a low pH and continuous improvement was observed in biochar-amended treatments T_1 and T_3. However, the impact can be tested better through long study periods. Positive responses were measured for growth parameters during the 35-day incubation. In addition, biochar pre-treatment or liming may be required to neutralize acidity during further cultivation of growth stages on pH-sensitive crops. Future work should use laboratory-quality K measurements rather than ion-exchange, which would enable direct comparison to peer-reviewed benchmarks of nutrient availability. Experiments with full replicate datasets should also be analyzed using ANOVA and Tukey's HSD post-hoc analysis to formally confirm the significance of treatment differences observed here.

4. Conclusion

This study showed that combined applications of coconut husk biochar and palm fiber T_3 significantly improved soil water retention as well as the growth performance of Pak Choi when irrigation was limited, thus outperforming single-amendment treatments and the control. At Week 5, dry biomass was significantly greater than control (+180%); T_3 exhibited the highest plant height (15.67 ± 0.58 cm), fresh biomass (34.67 ± 0.58 g), dry biomass (3.50 ± 0.00 g), and soil moisture retention (32.67 ± 2.52%). Such observations provide definitive evidence of synergy at work: the microporous structure of biochar improves retention of both water and nutrients, and palm fiber acts to reinforce soil aggregate stability and root zone aeration, together overcoming the most significant deficiencies presented by sandy loam soils under water deficit.

Higher electrical conductivity in biochar-treated T_0, T_1 and T_3 was due to improved potassium availability rather than detrimental salinisation. K driven alterations in stomatal control and plant turgor were further supported by longer-lasting slow-release kinetics of K. In contrast, only 30% T_2 used palm fiber alone but surprisingly produced the second highest leaf count despite a comparatively low plant height; the relationship between morphology and substrate utility may be more complex than it appears. Soil pH was low (approximately 4.0) in biochar-amended treatments and although this did not appear to limit plant growth over the 35-day period of cultivation, it is nevertheless an important consideration for long-term growing trials that may be undertaken with functional soil/cultivar combinations including biochars and should be addressed by pre-treating or otherwise buffering soil pH as appropriate in future experiments.

Overall, the suitability of the combined biochar–palm fiber amendment as a sustainable and locally available soil management strategy with practical implications for smallholder agriculture throughout water-stressed tropical regions is promising. Conclusions Should formal ANOVA, applicable field-scale validation work with appropriate/design based and optimized amendment rates, and standardization laboratory nutrient extraction analysis methods confirm the agroecological application of this combined amendment system; future research should/could be appropriately directed toward focused field scale studies.

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